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Relevance of Remote Sensing to Management of Heavy Metal Pollution in Soils and Plants: A Review

[1]Dr. Amukali, O., [2]Dr. Bariweni, P. A., [3]Imaitor-Uku, E. E., [4]Sophia, M. J.
[1]Researcher: Department of Environmental Management, Niger Delta University, Wilberforce Island, Amassoma, Bayelsa State, Nigeria.
[2]Reader: Department of Marine environment and Pollution Control, Nigeria Maritime University, Okerenkoko, Delta State, Nigeria.
[3]Lecturer: Department of Geography, Jasper Boro College of Education, Sagbama, Bayelsa State, Nigeria.
[4]Lecturer: Department of Economics, Jasper Boro College of Education, Sagbama, Bayelsa State, Nigeria.

Abstract: *Remote sensing technology has been used to detect, prevent and manage heavy metal pollution of soils and plants. Heavy metals are generally defined as metallic elements whose densities are greater than 5.0 g* cm^{-3} *or metalloids whose densities might be less than 5.0 g* cm^{-3} *but with high propensities to cause toxicities in living systems. Soils and plants are highly vulnerable to heavy metal pollution and effective management of which should focus on prompt monitoring of vast geographical regions within very short time-frames. Remote sensing remains an indispensable tool for studying vast geographical areas of land without being in physical contact with the objects studied. Thus, the need for a review of the relevance of remote sensing in managing heavy metal pollution of soils and plants arises. Principles of spectroscopy, benefits of remote sensing and implications for use in managing heavy metal pollution of soils and plants were evaluated in this discourse. Finally, illustrative examples of studies that applied remote sensing techniques for managing heavy metal pollution of soils and plants were considered. It was observed that remote sensing has been, still is and would continue to be a valuable tool for managing heavy metal pollution of vast geographical areas consisting of soils and plants, within short time-frames.*

Key Words*: Remote Sensing, Heavy Metals, Soils, Plants.*

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I. Introduction

Lillesand *et al*., (2003) defined remote sensing as the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in direct contact with the object, area or phenomenon under investigation. Remote sensing, in recent years, has become an important discipline for solving lots of environmental-oriented problems. It has become an increasingly important science for advancing understanding of environmental processes, conditions, and changes affecting both human and ecological health (Slonecker & Fisher, 2014). Advancements in sensor technology and processing algorithms have resulted in technical capabilities that can record and identify earth surface materials, including waste products, based on the interaction of electromagnetic energy with the molecular structure of the material being sensed (Goetz *et al*., 1985; Green *et al*.,, 1998; Clark 1999; Clark *et al*., 2009).

Remote sensing technology has been used to study a variety of phenomena; land use land cover changes (Twumasi & Merem, 2006), air pollution (Fagbeja, 2008), ground water studies (Maruo *et al*., 2002), plant and tree health (Zinnert *et al*., 2012), flood mapping and urban growth (Lopez-Pamo *et al*., 1999), heavy metal pollution (Choe *et al*., 2008), general superficial hazardous waste (Slonecker & Fisher, 2014) as well as a couple of other earth's phenomena.

According to Wilcke (2000), heavy metals are pollutants of high health and environmental concerns owing to their toxicities and persistence in the environment. The term heavy metal is used to describe metallic elements whose densities are greater than 5.0 g cm^{-3} (Barakat, 2011). But, metalloids whose densities are less than 5-0 g cm-3 but with high potentials to be toxic are also classified as heavy metals. Thus, it could be defined within that context as metallic elements whose densities are greater than 5.0 g cm^{-3} or metalloids whose densities might be less than 5.0 g cm^{-3} but with high propensities to cause toxicities in living systems. These include metals like Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, and Zn (SSSA 2008; Amukali, 2019). Metalloids whose densities might be less than 5.0g cm-3 but with relatively high toxicity levels are considered as heavy metals. Some of these elements are exclusively toxic (e.g. Cd, Cr, Hg, etc) while some others are essential for plant nutrition (e.g. Co, Cu, Fe, Mn, Ni, Zn, etc) but become a problem when the concentration is high enough to induce toxicities. Alloway (1995) identified major sources of heavy metals in soils to include a.)

geochemical, b.) anthropogenic (human activities) like mining and smelting, agriculture materials (e.g. fertilizers, pesticides, sewage sludge, etc), fossil fuel combustion, metallurgical and chemical industries, sports and military ammunition, and c.) atmospheric deposition.

Alloway (1995) stated that the toxicity of metals is intrinsic to their atomic structure and this makes it difficult for them to be transmuted and/or mineralized quickly to a total innocuous form. Furthermore, Vacha *et al*., (2012) stated that heavy metals are contaminants of major environmental and health concerns. Heavy metals are primarily contained in soils and released from their bound states through either the weathering of parent rock materials or from human activities (Mirsal, 2004). Ezeonu *et al*., (2012) reported that soils contaminated with heavy metals cause several environmental and human health problems, which calls for an effective technological solution. According to them, many affected sites around the world remain contaminated, because it is expensive to clean them up by available technologies. That notwithstanding, mapping heavy metal contaminated sites requires a great deal of hard work to be able to sample and report the extent of the heavy metal pollution in a timely manner.

Two major sources account for high levels of heavy metals in several media of economic importance to man that could make such media, contaminated; these areas- natural and their anthropogenic counterparts. Natural sources are those that evolved by nature as compared to the anthropogenic counterparts which occur in specific environments owing to their artificial introduction into such environments (Enger & Smith, 2010). Generally, heavy metals occur in natural systems at typical background concentrations as natural resources in such specific environments. At such levels, they might not necessarily constitute a threat to the environment. However, some authorities reiterate the fact that anthropogenic sources can induce higher concentrations of heavy metals relative to their normal background values and that when these occur, heavy metals are considered serious pollutants because of their toxicities, persistence and non-biodegradable conditions in the environment, thereby constituting threat to human beings and other forms of biological entities (Aina *et al*., 2009; Nwuche & Ugoji, 2008).

Heavy metal pollution has become a worldwide burden. For instance, according to Lone (2008), all countries have been affected by heavy metal pollution problem, though the area and severity of pollution vary enormously from one geographical area to the other. McGrath *et al*. (2001) reported that in Western Europe, for instance, that about 1,400,000 sites were affected by heavy metals, of which, over 300,000 sites were found to be contaminated. Although, it has been opined that the estimated total number of heavy metal contaminated sites in Europe could be much larger, as pollution problems increasingly occurred in Central and Eastern European countries (Gade, 2000). According to McKeehan, (2000), in the USA, there were over 600,000km brown fields which were contaminated with heavy metals and needed reclamation. Quoting government statistics, Ibid (2000) further stated that coal mine alone has contaminated more than 19,000km of US streams and rivers with heavy metals, acid mine drainage and polluted sediments. In addition, it was further estimated that more than 100,000ha of cropland, 55,000ha of pasture and 50,000ha of forest have been lost to heavy metal pollution (Ragnarsdottir & Hawkins, 2005).

The problem of land pollution has been reported to be a great challenge in China, where one-sixth of total arable land has been polluted by heavy metals, and more than 40% has been degraded to varying degrees due to erosion and desertification (Liu, 2006). Soil pollution is also severe in India, Pakistan and Bangladesh, where small industrial units are pouring their untreated effluents in the surface drains, which spread over near agricultural fields. Lone *et al* (2008) reported that in these Three countries, raw sewage is often used for producing vegetables near big cities and heavy metals that have been identified in such polluted environment included As, Cu, Cd, Pb, Cr, Ni, Hg and Zn.

To effectively address the high heavy metal problems in such contaminated sites, a key factor is proper mapping of the affected areas. However, constraints to effective mapping of heavy metal pollution in soils are mainly due to the fact that soil samples to be studied ought to be 'contacted' and the samples collected for onward transmission to laboratories where they could be analyzed following standard analytical procedures and processes. This implies that a vast majority of soils that one has not come in 'contact' with, could be excluded during sampling. Thus, in order to adequately map broader soil surfaces with a higher propensity to cover very large study areas, there is need to employ technologies that would not necessarily mean being in contact with the soils under investigation. Under such circumstances, remote sensing becomes the ultimate instrument of choice. Thus, this work was conceived to review advances that have been made in the use of remote sensing for effectively mapping heavy metal contamination of soils. This was the focus of this work.

The concept of hyper-spectral reflectance spectroscopy has been adopted as a guiding principle in this present discourse. This is because hyper-spectral images provide rich spectral, and generally spatially continuous information, that can be used for determining more detailed spectral properties of the soil surface and mineralogy, which can in turn be applied for mapping and monitoring soil contamination (Maliki *et al*., 2012). Figure 1 showed image of spectrally detectable soil components in graphics form as it aids proper understanding soil spectral signatures.

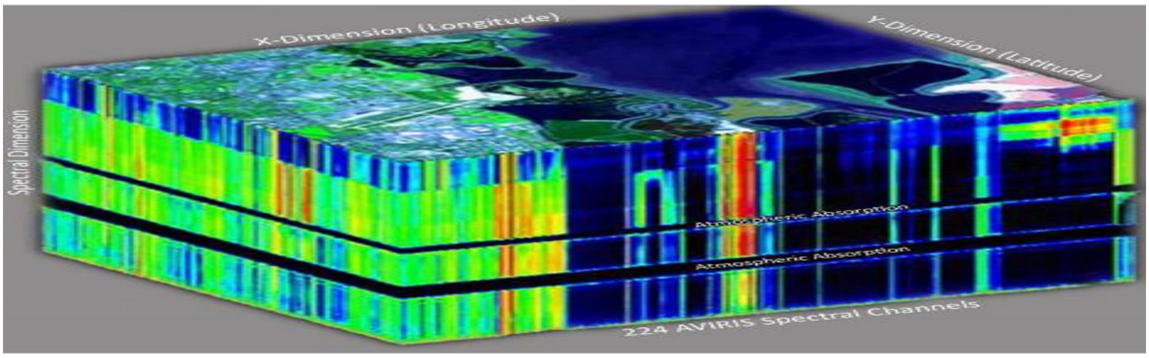

Figure 1: Example of Image Cube of Soils of Moffett Field, California. (Source: Slonecker & Fisher, 2014)

II. Relevance of Remote Sensing to Heavy Metal Pollution Control in Soils and Plants

One of the primary concerns for remote sensing analysis of contaminated media on the earth's surface is heavy metal contamination. Both the direct reflectance of metals in the soil matrix and the effect of metals on vegetation reflectance are potential observables on the earth's environment, thus the need to highlight importance of remote sensing to managing heavy metal contaminated soils and plants..

1. Relevance of Remote Sensing to Managing Heavy Metal Contamination of Soils

Many naturally occurring metals are constituents of minerals contained surficially or liberated after crustal disintegration of the weathered rocks. In mineral forms, metals can occur in complexes with other constituents. For instance, Pb occurs as galena just as Zn occurs as sphalerite. These metals occur naturally throughout the earth's crust and can be identified through field or imaging spectroscopy. However, when mined for the specific metal or used in industrial processes, waste metal concentrations in soils can be discharged in magnitude higher than natural concentrations and become risks to human and ecological health. The identification of metals and estimation of their concentrations in soils generally involve wet chemical acid digestion and methods such as USEPA Method 7421 for Pb, USEPA Method 7060A for As and USEPA 3052 for Fe, Zn, Cd, Cr, Co, Ni and Mn (USEPA, 1996), to mention but a few. In recent years, XRF methods (USEPA Method 6200) have also become accepted field methods for the determination of metals in soils (Amukali, 2019).

All of the above-mentioned methods require the collection of samples and laboratory analysis or, in the case of XRF technology, physical contact with the soil. Being physically in contact with sampled soils could pose limitations to extent of geographical areas sampled. This necessitates the need for technologies and tools that could be used to sample vast areas of soils without necessarily being in contact with the affected soils. A remote sensing method that might identify soil contamination remotely without physical contact has been a major new monitoring tool. Several studies have indicated the possibility of applying field and imaging spectroscopy in the identification of minerals containing heavy metals as an indicator of contamination in mining areas (Farrand & Harsanyi, 1997; Ferrier, 1999). Montero *et al*., (2005) assessed the potential of abandoned mines for acid mine drainage (AMD) by characterizing waste rock associated with acid drainage.

Studies by Kemper and Sommer (2002) and Choe *et al*., (2008) have demonstrated that direct, stand-off detection of high metal concentrations in soils is possible. Wu *et al* (2007) in a separate study showed that visible and near-infrared (VNIR) spectroscopy produced strong negative correlations with certain metals As, Cd, Cr, Cu, Hg, Pb, and Zn in contaminated soils, depending on iron oxide and organic carbon content while Choe *et al*., (2008) demonstrated that a band ratio of 610/500 nm and 1,344/778 nm correlated with concentration of Pb, Zn and As in soils. Wu *et al*., (2007) in their study demonstrated that continuum removed band depths at 610 nm and 830 nm and opined diagnostic presence of Cr and Cu in vulnerable soils. Mohammed et al., (2018) carried out an assessment of terrestrial oil spill dynamics using field spectra and sentinel 1 h-α decomposition and established the importance of remote sensing technology in monitoring oil spill dynamics.

2. Relevance of Remote Sensing to Managing Heavy Metal Contamination of Plants

Plants are veritable tools for monitoring of heavy metal environmental contamination as they end up bioaccumulating them into their tissues and could transfer same into other dependent organisms that feed directly or indirectly on them in the food chain. Thus, plants stand as key aspects in the study of fugitive hazardous wastes in the environment and these could reflect on vegetation cover. Heavy metals could come in contact with plants either through atmospheric intake via stomatal in leaves or lenticels on the stems or through roots of plants that are deeply rooted in contaminated soils (Dutta, 2008).

Zinnert *et al*., (2012) stated that remote sensing of vegetation stress has been, and continues to be, a key aspect of remote sensing research. Use of remote sensing in assessing heavy metal concentrations in plants started a long time ago. As far back as 1879, Rood (1879) used crude spectrographs to document differences in vegetation reflectance in different broad bands of the visible spectrum. Later on, other earlier researchers like Willstatter and Stoll (1913), and later in (1918) collaborated the same feat. Such earlier efforts necessitated further researches that better shaped remote sensing researches with respect to vegetative stress. For instance, Schull (1929) studied and measured the reflectance of various leaves using a prism spectrophotometer to attempt to better explain leaf-energy interactions that occur in photosynthesis. As aerial photography, film, and camera systems became available and more sophisticated, applications for crop monitoring became routine agricultural practice and this culminated into Colwell (1956) coming up with a research work that helped develop ways of identifying crop diseases from aerial photography.

Slonecker and Fisher (2014) reported that as both spectroscopic and remote sensing systems developed further, specific patterns of vegetation stress began to emerge and spawned a flurry of research starting in the 1990s. Ibid (2014) further opined that the shift in the "red edge" of vegetation reflectance (680 nm to 730 nm), related to plant health and/or stress, was identified and utilized in a number of research studies and is still being used today in studying vegetation condition. Owing to the paradigm shifts to the quantification approach adopted in most environmental-oriented studies, Thenkabail (2000) was able to develop a series of special spectral calculations, called "vegetation indices," to maximize and take advantage of high-spectral resolution and specific quality of vegetation growth and health. Slonecker and Fisher (2014) stated that vegetation indices are derived from the spectral reflectance properties of vegetation and are designed to accentuate a specific property of vegetation like leaf moisture content.

III. Constraints to Spectral Reflectance in Soils

1. **Spectral Mixing:**

A search through the literatures have shown that there existed previous studies that established the propensities of heavy metals in soils possessing spectral features that lie within the visible and near-infrared (NIR) regions. Many of these studies used these spectral features in detecting trace metal concentrations in the environment (Kemper & Sommer, 2003; Choe *et al*., 2008; Ji *et al*., 2010), thus establishing opportunities for detection of heavy metal pollution in such environments, depending on the quantities of heavy metals encountered in such environments. However, the quantitative assessment of soil components using reflectance spectra is a challenging problem because the assessment of the sub-pixel abundance of soil materials is complex (Garcia-Haro *et al*., 2005).

In practice most of the extracted pixel spectra would not be exclusively from the metal contaminant, but would be a complex mixture of spectra from various land surface elements (Kemper & Sommer, 2002 ; Garcia-Haro *et al*., 2005). Thus spectral mixing is an important issue to resolve in any reflectance spectroscopic study. It has been observed that in recent years, spectral mixture analysis (SMA) has developed as a widely used process for multi or hyper-spectral image processing. Luckily, the work of Garcia-Haro *et al*., (2005) has been able to solve this massive problem. In their work, they devised a unique technique that could identify the sub-pixel proportions of ground, plants and other materials represented in each pixel, where each of the components was labeled as an 'End-Member' (EM) and these elements fundamentally contributed to the observable spectral signal of the mixed pixels.

The Spectral Mixture Analysis (SMA) was developed to help decompose the reflectance spectrum of each pixel to the proportional spectral involvement (Kemper et al., 2000) thus giving rise to various spectra from EMs combining to form a single pixel spectrum, which is termed a-mixture model‖ (Ibid, 2000) and these models are then used in the un-mixing analysis. Maliki *et al*., (2012) pointed out that SMA permits repeatable and accurate extraction of quantitative sub-pixel information including physical models of surface processes, when supported by ground data. Furthermore, Garcia-Haro *et al*., (2005) specifically stated that SMA offers an efficient mechanism for understanding and classification of multidimensional imagery in remote sensing and this had been made possible owing to improvements in sensor spectral resolution since it allows for the quantification of the abundance of different materials within a single pixel using linear spectral un-mixing (Plaza *et al*., 2002). Maliki *et al*., (2012) reported the use of Spectral Mixture Analysis (SMA) modeling approach for field and airborne hyper-spectral data. Variable Multiple End-member Spectral Mixture Analysis (VMESMA) has also been used to estimate the quantities and distributions of remaining tailing materials by Schwartz *et al*. (2011). Already, VMESMA tools have been used by various authorities for providing quantitative information about the distribution of residual heavy metal contamination of surface constituents (Kemper *et al*., 2000; Plaza *et al*., 2002; Kemper & Sommer, 2003; Garcia-Haro *et al*., 2005).

2. **Soil Spectroscopy:**

It could be observed from available literatures that the last two decades have witnessed the evolution of a couple of studies that explored new remote sensing techniques utilizing reflected radiation of soils (Wu *et al*., 2005a; Wu *et al*., 2007; Ben-Dor *et al*., 2009; Minasny *et al*., 2009; Bilgili *et al*., 2010) in establishing the presence or absence of particular phenomena. As a result of these studies, the reflectance radiation across the VIS-NIR and SWIR in the region between 400-2500 nm (figure 1) is often considered a useful region with which to predict unknown soil properties. Such techniques are becoming more significant for the cost-effective coverage of large areas of lands and can provide chemical information relatively quicker as compared to traditional field sampling and subsequent chemical analyses. That notwithstanding, Ben-Dor *et al*., (2009) observed that the spectrally assigned position of minerals can be affected by chemical composition and physical conditions at the surface. Previous studies have shown that many soil properties have distinct spectral signatures (Ben-Dor *et al*., 2002; Kemper & Sommer, 2002; Bray *et al*., 2009). These included studies that focused on;

- cation exchange capacity (Fox & Metla, 2005),
- soil organic matter content (Galvão & Vitorello, 1998; Ben-Dor *et al*., 2002; Fox & Metla, 2005),
- iron content (Fox & Metla, 2005; Pastor *et al*., 2008) as well as
- soil electrical conductivity (Shrestha, 2006)

These constituents provide another possibility of identifying soil characteristics and assessment of soil properties quantitatively using field or laboratory radiometry (Bray *et al*., 2009; Ji *et al*., 2010; Yaolin *et al*., 2011). Kooistra *et al*. (2001) applied visible-near-infrared spectroscopy to assess soil contamination in river floodplains soils in the Netherlands and concluded that, in floodplain soils, metal concentrations depended on the exchange capacity of the soil. Soil surveys using VNIR spectra have become valuable techniques for identification of several soil properties and can be applied for soil conservation (Pastor *et al*., 2008). It is therefore clear that remote sensing techniques have the potential to accurately identify soils properties for different environmental and agricultural purposes.

3. **High Spectral Soil Components:**

Remote sensing studies focusing on soils are mainly possible through distinctive investigation of the component Soil Organic Matter (SOM). This is because the SOM has distinctive spectra particularly in the NIR due to formation of covalent bonds with a variety of molecules (Schwartz *et al*., 2011). Basis for such studies predicated mainly upon the principles of reflectance. Studies that focused on SOM as investigative evidence for accurately predicting heavy metal contamination of soils using reflectance spectroscopy exist (Krishnan *et al*., 1980; Rossel *et al* (2006). Thus, investigative studies of this nature could be used to complement normal laboratory analysis of such soils using AAS technique.

For instance; estimation of SOM was more appropriate in the visible region (Krishnan *et al*., 1980). This was also in agreement with the work of Rossel *et al* (2006) who observed that the prediction of soil organic carbon (SOC) was better in the VIS range at 410, 570 and 660 nm. Later on, some researchers reported a significant correlation between soil organic matter and spectral reflectance in the range 545 - 830 nm (Lu *et al*., 2007; Yaolin *et al*., 2011). The studies also indicated that a good correlation between soil properties and spectroscopy occurred when the first-order derivative of spectral reflectance was used (Lu *et al*., 2007; Yaolin *et al*., 2011). Thus, it could be safely stated that the number of spectral regions and quantitative predictions of SOM and SOC are very important concepts in studying the heavy metal levels in vulnerable soils. In another study, it was observed that the concentration of SOM is inversely related to reflectance in the VIS and NIR range, especially, when the organic content is more than 2% (Summers, 2009). Soil organic carbon and organic matter as the case may be, has been predicted using multivariate analyses and spectral response in the VIS, NIR and MIR regions of the electromagnetic spectrum for heavy metals. For instance, Iron oxide content has been accurately predicted in the VNIR region using reflectance spectroscopy due to the characteristic absorption features of iron oxide (Ben-Dor & Banin, 1995; Chang *et al*., 2001; Kemper & Sommer, 2002; Wu *et al*., 2007).

Ben-Dor and Banin, (1995) and Ben-Dor *et al*., (2009) reported that four distinct regions most commonly used for the determination of iron oxide content included 550-650,750-950, 1406 and 2449 nm respectively. A recent study indicated that the absorption features of Iron oxides at wavelengths between 400-1300 nm can best be used to predict iron oxide content (Summers, 2009). Earlier studies established that the spectral features of clays were most prevalent in the NIR region where distinctive absorption bands can be used to provide quantitative information on clay mineralogy (Al-Abbas *et al*., 1972; Wetterlind *et al.*, 2008) and reflectance spectroscopy as well as regression modeling been used for prediction of total clay content (Waiser *et al*., 2006; Rossel *et al*., 2009; Summers, 2009). In addition, Chabrillat *et al*., (2002) also found that hyper-spectral imagery can be used to reliably predict clay mineralogy at 2200 μm due to the characteristic features of the clay minerals. Similarly, Clark (1999) found that clay minerals showed characteristic absorption bands at approximately 2200μm.

In general, finer soil textures were found to be darker than coarse textured soils (Summers, 2009), and consequently soils with sand or silt (> 0.002 mm) had higher spectral reflectance than clay minerals (< 0.002 mm) due to the increased water (high absorption of spectra) filling capacity of clay. All of these studies confirm that VNIR spectral based techniques have the potential to accurately help in identifying a myriad of different soil properties.

IV. Need for Intensification of Use of Remote Sensing in Heavy Metals Pollution Management

Heavy metal pollution has assumed status as a global health and environmental problem, thus, requires sophisticated advancements in technologies for quantitatively and qualitatively sampling and analyzing very large geographical areas, phenomena or systems within very short time frames. The timely and correct use of remote sensing techniques for determining presence of heavy metal pollutants in soils and plants is a good tool in this regard. But, owing to facts as remote sensing is a discipline that has very low 'noise level', highly quantitative and technical in nature, studies utilizing this technology in heavy metal studies have been fewer than other methods. This should not be so. Rather, despite doing ground truthing, physical sampling and carrying out laboratory analyses, researchers should use remote sensing to complement such studies. This would help increase the 'noise level' of remote sensing as a reliably viable tool for heavy metal pollution-centered researches and help better presentation of data in geospatial formats for better understanding.

Within the purview of this work, it could be safely stated that as a scientific endeavour, remote sensing seeks to make heavy metal pollution investigations better conceptualized, generate reliable results faster and enhance efficient generation of accurate data for predictions of present and futuristic events. This is the reason why studies on remote sensing technologies for investigations of heavy metal pollution should be intensified by researchers.

V. Conclusion

As long as industrial and household-related activities go on in different parts of the earth, heavy metal-bearing wastes of different aetiological backgrounds would continue to be discharged into the environment, directly or indirectly. Heavy metals are generally persistent and very toxic to living systems when certain threshold levels are exceeded. They could become highly ubiquitous and very difficult to track, quantify or manage. Thus, the need to track the sources, quantify and manage heavy metal pollution over very large geographical locations consisting of soils and plants in a timely manner can never be over-emphasized.

Remote sensing remains the technology of choice for studying very large geographical locations and making highly accurate predictive conclusions within very short time frames. This work has been able to look at various studies that employed remote sensing technologies for studying impacts of heavy metals in soils and plants. With time, more sophisticated equipment, with better resolutions would be developed and remote sensing would become a 'one-stop' choice for investigations of heavy metal-related pollution issues in soils and plants.

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