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Toxic metals in East African agro-ecosystems: Key risks for sustainable food production

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ABSTRACT

The dramatic increase in world population underpins current escalating food demand, which requires increased productivity in the available arable land through agricultural intensification. Agricultural intensification involves increased agrochemicals use to increase land productivity. Increased uses of agrochemicals pose environmental and ecological risks such as contamination and water eutrophication. Consequently, toxic metals accumulate in plant products, thus entering the food chain leading to health concerns. To achieve this study, secondary data from peer-reviewed papers, universities, and government authorities were collected from a public database using Tanzania as a case study. Data from Science Direct, Web of Science, and other internet sources were gathered using specific keywords such as nutrient saturation and losses, water eutrophication, potentially toxic metal (PTEs), and impact of toxic metals on soils, water, and food safety. The reported toxic metal concentrations in agro-ecosystem worldwide are linked to agricultural intensification, mining, and urbanization. Statistical analysis of secondary data collected from East African agro-ecosystem had wide range of toxic metals concentration such as; mercury (0.001–11.0 mg Hg/kg), copper (0.14–312 mg Cu/kg), cadmium (0.02–13.8 mg Cd/kg), zinc (0.27–19.30 mg Zn/kg), lead (0.75–51.7 mg Pb/kg) and chromium (19.14–34.9 mg Cr/kg). In some cases, metal concentrations were above the FAO/WHO maximum permissible limits for soil health. To achieve high agricultural productivity and environmental safety, key research-informed policy needs are proposed: (i) development of regulatory guidelines for agrochemicals uses, (ii) establishment of agro-environmental quality indicators for soils and water assessment to monitor agro-ecosystem quality changes, and (iii) adoption of best farming practices such as split fertilization, cover cropping, reduced tillage, drip irrigation to ensure crop productivity and agro-ecosystem sustainability. Therefore, robust and representative evaluation of current soil contamination status, sources, and processes leading to pollution are paramount. To achieve safe and sustainable food production, management of potential toxic metal in agro-ecosystems is vital.

1. Introduction

The agricultural ecosystems of East Africa embrace a complex socio-ecological system that is sensitive to climatic and environmental changes (Wynants et al., 2019). East African agro-system includes crop farming (arable), livestock production, fishing (aquaculture), conservation activities, and rural settlements. The East African agro-ecosystem is complexity making the system very difficult to be monitored and managed. The highland and lowland areas of the agro-ecosystem are home to different natural and anthropogenic activities which positively and negatively influence agro-ecosystem functionality. Farming activities and other anthropogenic activities in or in proximity to the agro-ecosystem have profound environmental and ecological influences (Moss, 2008). The increasing world population requires more food and fiber production, putting pressure to intensify farming to maximize yields. Application of different agrochemicals such as fertilizer, pesticides, herbicides, organic manure, and growth regulators has been employed to increase production per unit area to meet increased food

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demand (Kimaro, 2019). Application of agrochemicals such as inorganic fertilizer provides higher nutrients like nitrogen-N, phosphorus-P, potassium-K, and other micronutrients required for crop production and high yield. In most developing countries, despite the increased use of agrochemicals (Steffen et al., 2018), there is little training provided to farmers on application rate, best practices for agrochemicals uses and management. In addition, there is a lack of documented guidelines for the maximum limits of the amount of agrochemicals to be used in a particular crop, area, or system to ensure high yields and environmental safety (Matowo et al., 2020). Besides the availability of fertilizer recommendations in East African countries, most of them are more than thirty years old, which might be outdated following current climatic changes and their impact on environmental process responses. Of particular concern, the use of commercial fertilizer and other agrochemicals is often conducted without proper advice from agricultural officers (Isham, 2005). The rate of fertilizer and pesticide used has dramatically increased in East Africa; for example, pesticide application in horticultural crops and paddy farming areas has increased from 1 to 5 per cropping season to 1–41 per cropping season (Nonga et al., 2011). The situation raises the production cost and is likely to increase the pesticide resistance to crop pests and increase environmental contaminations from pesticide residuals. Therefore, the application of agrochemicals higher than plant requirements or above recommended is likely to result in environmental pollution (De López Camelo et al., 1997; Kelepertzis, 2014; Khani et al., 2017; Shah et al., 2013). For example, excess amounts N ($>$1.0 mg/L) and P ($>$0.01 mg/L) in aquatic ecosystems have been observed to have detrimental impacts on the system (Balmford et al., 2012). The increase of N and P and pesticide residues to surface water and groundwaters increases potentially toxic metal accumulation (PTEs) and eutrophication (Moss, 2008; Sharpley, 2015; Torrent et al., 2007).

Potentially toxic metals (PTEs) are elements with potential toxicity effects on soil invertebrates, plants, and animals. PTEs are non-essential elements such as mercury (Hg), lead (Pb), chromium (Cr), cadmium (Cd), and arsenic (As) which are toxic to plants, animals, and humans (Abdu et al., 2011; Addis and Abebaw, 2017; Li et al., 2021; Lü et al., 2021; Qin et al., 2021; Renu et al., 2021). Other PTEs such as iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), cobalt (Co), and selenium (Se) are plant micronutrients at low concentrations. PTEs such as Cd, Pb, Hg, and Cr are known for their toxicity and bioaccumulation potential in the environment and are considered critical pollutants by regulatory authorities (Gujre et al., 2021; Heidari et al., 2021; Li et al., 2021; Xu et al., 2017). The concentration of PTEs in soils within agricultural ecosystems is a key environmental quality indicator because soil is a primary source of PTEs to plants and food chain (Liu et al., 2007; Ma et al., 2021; Qin et al., 2021; Renu et al., 2021; Singh et al., 2020). PTEs accumulation in soil and plant materials can elevate its level in the human body via food products posing a health risk (Chabukdhara and Nema, 2013; Phuong et al, 2008, 2010).

In parallel, the challenge of toxic metal pollution has been recognized across Africa (Nriagu, 1992). In East Africa, PTEs accumulation in agro-ecosystems is governed by agriculture intensification, farming systems, industrialization and urbanization, climate and land-use change. These collectively influence the agro-ecosystem, together with regulatory policies, leading, directly and indirectly, to either sustainably increased food production or reduced production and agro-ecosystem degradation (Fig. 1). Appropriate consideration of toxic metal accumulation in agro-ecosystem is essential in establishing best agronomic practices and management systems to ensure sustainable agro-ecosystems productivity and reduced pollution risks. This review outlines the pollution risk of toxic metal accumulation and its implications on sustainable food production in the East African agro-ecosystem.

2. Review scope

In terms of spatial scope, this review covers the broad East African region with a wide array of environmental settings and intensive anthropogenic activities accelerating high rates of change. The temporal

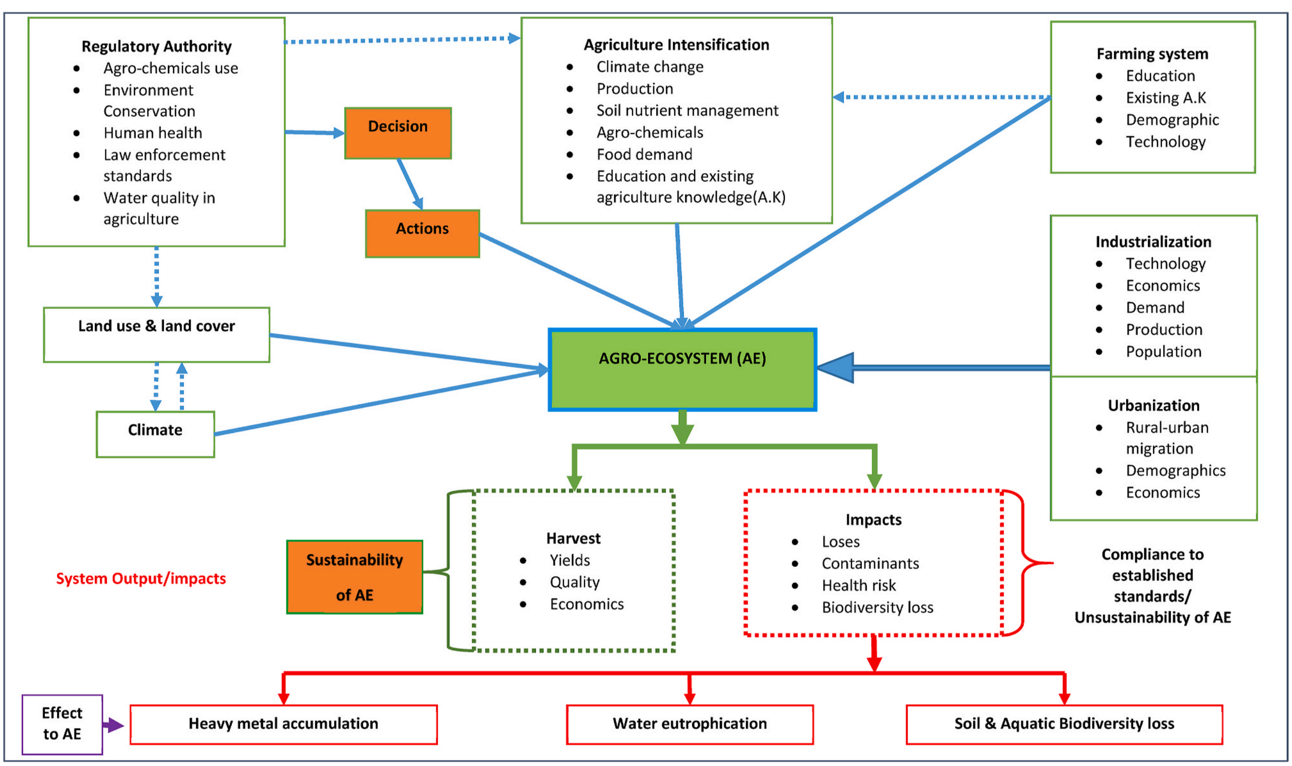

Fig. 1. Diagrammatical portrayal of factors and drivers influencing PTEs accumulation in East Africa Agro-Ecosystem. Bold words in a square are factors and bullets are drivers, the dotted box indicates expected system output/impacts; dotted line shows the indirect or partial influence of a factor to agro-ecosystem or other factors/driver; a solid line indicates direct influence/effect to agro-ecosystem) (Source: Author).

scope opens with the early 1970s, a period characterized by lower impact human activities, low urbanization near farming areas, high rainfall, and less surface runoff water in East Africa. Then was followed around 1980 by introducing pastoralism, intensive agriculture, and urbanization which intensified local to global connections exacerbating high production, an increased area under cultivation, deforestation, eutrophication, and toxic metal toxic contamination. East Africa (Fig. 2) hosts a rich diversity of environmental capital, including large river basins (i.e., Mara, Usangu, Rufiji, Kilombero) and several major rivers (i. e., Great Ruaha River, Nile, Malagarasi, and Mara River). The contemporary region is a center for field crop and vegetable production, dairy farming, fishing, aquaculture, and culturally diverse urbanized and rural populations (Fox, 2004; Kashaigili et al., 2006). At present, few effective management strategies operate to address unregulated agrochemical uses, soil nutrient depletion, eutrophication, and PTEs contaminations due to intensive agricultural activities. This novel and systematic review of East African agro-ecosystem aim to identify the risk of toxic metals, key knowledge gaps, and recommendations for sustainable food production in the context of the UN Sustainable Development Goals (UN, 2015). The authors use the East African agro-ecosystem as an example; however, agro-ecosystems in different parts of the world face the same challenges.

3. Literature review methodology

This review was completed through a thorough search of available literature, including peer-reviewed publications and reports of ongoing studies on nutrient dynamics and losses, water eutrophication, and toxic metal accumulations in East Africa and other parts of the world from the 1970s to the present. Data from Science Direct, Web of Science, and other internet sources were gathered using specific keywords such as "nutrient saturation and losses", "water eutrophication", "PTEs accumulation", "impact of toxic metals on soils, water, and food safety". Also, the search included university student dissertations and government reports as grey literature from professional colleagues working in the region. Later on, the search query was narrowed down towards a new precise definition concerning PTEs. Studies from different countries in the region were compared with the current status of the entire agro-ecosystem in East Africa to raise awareness of the pollution risks on the agro-ecosystem.

4. East Africa agro-ecosystems and farming systems

As the author uses the East African agro-ecosystem (EAA) as a case study to address the toxic metal contamination in farming, the EAA is complex with several interactions which pose a management challenge. In EAA, crop production is mainly rainfed where food crops (maize, beans, sweet potatoes, millet, etc.) and cash crops (coffee, banana, tea) are produced, while in the lowland irrigated crops (rice, horticultural crops, and sugarcane) are grown. Animal production is mainly free-range, and in few cases, is raised by zero grazings. Mixed farming is practiced in some parts of the region, such as the Lake zone, Southern Highlands, and the Eastern zone of Tanzania and Kenya, where crop and animal production are conducted simultaneously, especially after crop harvest (Kimaro, 2019). The farming practices, especially in irrigated areas, different crops are grown in the same piece of land up to six times a year, which further complicates the agro-ecosystem management and monitoring (Nonga et al., 2011). Vegetable production is very dynamic in agro-ecosystem and heavily managed with agrochemicals due to the premium price of its product and its fast cropping cycle (Kibassa et al., 2013). In addition, systems have communities of different ethnic and varied socio-economic backgrounds and values that influence land use, planning, and tenure, increasing agro-ecosystem complexity. All these make agro-ecosystem complicated and fragile hence tricky to manage. The introduction of advanced technologies expanded the utilization of the agro-ecosystem as a large area is easily cultivated or converted to farmland, but also less usefuly land has been utilized for livestock and aquaculture decreasing the area of the ecosystem that can rest as conserved land.

Agriculture intensification has led to broader adoption of monoculture cropping systems for easy mechanization, which has increased agrochemical uses. While agrochemicals use improve production per unit area and stresses agro-ecosystem due to enhanced pollution risks from overuse of agrochemicals (fertilizer, pesticides, herbicides, and growth regulators). Furthermore, the installation of livestock facilities to help dairy farming further complicates the agro-ecosystem (Jepson et al., 2014; Moss, 2008; Nonga et al., 2011). Any agro-ecosystem is under the influence and pressure of different factors and drivers such as

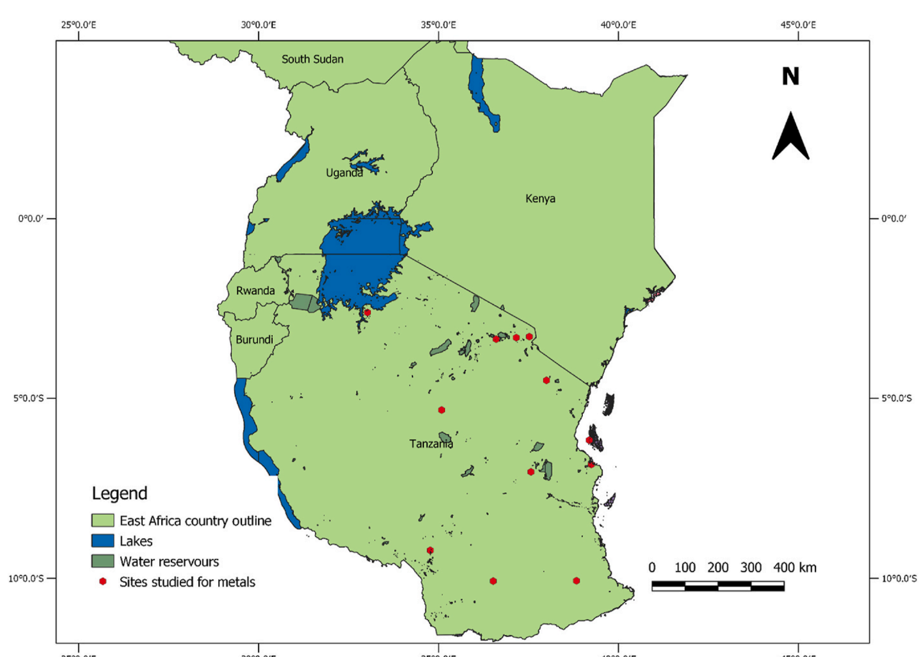

Fig. 2. The map showing East Africa countries and sites studied for metal distribution in topsoils (source: author).

regulatory authorities, which determine agrochemicals and the amount to be used (Fig. 1), influencing agro-ecosystem production and sustainability. Agricultural intensifications subjects agro-ecosystem to pollution risks as it enhances agrochemicals' use.

East Africa agro-ecosystem has several farming systems; from the humid highlands of Uganda, the coastal areas on Tanzania and Kenya to the drylands of Sudan where cropping systems including maize, sorghum, rice, beans, and wheat are common, as well as extensive grazing and high production of vegetables, coffee, and tea. The common farming systems include *1). Irrigated Farming System (IFS):* This involves large and smallholder farmers; this is common in irrigated flat land such as Gezira in Sudan, Usangu, Rufiji, and Kilombero basins in Tanzania. The IFS includes more than 35 million hectares in East Africa (FAO, 2000). Paddy, sugar cane, flowers, and vegetables are common crops grown in IFS; IFS is usually supplemented by rainfed cropping.; *2). Tree Crop Farming System:* this is based on the production of cash and food crops such as coffee, cashew, tea, oil palm, fruits such as mango, avocado where annual crops are grown between tree lines for subsistence and sometimes a few cattle are raised in this farming system. *3). Highland Perennial Farming System*; this is common in the highland areas for perennial crops such as banana, coffee, plantain and supplemented by crops such as sweet potato, beans, and cereals. This system is standard in subhumid and humid agro-ecological zones of Uganda, Rwanda, Burundi, and Tanzania. The system is characterized by lessening farm size, soil fertility, yield return, and incomes (FAO, 2015); *4). Mixed Farming System*: This farming system is mainly located at mid (1800 m) to high (3000 m) altitudes, in subhumid or humid agro-ecological zones. The system involves animal production (e.g., cattle, goat, and sheep) and crop farming such as maize, millet, peas, broad beans, and potatoes. The system is typically characterized by a single cropping season; whenever are two, the second is a very short season. In general, the farming system in East Africa is challenged by different problems such as soil fertility decline through erosion and uncontrolled agrochemicals use, leading to pollution risk due to metals and nutrient accumulation in the agro-ecosystem.

5. Toxic metal accumulation on soils and water in agro-ecosystem

5.1. Sources of metals/pollutants in agro-ecosystem

Toxic metals are elements with potential environmental pollution and toxicity to humans, plants, and animals as they influence biochemical reactions, which might affect the environmental quality (Zhao et al., 2010). The entry of toxic metals into agro-ecosystem and food raises health concerns and may affect the system's sustainability (Simon et al., 2016). The common sources of PTEs in agro-ecosystem are both natural and anthropogenic; natural sources include emissions from dust, volcanoes and weathering product of rocks which are rich in metals, where their intensity vary along the landscape depending with

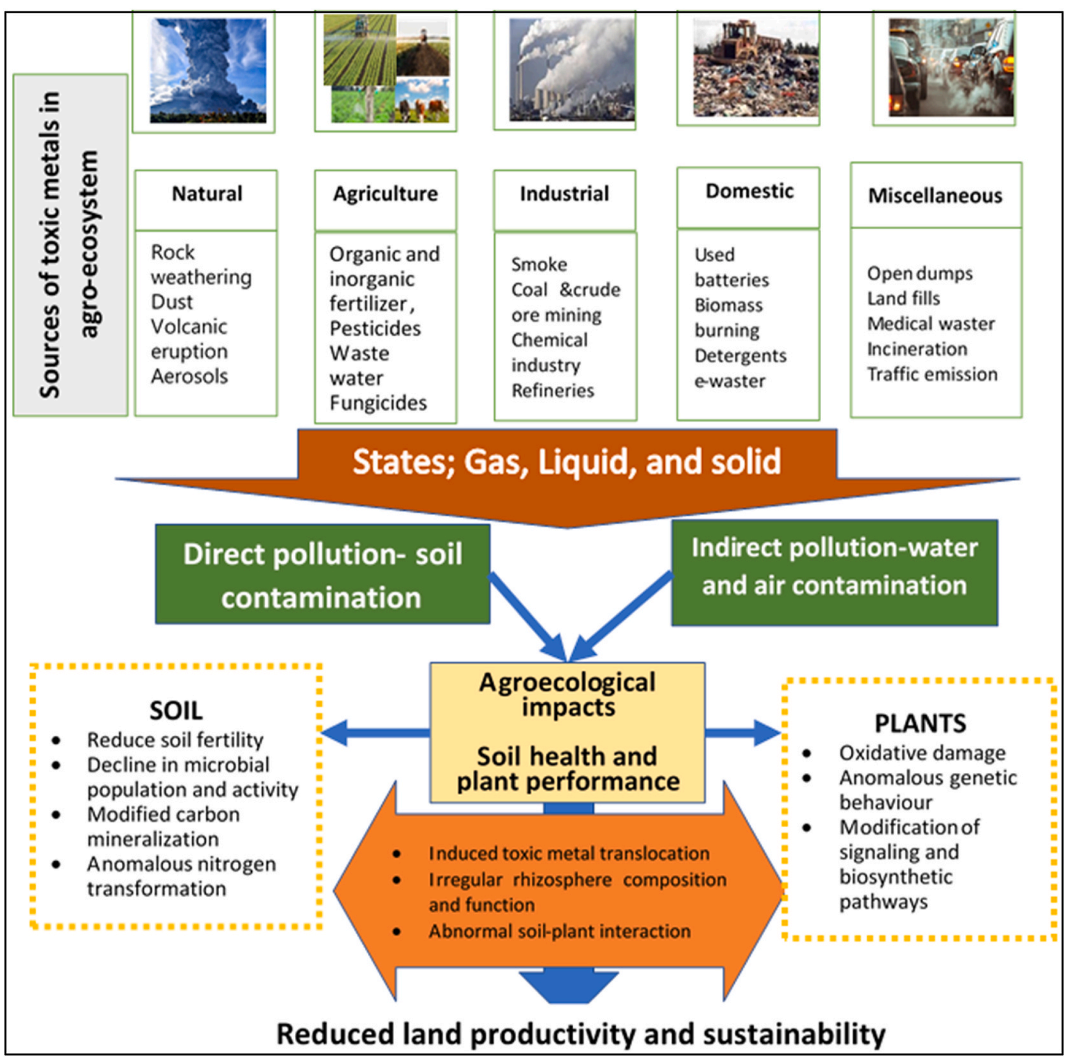

Fig. 3. The diagrammatic portrayal of major sources and the effect of toxic metals in agro-ecosystem (adapted from Srivastava et al., 2017).

other associated activities and climate changes (Abdu et al., 2011; Jepson et al., 2014; Nagajyoti et al., 2010; Shefali et al., 2019; Srivastava et al., 2017; Tutic et al., 2015). Anthropogenic sources include mineral mines, industrial and agrochemicals such as pesticides, fertilizer, herbicides, and growth regulators application in agricultural soils, surface runoff from manufacturing and processing industries (Fig. 3). Several studies have concluded that essential metals (copper - Cu, zinc – Zn, chromium - Cr, and manganese- Mn) and non-essential metals (cadmium – Cd and lead - Pb) are highly poisonous to soil microbes, aquatic life, animals, and human in large doses and have been accumulating in agro-ecosystem of in different parts of the world (Abdullahi et al., 2014; Guo et al., 2020; Kibassa et al., 2013; Lema et al., 2014; Lugwisha, 2016; Machiwa, 2010; Mahugija and Sheikh, 2018; Marwa et al., 2012; Mwegoha and Kihampa, 2010). Most agro-ecosystems in East Africa are located and connected to other ecosystems such as flood plains, mining areas, industrial areas, urban runoff drainage, and dumping areas. This makes the agro-ecosystem prone to pollution risks and toxic metal accumulation; therefore, increasing metal concentration compromises the agro-ecosystem's environmental quality (soil and water) and sustainability.

The geological source of toxic metals is soil parent materials; for example, rock phosphates are rich in Cd, Cr, and Pb (Lema et al., 2014). These elements can be activated to available forms in soil and water by altering different conditions such as temperature, pH, and redox changes. Soil erosion transfers soil particles from one point and deposits them in agricultural land and water bodies which are likely to aggravate toxic metal distribution in agricultural land (Nagajyoti et al., 2010). The concentration of toxic metal in farming and non-farming areas has been observed to increase in different parts of the world, such as Kenya, Iran, China, Spain, and other African countries (Kinuthia et al., 2020; Mungai et al., 2016; Sayo et al., 2020).

Moreover, the absence of standardized agricultural management and joint environmental conservation laws enforcement has accelerated agro-ecosystem pollution in East Africa (Mungai et al., 2016). The concentration of metals in the environment from anthropogenic causes has been observed to be a significant pathway and has been increasing in recent years, raising ecological and public health concerns (Kinuthia et al., 2020; Mungai et al., 2016; Sayo et al., 2020). Studies in East Africa agro-ecosystems have identified industrial, agricultural, mining, domestic, and technological applications activities as the primary source of metal accumulation in agricultural soils and water (Kinuthia et al., 2020; Koleleni and Mbike, 2018; Lema et al., 2014; Mungai et al., 2016; Sayo et al., 2020; Simon et al., 2016). Additionally, contaminated urban storm runoffs, wastewater used in irrigation, and agrochemicals use, i.e., fertilizer and pesticides, detergents, fossil fuels burning, and automobile traffic, have also been determined as potential sources of contaminants in agricultural soils and water (Mahugija and Sheikh, 2018). For example, in a study conducted by Machiwa (2010) in Geita district in Tanzania, mercury (Hg) levels in agricultural soils were observed to be high (3.2–69.3 μg/kg) in farming areas located closer to gold mining areas exceeding maximum allowable limit of 0.005 mg/kg. In addition, the study by Almås and Manoko (2012) on the distribution of trace metals in soils, sediment, and water in areas close to mining areas in Geita and Mara regions in Tanzania reported a high concentration of As (720 mg/L) in soils and water a value which was twice the WHO maximum allowable limit of As in drinking water.

Agricultural intensification and increased use of inorganic/organic fertilizer further expose soil and water to pollution risks by toxic metals (Mshana, 2015). The study by Lema et al. (2014) and Awotoye (2011) in Tanzania and Nigeria found that soils amended with rock phosphates were enriched with zinc, copper, lead, and cadmium than where no phosphatic fertilizer was applied. However, the mean values were within the acceptable range except for Cd (5.30 μg/g) were above the permissible limit (3 μg/g) in agricultural soils. Therefore, excessive use of phosphatic fertilizer could contribute to increased toxic metals in soils and water. Studies by Malidareh et al. (2014) on levels of As, Cd, and Pb on paddy farms in Northern Iran before and after phosphatic fertilizer application reported increased concentrations of toxic metals ranged from 0.001 mg/kg – 0.007 mg/kg (As) and 0.066 mg/kg – 0.103 mg/kg (Pb) while afterward, the level increased in the range of 0.10 mg/kg – 0.30 mg/kg for As, and 0.201 mg/kg – 0.447 mg/kg for Pb, which exceeded the maximum permissible limit of 0.2 mg/kg for As and 0.1 mg/kg for Pb allowed in agricultural soils (Koleleni and Mbike, 2018). The study by Atafar et al. (2010) conducted to assess the influence of fertilizer application to Cd, Pb, and arsenic (As) in durum wheat farms in Mahidasht province in Iran after fertilizers and pesticides application reported significantly increased concentration of Cd, Pb, and As compared to non-durum wheat fertilized fields.

Furthermore, the study report that the concentration of Pb and As increased dramatically compared to Cd concentration; this can be related to the overapplication of fertilizers and pesticides (Goncalves et al., 2014). This scientific evidence indicates that the application of inorganic fertilizers, pesticides, and other agrochemicals may be an essential source of toxic metals in farming areas. Historical studies showed toxic metals due to air pollution, mining, and untreated wastewater in Africa (Mataba et al., 2016; Mongi et al., 2020; Nriagu, 1992). Adding to this knowledge, this study indicates that fertilizers and agrochemicals use in East African agro-ecosystems required improved management and mitigation strategies to ensure sustainability.

5.2. Exposure pathways of toxic metals in soils and water

Toxic metals in soils and water accumulate from different sources through different pathways. The common pathways include point source pathways where metals from municipal waste, industries, and other contaminated urban waste are introduced to the soil or water bodies directly (direct pollution); from a single source either by accidental or deliberately by human activities (Abdu et al., 2011; Srivastava et al., 2017; Tutic et al., 2015). This was a common pathway in past decades as there were no strict regulations and guidelines on the discharge of wastewater and dust to the environment, especially in developing countries (Nriagu, 1992). The point source pathway is typical in urban areas where there is high wastewater, dust, and aerosols production as a result of a large number of industries and over-population, mostly in developing countries where waste management systems are not well developed (Kinuthia et al., 2020; Mungai et al., 2016; Sayo et al., 2020). The study conducted by Mungai et al. (2016) in accumulation and distribution of metals in wastewater and soils in farming areas in Nairobi-Kenya and study by Herman and Kihampa (2015) in Dar es salaam-Tanzania conclusively pointed out mining tailings, industrial and urban effluents as a common point source of toxic metals in farming areas. Furthermore, Machiwa (2010) studied the concentration of toxic soil metals (Zn, Pb, Cu, Cd, and Cr) in farming areas in Dar es salaam-Tanzania found that industrial effluents were the primary source of metals in farming areas in the study area. All these signify that point sources have much reduced but do still exist, especially in industrialized and urbanized cities (Herman and Kihampa, 2015; Machiwa, 2010; Mwegoha and Kihampa, 2010).

Secondly, toxic metals accumulate in the agro-ecosystem through non-point or diffuse source pathways (NPSP), where metals are released in soils and water slowly from non-preidentified sources; however, their coverage could be extensive. In this pathway, metals accumulate in agro-ecosystem through materials and equipment used such as agrochemicals applied like fertilizer, pesticides, herbicides, etc.; use of treated and untreated wastewater for irrigation, use of surface water runoff from urban or industrial areas. Although the use of wastewater in agriculture reduces the demand for freshwater resource withdraws and is potential nutrients sources (i.e., N, P, and K) required by plants, it is a potential source of contaminants in soils, water, and food products (Sayo et al., 2020; Singh et al., 2012). For example, the study by Sayo et al. (2020) observed higher concentration Cu, Zn, Cd, and Pb (i.e., 0.484–1.834 mg/L (Cu), 1.432–4.612 mg/L (Zn), 0.015–0.353 mg/L

(Cd), 0.011–2.123 mg/L (Pb)) in wastewater which was used in vegetable irrigation in Embu county in Kenya, which were above WHO permissible limit for wastewater used in agriculture/irrigation which is 0.2 mg/L for Cu, 2 mg/L for Zn, 0.01 mg/L for Cd and 0.5 mg/L for Pb (WHO, 2006).

The NPSP is more common in the East Africa agro-ecosystem, and other agro-ecosystem in different parts of the world as they are not pre-identified and not easily detected until a higher level of toxic metals and a possible visible effect has been observed. This pathway includes toxic metals from fertilizers, herbicides, pesticides (such as As, Cr, Co, Pb, and Ni from glyphosate-based herbicide and pesticides (Defarge et al., 2018)), growth hormones; home detergents; contaminated urban runoffs, and irrigation water, and leakages from farm machines (Table 1) (Srivastava et al., 2017; Teng et al., 2010; Tutic et al., 2015; Wu et al., 2020). Therefore, a better understanding of the toxic metal pathways in agricultural areas is vital for establishing immediate control strategies and avoiding further metal accumulation in the agro-ecosystem.

5.3. Contemporary drivers for increased toxic metals in East African agro-ecosystem

High levels of toxic metals in soils and water in agro-ecosystem are driven both by pedogenic (linked to weathering of the parental material of the particular area) and anthropogenic activities (Bolan et al., 2003; Naidu and Bolan, 2008). Generally, the metals derived from soil parent materials are in forms that are not readily available for plant uptake and have less risk to the environment (Khan and Ansari, 2005). In East Africa, several drivers accelerate the accumulation of metals in agro-ecosystems, i.e., soils and water (Bolan et al., 2003). These drivers include (i) population growth, (ii) agricultural intensification, (iii) increased urbanization and industrialization in peri-urban areas, (iv) natural process (weathering), and (v) mining tailings from gold and diamond mines.

Population growth; An increasing population at a rate of 6.2% in East Africa results in more mouths to feed, requiring increased food production to meet increased food demand (Dániel et al., 2019). The increased number of people increased urbanization and decreased the available arable land as it is taken for settlements and industries; hence to ensure maximum productivity, high use of agrochemicals like fertilizer, herbicides, pesticides, and growth regulators are employed to increase production per unit area (Jepson et al., 2014; Moss, 2008; Zhou et al., 2014). Population growth in East Africa increased settlements in rural and near farming areas and increased domestic and industrial waste products, which when poorly handled, ends up in soils and water, increasing the level of metals and nutrients to unacceptable levels (Fig. 3) in agro-ecosystem (Moradi et al., 2013). The study conducted in Nairobi and Dar es salaam major cities of East Africa, observed that agricultural fields located close to these cities and along highways were associated with high metal concentrations due to increased waste production as a result of the population (Mwegoha and Kihampa, 2010).

Table 1
Different sources of metals in agricultural soils and possible metals associated with them.

Source	Formulations	Metals included	Reference
Glyphosate-based herbicides	Bayer GC, clinic Ev, glyfos and glyphosan	As, Cr, Co, Pb, and Ni	Defarge et al., (2018)
Pesticide s formulation	Eyetak, Folpan, matin, polysect	As, Cr, Co, and Ni	Defarge et al., (2018)
Urban runoffs	Stormwater	Zn, Pb, Cr, Va,	Mahugija & Sheikh, (2018)
Leakage from farm machines	Smoke, liquids	Pb, Cr	Shemdoe, (2010)
Industrial wastewater	–	Cu, Zn, Cd, and Pb	Sayo et al., (2020)

However, population increase can be considered a factor behind other factors to accelerate toixc metal contaminations. Currently, there is limited information on the influence of population growth and toxic metals accumulation in soils and water in urban areas in East Africa as less attention is given to the topic.

Agricultural intensification: The decrease of available arable land due to urbanization necessitates agricultural intensification through improved seed and planting materials and increased use of agrochemicals to increase productivity (Fig. 3 and Table 2) (Clover, 2003). All these have ingredients associated with different metals impurities, which, when excessively used, would increase toxic metal levels in agro-ecosystem (Kinuthia et al., 2020; Mungai et al., 2016; Sayo et al., 2020). The use of rock phosphate fertilizer has been reported to upsurge the concentration of Cd, Pb, Cu, and Cr in soils, the use of calcium-based fertilizer known to increase the concentration of Cd, Mn, and Zn, and excessive use of phosphate-based herbicides can increase the Hg, Ag and Cu to soils and water (AlKhader and Asad, 2015; Naidu and Bolan, 2008; Zalidis et al., 1999). The use of pesticides and wastewater also has been identified as the key contributor of metals in agricultural soils; the use of these contaminated inputs can cause degradation of agricultural soils, making food production unviable at these locations (Abdu et al., 2011; Nagajyoti et al., 2010; Shefali et al., 2019; Srivastava et al., 2017). The use of agrochemicals by most farmers is often not done correctly. Farmers use often use pre-determined recommendations without professional assistance but also use highly productive varieties which require high macro and micronutrient application, which increase the chance of environmental contamination. In recent years, increased use of fertilizers in Brazilian soils was observed to be associated with increased content of heavy metals due to high use of contaminated fertilizer (da Silva et al., 2016; Goncalves et al., 2014). Therefore, monitoring and a better understanding of agricultural intensification and toxic metals accumulation in soils and water would help put management strategies in place to balance high yields whilst keeping the environment safe.

Increased urbanization and industries in peri-urban areas: The increase of a number of industries had accelerated the production of large quantities of contaminated waste (wastewater and dust), which when poorly handled, end up in agricultural soils and water. Studies have found that agricultural soils and water close to industrialized cities are more polluted than those in non-industrialized cities; runoff water and dust from urban areas could potentially add toxic metals in soils and water in agro-ecosystems. (Liu et al., 2015; Mwegoha and Kihampa, 2010, 2010, 2010; Zhou et al., 2014). For example, many paddy farming areas, especially in Lake Zone and Southern Tanzania, which uses surface water, runoffs for irrigation, were reported to contain an elevated concentration of nutrients (N and P) and metals. In addition, industrial activities such as mining (Fig. 3) emit metals to the environment. For instance, the use of Hg in gold mines contributed to elevated Hg levels in soil and sediment in agro-ecosystem around areas in Geita Tanzania (Machiwa, 2010; Mataba et al., 2016).

Natural Sources; The degradation of rocks can release a certain amount of metals to the environment and can be taken to a far distance by water and wind (Fig. 3). This depends on the rock's chemical composition, weather, and climatic condition (Abdu et al., 2011). Some geologic materials have high concentrations of metals; example geological materials are are rich in Mn, Cr, Co, Cu, Ni, Zn, Sn, Cd, Hg, and Pb. In contrast, volcanic materials are rich in Al, Zn, Mn, Pb, Ni, Cu, and Hg (Nagajyoti et al., 2010). Likewise, forest fires also contribute to environmental heavy metals to some extent by the production of volatile heavy metals like Se and Hg (Srivastava et al., 2017). The study conducted by Banzi et al. (2015) on the distribution of trace metals in bare land (non-cultivated land) in Southern Tanzania observed appreciable amount of Zn (13.8 mg/kg), Cu (10. mg/kg), Pb (25.2 mg/kg), and Cd (13.8 mg/kg) (Tables 3–8). This indicates that sometimes, elevated levels of toxic metals could result from natural sources or the geology of the parent material in the particular area, which can be available to

Table 2
The potentially toxic metals (μg/g) which can be added in agricultural soil from agrochemicals, sewage sludge, farmyard manure, and compost used in agriculture (Srivastava et al., 2017).

Metals	Pesticides	Lime	N-fertilizer	P-Fertilizer	Farmyard manure	Compost	Sewage sludge
Cr	–	10–15	3.2–19	66–245	1.1–55	1.8–410	8.40–600
Ni	–	10–20	7–34	7–38	2.1–30	0.9–279	6–5300
Cu	–	2–125	–	1–300	2–172	13–3580	50–8000
Zn	–	10–450	1–42	50–1450	15–556	82–5894	91–49000
Cd	–	0.04–0.1	0.05–8.5	0.1–190	0.1–0.8	0.01–100	<1–3410
Pb	11–26	20–1250	2–120	4–1000	0.4–27	1.3–2240	2–7000

Table 3
Distribution of Copper (Cu) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Soil concentration (mg/Cu kg)				Regulatory values > 100 mg Cu/kg		Extraction Method	References
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	4.045	14.58	15.00	22.80	5.91	0	0	DTPA	Machiwa, (2010)
CM	Cereals (Maize)	Lindi	20	4.494	82.83	70.10	169.20	1.28	5	25	EDXRF	Koleleni and Mbike, (2018)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	5.393	0.158	0.14	0.34	0.07	0	0	DTPA	Kitundu and Mrema, (2006)
Veg	Vegetables	Morogoro	9	2.022	0.436	1.50	7.19	0.28	0	0	DTPA	Lugwisha, (2016)
Ctf	Soils in treated coffee farms (tf)	Arusha & Kilimanjaro	31	6.966	312.00	281.50	806.00	177.75	14	45.20	Aqua regia	Senkondo et al., (2014)
Cutf	Soils in untreated coffee farms (utf)	Arusha & Kilimanjaro	5	1.124	29.00	27.00	32.00	6.00	0	0	Aqua regia	Senkondo et al., (2014)
BL	Bare land	Ruvuma	84	18.88	10.00	9.900	25.10	4.10	0	0	EDXRF	Banzi et al., (2015)
Mix W	Mixed woodland	Tanga	54	12.14	2.98	2.72	8.19	2.11	0	0	DTPA	Meliyo et al., (2015)
GL	Grassland	Kilimanjaro	42	9.44	8.49	8.79	24.67	6.03	0	0	FTMIRS	Mathew et al., (2016)
IA	Industrial areas	Zanzibar	108	24.27	51.04	51.07	167.00	43.55	7	6.50	Aqua regia	Mahugija and Sheikh, (2018)
UAS	Urban agriculture soils	Dar es salaam	24	5.39	13.91	15.51	21.07	4.12	0	0	Aqua regia	Mwegoha and Kihampa, (2010)
NMA	Near Mining areas	Singida	26	5.84	14.47	15.00	29.42	5.14	0	0	Aqua regia	Herman and Kihampa, (2015)
Total			445	100	**44.99**	15.00	806.00	21.36	**26**	**5.84**		

NB: FTMIRS means Fourier Transform Mid-Infrared reflectance Spectroscopy, EDXRF means Energy Dispersive X-ray Fluorescence, DTPA means Diethylenetriamine pentaacetate. The table is adapted with modification from Ballabio et al. (2018).

Table 4
Distribution of lead (Pb) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Concentration of Pb (mg/kg)				Regulatory Value Conc>200 mg/kg		Extraction Method	References
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St. Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	6.23	19.39	19.65	28.50	6.02	0	0	DTPA	Machiwa, (2010)
CM	Cereals (Maize)	Lindi	20	6.92	14.33	19.10	20.30	0.40	0	0	EDXRF	Koleleni & Mbike, (2018)
Veg	Vegetables	Morogoro	9	3.11	0.66	0.75	1.16	0.28	0	0	DTPA	Lugwisha, (2016)
BL	Bare land	Ruvuma	84	29.07	25.20	24.70	42.50	7.80	0	0	EDXRF	Banzi et al., (2015)
IA	Industrial Areas	Zanzibar	108	37.37	32.54	51.07	111.53	35.77	0	0	Aqua regia	Mahugija & Sheikh, (2018)
UAS	Urban agriculture soils	Dar es salaam	24	8.30	16.89	15.51	22.85	1.80	0	0	Aqua regia	Mwegoha & Kihampa, (2010)
NMA	Near Mining areas	Singida	26	9.00	13.55	13.29	22.24	3.50	0	0	Aqua regia	Herman & Kihampa, (2015)
Total			**289**	**100**	**17.51**	**19.10**	**111.53**	**7.94**	**0**	**0**		

plants or systems when certain physicochemical conditions are altered.

Mining tailing: Drainages from mining areas are a potential source of toxic metals such as Hg, Cd, Pb, Cu, and Cr when are released to rivers or environment untreated/partially treated; in mining activities, metals like Hg are used in gold cleaning from its ores. Studies conducted in the Lake zone of Tanzania (Fig. 4) in paddy farming areas found elevated levels of Hg, Cd, Cr, Pb, and Cu, and the possible sources were the tailing from gold mines (Herman and Kihampa, 2015; Simon et al., 2016). Therefore, drainages and runoffs from mining areas should be avoided to enter agricultural land and water bodies untreated/partially treated to prevent the accumulation of metals. Because most of them have health risks to humans and other organisms. Studied by Mataba et al., (2016)

Table 5
Distribution of Chromium (Cr III) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Concentration of Cr III (mg Cr III/kg)				Regulatory Value Conc>100 mg CrIII/kg		Extraction Method	References
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	10.00	19.14	18.35	39.40	8.11	0	0	DTPA	Machiwa, (2010)
BL	Bare land	Ruvuma	84	46.67	31.10	30.40	54.90	7.40	0	0	EDXRF	Banzi et al., (2015)
UAS	Urban agriculture soils	Dar es salaam	24	13.33	348.93	376.02	502.33	113.47	24	100	Aqua regia	Mwegoha & Kihampa, (2010)
NMA	Near Mining areas	Singida	54	30.00	28.15	28.50	33.40	4.11	0	0	Aqua regia	Bitaka et al., (2009)
Total			180	100	106.83	29.45	502.33	33.27	**24**	**13.33**		

Table 6
Distribution of cadmium (Cd) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Concentration of Cd (mg Cd/kg)				Regulatory value Cd Conc>1 mg/kg		Extraction Method	Reference
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St. Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	11.18	0.48	0.48	0.88	0.22	0	0	DTPA	Machiwa, (2010)
Veg	Vegetables	Morogoro	9	5.59	0.02	0.025	0.03	0.01	0	0	DTPA	Lugwisha, (2016)
BL	Bare land	Ruvuma	84	52.17	13.80	13.8	37.30	6.00	84	100	EDXRF	Banzi et al., (2015)
UAS	Urban agriculture soils	Dar es salaam	24	14.91	0.34	0.36	0.62	0.15	0	0	Aqua regia	Mwegoha & Kihampa, (2010)
NMA	Near Mining areas	Singida	26	16.15	7.40	7.60	11.70	1.20	26	100	Aqua regia	Herman & Kihampa, (2015)
Total			**161**	**100**	**4.41**	**0.48**	**37.30**	**1.52**	**110**	**68.32**		

Table 7
Distribution of Zinc (Zn) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Concentration of Zn (mg Zn/kg)				Regulatory value with Zn Conc>5 mg/kg		Extraction Method	References
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St. Dev	No. samples	Share (%)		
CR	Cereals (Rice)	Lake zone	18	4.58	59.80	67.20	158	41.24	18	100	DTPA	Machiwa, (2010)
CM	Cereals (Maize)	Lindi	20	5.09	75.27	64.50	134.6	41.98	20	100	EDXRF	Koleleni & Mbike, (2018)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	6.11	0.27	0.24	0.36	0.41	0	0	DTPA	Kitundu & Mrema, (2006)
Veg	Vegetables	Morogoro	9	2.29	7.59	1.50	24.80	8.81	7	77.7	DTPA	Lugwisha, (2016)
BL	Bare land	Ruvuma	84	21.37	13.80	13.80	37.30	6	84	100	EDXRF	Banzi et al., (2015)
Mix W	Mixed woodland	Tanga	54	13.74	1.16	2.72	19.6	2.74	21	38.90	DTPA	Meliyo et al., (2015)
GL	Grassland	Kilimanjaro	50	12.72	2.80	5.60	10.34	1.97	20	40	FTMIRS	Mathew et al., (2016)
IA	Industrial areas	Zanzibar	108	27.48	192.6	67.51	328.9	90.35	108	100	Aqua regia	Mahugija & Sheikh, (2018)
NMA	Near Mining areas	Singida	26	6.62	1.29	1.17	2.61	0.52	0	0	Aqua regia	Herman & Kihampa, (2015)
Total			**393**	**100**	**39.40**	**5.60**	**328.90**	**21.56**	**278**	**70.74**		

on the distribution of trace metals in an aquatic ecosystem near Nyamongo gold mine in Geita-Tanzania were observed increased concentration of As and Hg in water as a result of drainage from mining areas; however, the concentration was below the WHO maximum allowable limit in drinking water (0.01 μg/L for As and 0.006 mg/L for Hg) (WHO, 2018, 2006). A study by Machiwa (2010) in the lake Victoria basin-Tanzania reported mean concentrations of Cd (8.70 mg/kg), Hg (19.99 mg/kg), Pb (19.38 μg/kg), Cr (20.98 mg/kg), Zn (65.46 mg/kg) and Cu (14.58 mg/kg) in paddy soils collected from 18 sites within the basin. The Lake Victoria basin was chosen for the heavy metals investigation based on increasing mining activities, which increased mining tailing and wastewater production from mining areas to the agricultural fields in the basin, leading to elevated levels of toxic metals. However, the presence of potentially toxic metals in some plants depends on how these elements are present, either as a compound of mineralogical species or as free radicals, likewise the migration of these is given by the natural leaching of these in many cases or by wind or rain transport, so it is advisable to identify the original contamination of soils in future work.

6. Toxic metal distribution in East African agro-ecosystems

In East Africa, there not yet a joint effort to characterize the toxic metal accumulation in topsoils in agro-ecosystem; furthermore, there is

Table 8
Distribution of Iron (Fe) concentration per land use/cover type soils in Tanzania.

Land use/cover type		Region	Total number of samples		Concentration of Fe (mg/kg)				Sample with Fe Conc>100 mg/kg		Extraction Method	References
Code	Description	Region	Number	Share (%)	Mean	Median	Max	St.Dev	No. samples	Share (%)		
CM	Cereals (Maize)	Lindi	20	8.60	38427.08	41380	28933.70	88820	20	100	EDXRF	Koleleni and Mbike, (2018)
PIC Tea	Permanent industrial crops (tea)	Njombe	24	10.40	43.70	34.42	60.28	5.37	0	0	DTPA	Kitundu and Mrema, (2006)
BL	Bare land	Ruvuma	84	36.20	4.00	3.50	9.10	2.50	0	0	EDXRF	Banzi et al., (2015)
Mix W	Mixed woodland	Tanga	54	23.30	65.30	112.52	339.4	86.40	27	50	DTPA	Meliyo et al., (2015)
GL	Grassland	Kilimanjaro	50	21.60	130.41	193.43	310.60	49.20	32	64	FTMIRS	Mathew et al., (2016)
Total			**232**	**100**	**7734.10**	**112.52**	**28933.7**	**17792.7**	**79**	**34.1**		

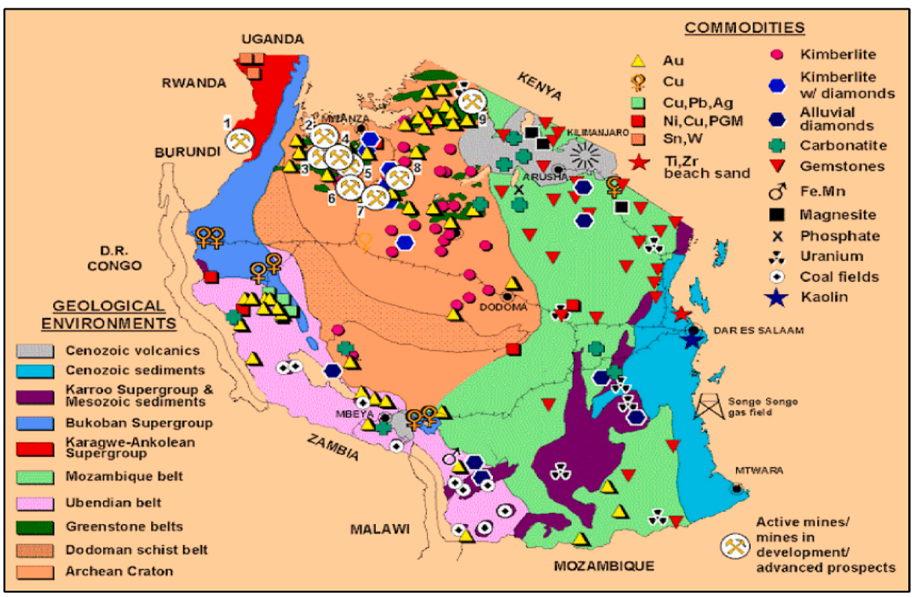

Fig. 4. The mining areas in Tanzania which can be possible source of metals in agro-ecosystem (Ministry of Minerals-Tanzania, 2006).

scant information on studies about toxic metal accumulation in agro-ecosystems where the currently available studies focus on the toxic metals around mining areas, neglecting the other ecosystems like agro-ecosystems which might be badly affected by increased toxic metal concentrations. While the agro-ecosystems in East African countries, i.e., Tanzania, Uganda, Kenya, Burundi, Rwanda, and South Sudan, are slightly different in the socio-cultural and environmental contexts, they face the same pressure from generally the same factors and drivers.

In the remainder of this review, the authors consider Tanzania as a specific example to outline the distribution of toxic metals in topsoils in East Africa agro-ecosystem to get a broader picture of agro-ecosystem quality and its sustainability in East Africa. Land use and farming practices have vital contributions on metals distribution, farming practices that deplete organic carbon and increase soil pH or accelerate weathering process influence accumulation and availability of metals (Chanda et al., 2011; Zhao et al., 2010). Mining activities can also influence the distribution of metals in the ecosystem. For example, in studies conducted in maize farming area in Mtwara Tanzania, farms located closer to gold mining areas reported increased levels (Tables 3–8) of metals in soils than those which were located far from mining areas (Banzi et al., 2015; Bitaka et al., 2009; Koleleni and Mbike, 2018). Therefore, adequate assessment is required to check the metal levels in soils, plants, and water to ensure their levels are within maximum allowable limits for human health and environmental safety. Different studies (Banzi et al., 2015; Bitaka et al., 2009; Kibassa et al., 2013; Koleleni and Mbike, 2018; Lugwisha, 2016; Marwa et al., 2012; Munisi and Semu, 2014; Mwegoha and Kihampa, 2010) have been conducted in Tanzania on metal distribution in different land uses reported most areas to have toxic metal concentration levels below the regulatory values (WHO/FAO) (WHO, 2018, 2006). However, some sites recorded (approximately 25%) metal concentrations exceeding regulatory values (see Tables 3–9).

Coffee and vegetable farming areas have been reported to have a higher accumulation of Cu, Pb, and Cr because coffee and vegetable production historically have been treated with many copper-based fungicides and insecticides (Senkondo et al, 2014, 2015). Studies in paddy farming areas in the Lake Zone of Tanzania have observed different soil metals accumulation which have been contributed by surface water runoffs from mining areas, which increased the PTEs in

Table 9
Potential ecological risk levels of heavy metals (Hakanson, 1980).

Risk Level	Low	Moderate	Considerable	High	Very high
E_r^i	<40	40–80	80–160	160–320	>320
RI	<95	95–190	190–380	–	>380

soils and rice grains in a range of Cu (70.1–169 mg/kg), Pb (19.39–28.50 mg/kg), Cr (19.14–39.40 mg), Cd (0.48–0.88 mg/kg) and Zn (59.8–158 mg/kg) in soils. These values were above the WHO and USEPA maximum allowable limits for heay metals in agricultural soils (i. e., 2, 0.1, 1, 0.1, and 5 mg/kg, for Cu, Pb, Cr, Cd, and Zn, respectivelly) and Cu (0.8–3.7 mg/kg), Cd (0.001–0.12 mg/kg), Pb (0.001–0.29 mg/kg), Cr (0–0.03 mg/kg), Zn (4.10–48.7 mg/kg), and Hg (0.1–11.4 mg/kg) in rice grains (Machiwa, 2010; Simon et al., 2016). The amount of PTEs accumulated in soils, plant samples, and grains provide a warning that crops growing in areas enriched with toxic metals (Pb, Cd, Zn, Hg, Cr, and Hg) or receiving contaminated runoffs from mining areas or urban areas may affect soil and water quality in agro-ecosystem threatening the health of water users and soil inhabitants.

The study by Mahugija and Sheikh (2018) in urban agriculture where industries and automobile activities are conducted in Dar es Salaam and Zanzibar, Tanzania reported higher concentration (in mg/kg) of Zn (0.27–419.2), Cu (0.1–167), and Pb (0.02–271), indicating that industrial activities influenced the accumulation and distribution of these metals in agro-ecosystem. The soil metal concentrations in areas with automobile workshops were observed to be greater than in areas with no automobile workshops indicating anthropogenic influences. This indicates that uncontrolled or unmonitored runoff from urban and industrial areas can be a important source of PTEs contamination and distribution in water and soils in peri-urban farming areas. The study found that 51.11%, 40%, and 18% of sampled areas had a concentration of Zn, Cu, and Pb above the Tanzania Bureau of Standards (TBS) and WHO permissible limit of 150 mg/kg and 100 mg/kg, respectively. Therefore, the distribution of metals in topsoils varies with land use activities of a particular area and associated anthropogenic activities. This calls for a specific need for assessing soil and water quality of urban and peri-urban farming areas with respect to PTEs as they may cause a health risk and compromise soil and water biodiversity and sustainability of agro-ecosystems for sustainable food production.

Copper (Cu): The distribution of copper (Cu) in topsoils in different land use in Tanzania was observed to vary significantly among land uses (Table 3). Higher values recorded in farming/land uses, which involves uses of copper-based agrochemicals biocide such as coffee farming (312 mg/kg), maize farming areas (82.83 mg/kg), paddy farms (14.58 mg/kg), and vegetable production. Among 445 soil samples, 26 samples were observed to have Cu concentration exceeding the maximum allowable limit (100 mg/kg) for agricultural soils. This indicates that the soil might pose environmental contamination and phytotoxicity effects to crops. However, the study by Fagnano et al., (2020) conducted in Italian soils observed that the concentration of Cu of 100 mg/kg soil might be not enough to cause detrimental effect to plants, soil invertebrates, animals, human, and the environment, and their risk might be excluded. The 45.2% of the samples collected from conventional coffee farms were observed to have Cu concentration above Tanzania maximum allowable limit (of 100 mg/kg) for agricultural soils (URT, 2007). Industrial and mining areas have a higher contribution to copper distribution in peri-urban soils; the study conducted by Mahugija and Sheikh (2018) and Herman and Kihampa (2015) in soils from industrial and near mining areas from Zanzibar and Singida Tanzania reported a high concentration of Cu in soils which due to runoff and eroding soils from industrial sites to agricultural areas. Among 108 soil samples (Table 3) from industrial sites, seven soil samples, about 6.5% of the collected soil samples had Cu concentration above the maximum allowable limit for agricultural soils (URT, 2007). This indicate that despite copper is essential for crop production but its excess amount in soils can affect plant growth, biodiversity and quality of produced products (Mng'ong'o et al., 2021).

Lead (Pb): The concentration of lead (Pb) in different land use in Tanzania was observed to be high in agro-ecosystem located close to mining and industrial areas (Table 4). The study conducted by Banzi et al., (2015), Koleleni and Mbike (2018) and Machiwa (2010) observed a higher concentration of Pb in the soil in paddy and maize growing areas (19.65 and 19.1 mg/kg, respectively). Furthermore, studies found that some bare land, industrial sites, urban agriculture soils, and near mining areas had a higher concentration of Pb, i.e., 24.7, 51.07, 15.51, and 13.29 mg/kg, respectively. However, these values were below Tanzania's maximum allowable limit of Pb (100 mg/kg) in agricultural soils; however, most of them were above the USEPA maximum permissible limit of Pb in agricultural soils (USEPA, 2014). This proposes that any crop grown in these areas will be likely to accumulate lead which might raise health concern to its users because there is a direct link of Pb accumulation in soils with the amount of Pb in plant samples (Banzi et al., 2015; Koleleni and Mbike, 2018; Machiwa, 2010). The higher values in bare land in Ruvuma-Tanzania (Table 4) indicate that the geological materials have an appreciable amount of Pb (Banzi et al., 2015), which can be transported to nearby agro-ecosystem through runoff and erosion.

Chromium (Cr): The concentration of chromium (Cr) in topsoils from different land use were observed to vary from place to place and from land use to land use (Table 5). Based on the 180 samples collected, it is observed that the concentration of Cr was higher in urban agriculture (348.93 mg/kg), near mining areas (28.50 mg/kg), and bare land (31.10 mg/kg), which suggest that higher values might be due to geological compositions (Table 5). The mean values of Cr from urban agriculture were observed to be higher than the maximum allowable limit in agricultural soils (100 mg/kg), this indicates that plants growing in those areas might be subjected to Cr toxicity, and the food product produced might have Cr which likely to cause human health risks (Mwegoha and Kihampa, 2010). However, new existing findings report that the toxicity of Cr to plant and food products is very low because Cr is less bioavailable to plants and microbes in soils due to reactions or adsorption to other metals in the soils (Visconti et al., 2019). Among 180 soil samples 24 samples, approximately 24% were observed to have Cr more than Tanzania's maximum allowable limit (100 mg/kg) for Cr in agriculture soils (URT, 2007). The analysis of Cr in paddy farming in Lake Zone Tanzania by Machiwa (2010) and Simon et al., (2016) observed an appreciable amount of Cr with a mean value of 19.14 mg/kg (Table 5); however, values were below Tanzania maximum allowable limit (100 mg/kg) for Cr in agricultural soils, but a value was observed to be higher than 1 mg/kg a USEPA maximum allowable concentration for Cr in agricultural soils (URT, 2007; USEPA, 2014). This indicates that soils can be termed polluted or unpolluted based on the maximum limit values used to make a decision. This calls for unified regulatory values to have the same environmental qualities during assessment although it may be difficult due to difference in the biogeochemistry of a particular area and land uses.

Cadmium (Cd): The concentration of cadmium (Cd) in topsoils from different land use was observed to be high in areas close to or near mining areas (7.4 mg/kg) and bare lands (13.8 mg/kg) with an appreciable amount of metal composition (Table 6). The concentration of Cd in the farming area studied was observed to be low (range 0.025–0.48 mg/kg) values that were observed below Tanzania and WHO maximum allowable limit for Cd in agricultural soils. This means that environmental quality based on these published research on the accumulation of Cd in agricultural soils is low. However, more studies have to be conducted since the recent research by Lugwisha (2016) conducted about five years ago where there might be severe changes in Cd accumulation. The Cd concentration in bareland and near mining areas was observed to be higher than 1 mg/kg, a maximum allowable limit for Cd in agricultural soils (Table 6). Among 161 samples collected, 110 samples had a Cd concentrations of greater than 1 mg/kg a Tanzania and USEPA maximum allowable limit for Cd in agricultural soils (URT, 2007). Since the levels of Cd are higher than allowable concentration, there is likely associated phytotoxicity and health risk to plants, soil biodiversity and other soil inhabitants, and food product contamination (Lugwisha, 2016).

Zinc (Zn) and Iron (Fe): The concentration of Zn and Fe and their distribution in topsoils in different land-use were observed to vary with land uses (Tables 7 and 8). High concentrations were observed in maize and paddy growing areas and industrials areas. For example, study conducted by Machiwa (2010); Lugwisha (2016), and Mahugija and Sheikh (2018) on the distribution of Zn and Fe in topsoils in different regions of Tanzania reported higher values of Zn in paddy farming areas (59.8 mg/kg), Maize growing areas (75.27) and near industrial areas (192.6 mg/kg). While the concentration of Fe was high in maize growing areas (38427.08 mg/kg), Grassland (193.43 mg/kg), mixed woodland (65.30 mg/kg), and in permanent industrial crops (tea) (43.70 mg/kg), this is likely to affect the availability of other plant nutrients such as phosphorus due to increased fixation by iron. Among 393 samples, 278 samples, about 70.74%, were observed to have Zn concentration greater than 5 mg/kg (Table 7), a maximum allowable Zn in agricultural soils. Although Zn is an essential plant nutrient, the higher concentration of Zn above 5 m/kg in soils is likely to affect the availability of other nutrients such as Fe, P and may cause yellowing and wilting of crops due to zinc toxicity. However, maximum allowable limits for most countries for Zn in agricultural soils range 100–200 mg/kg such as Tanzania set at 100 mg/kg, Canada set at 200 mg/kg China 200–300 mg/kg and Netherlands set at 720 mg/kg (CCME, 2007; URT, 2007; USEPA, 2014). Additionally, a higher concentrations of Zn in soils inhibit soil microbial growth and soil activity.

Iron (Fe) has a vital role in plant growth. Still, the excessive concentration of Fe in soils can alter the soil pH and affect the availability of other nutrients such as phosphorus. Among 232 soils samples (Table 8) which were considered in the study on the distribution of Fe in different land use in different regions of Tanzania, 79 samples, about 34.1%, had Fe concentration above the maximum allowable limit of 100 mg/kg in agricultural soils this indicated that there is a risk of P unavailability for plant uptake due to increased P fixation and lowered soil pH. The summary of toxic metal distribution in different sites studied is presented in Fig. 5.

7. Metal bioavailability and bioconcentration and its impacts in agro-ecosystems

The primary route of potentially toxic elements (PTEs) to humans is the intake of food. They enter the food chain principally by plants' uptake from the soil and, to a lesser extent, through foliar; PTEs transfer from soil to plant is complex and hardly predictable (Agrelli et al., 2017). High level of toxic metal in farming areas may accelerate the uptake of PTEs in plant system and grains; however other Physico-chemical soil properties like soil pH, organic carbon, soil texture, C/N ratio may alter the availability of metals to plants (Liu et al., 2015; Zhou et al., 2014). Usually plants take PTEs which are readily available (bioavailable forms). Thus bioavailability is the key for the feasibility in estimating the transfer of PTEs from soil to plants and food system in general (Agrelli et al, 2017, 2020, 2017; Brunetto et al., 2016; Fagnano et al., 2020; Visconti et al., 2019).

Different studies have reported a positive correlation ($p < 0.01$) of metals in the soils such as Zn, Cd, Pb, and metals in rice collected in farming areas in Iran and China (Liu et al., 2015; Nadeem and Saeed, 2013). This shows that higher metal concentrations in soils might initiate uptake and concentration of metals in rice grain and other edible parts of a plant, creating a phytotoxicity effect and health risks (Agrelli et al, 2017, 2020; Brunetto et al., 2016; Simon et al., 2016; Visconti et al., 2019). However, Chanda et al. (2011) study in paddy farming areas in India observed a high level of PTEs in agricultural soils, but there was no correlation in metal concentrations in rice grains. For example, a study conducted in China in paddy farming areas recorded a mean level of toxic metal as Cr (72.03 mg/kg), Pb (38.7 mg/kg), and Hg (3.0 mg/kg) in soils, but a concentration of Cr and Pb in rice grain from the same place were below detection limits (Chanda et al., 2011; Liu et al., 2015), the same scenario reported by Fagnano et al., (2020) and Visconti et al., (2019) in Italy. The bioavailability of toxic metal to plants and other soil inhabitants is a key in estimating harmful effects because a certain amount of toxic metal can be available in the soil but not available for plant uptake, hence unlikely to contaminate the food chain/system or they are harmless to soil inhabitants (Malidareh et al., 2014; Moradi et al., 2013; Nadeem and Saeed, 2013). Therefore, bioconcentration factor (BCF) explains the transfer and bioavailability of metal from soil to plants or plants edible parts help explain the bioavailability and bioconcentration of metals in the farming system (Lugwisha, 2016). The BCF is determined as a ratio of metal in plant parts/edible parts to that present in the soils where a particular crop is grown/obtained (Equation (1)).

$$Bioconcentration\ Factor\ (BCF) = \frac{[M\ Plant]}{[M\ soil]} \tag{1}$$

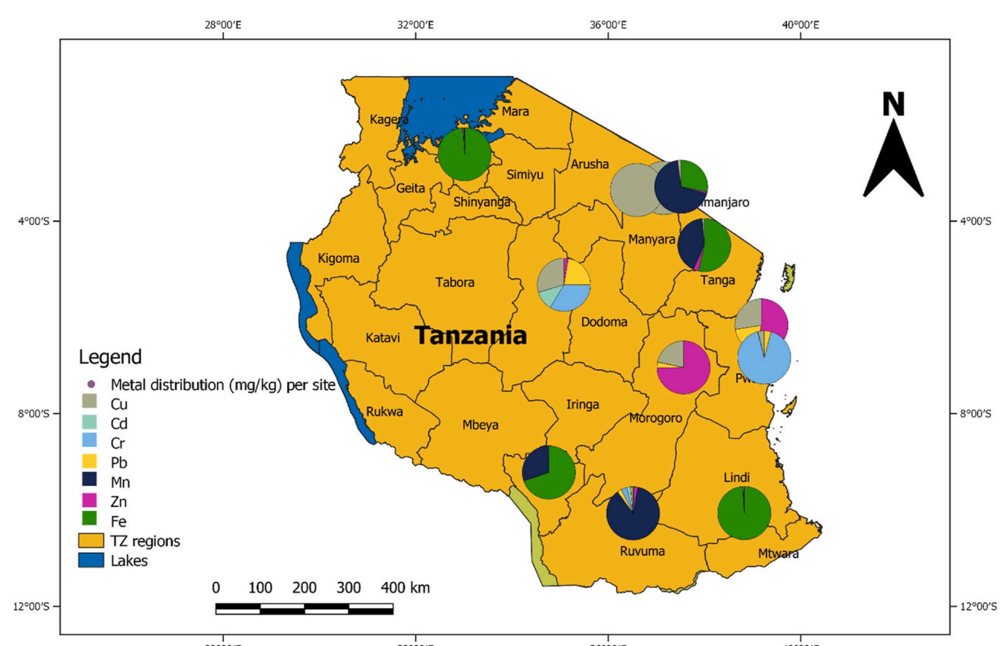

Fig. 5. The simple map showing the distribution (ratio) of toxic metals in each study area in Tanzania (Source: Author).

*where [M] plant and [M] soil represent the concentration of the metals in extracts in plants and soil respectively obtained/grown in a particular environment (*Lugwisha, 2016*).*

The BCF of above 1 indicates higher uptake of toxic metals in crop/plant than in soil whilst BCF of less than 1 indicates more toxic metals concentration in soil than those taken up by plants. Studies conducted by Lugwisha (2016) on BCF in vegetables in different parts of Morogoro region in Tanzania for cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) in tomatoes, cauliflower, cabbage, and onion observed to be as follows at Kihonda in onion (Cu = 7.41, Cr = 70.4, and Zn = 1.23), Mgeta in tomatoes (Cu = 0.19, Cr = 6.50, Zn = 3.64, and Cd = 0.043), Towelo in Cabbages (Cu = 24.44, Cr = 2.21, Zn = 31.73, and Pb = 1.06). High BCF indicates high metal concentrations in studied vegetables than those in soils and might not be safe for human consumption as it may pose a health risk to consumers. Therefore, a thorough examination of the relationship of toxic metals concentration in soils with metals in crop produced to estimate toxic metal bioavailability and bioconcentration would help estimate health risk and establish control measures to ensure the safety and sustainability of agro-ecosystem. We conclude that crops cultivated in contaminated soils could have moderate to high risk for PTEs uptakes and leading to human health risk (Agrelli et al., 2017).

8. Environmental risk assessment linked to water eutrophication and metals

The concentration of nutrients causing eutrophication such as nitrogen (TN) and phosphorus (TP) and toxic metal contaminations have environmental and ecological impacts in areas where they occur at elevated levels. The risk of toxic metal accumulation in a water reservoir in an agro-ecosystem can be estimated by using the potential ecological index and the total risk index values (Li et al., 2019). The ecological risk assessment involves the evaluation of the fertility of sediments by determining the organic index using organic carbon and organic nitrogen (equation (2)).

$$Organic\ index = Organic\ Carbon\ (\%)\ x\ organic\ Nitorgen\ (\%) \tag{2}$$

where organic carbon (%) represents total organic carbon (%), organic nitrogen (%) is TN(%) x 0.95, since TN includes organic N (OC–N) and ammonium-N, and OC-N occupies the majority (Li et al., 2019).

The organic index of <0.03 indicates Oligotrophic; Mesotrophic of 0.03–0.05, and Eutrophic >0.05, recently there is scanty information in the organic index in the East Africa agro-ecosystem hence calls for an establishment for such studies.

The potential ecological risk of each metal can be determined by the ecological risk index (equation (3)).

$$E_r^i = T_r^i \frac{C^i}{C_n^i} \tag{3}$$

where E_r^i is the potential ecological risk coefficient of the ith toxic metal; T_r^i is the metal toxicity coefficient, C^i and C_n^i are the concentration of toxic metals in the sample (soil/sediment) and background, respectively.

Studies in potential ecological risk in East African agro-ecosystem are rarely conducted; however, few studies have been conducted, including sediments from water bodies from farming areas or in proximity to farming areas. Which can be used as an indicator to reflect the pollution risk associated or resulted from and in agro-ecosystem to achieve United Nations Sustainable Development Goals (SDGs). The study by Olando et al., (2020) studied the toxic metal (Co, Cr, Cu, Mn, Pb, Zn, and Fe) and potential ecological risk index in Lake Naivasha sediment, which is surrounded by farming areas and reported E_r^i to be Co (10.29), Cr (1.55), Cu (11.80), Fe (10.42), Mn (2.86), Pb (6.50), and Zn (4.46), where Cu and Cr had the highest and lowerest potential ecological risk, respectively. Furthermore, the study found that the mean toxicity was in the order of Cu > Fe > Co > Zn > Mn > Cr, but all element showed E_r^i value of less than 40. The study concluded that high concentration of toxic metals in the lake sediments resulted from intensified agricultural activities around the lake and increasing urbanization in the area. The study by Mungai et al., (2016) on the potential ecological risk of eight toxic metals (Hg, Cd, As, Cu, Pb, Zn, Ni, and Cr) in surface agricultural soils in central Kenya reported toxic metal severity in order of Hg > Cd > As > Cu > Pb > Zn > Ni > Cr. Where the E_r^i were in the range of 0.01–10.39. Where ecological risk level posed by a single factor was low. However, Hg and Cd showed higher values, suggesting these elements might pose a risk to the environment and humans if not closely monitored. These are among few studies conducted in East Africa, and more studies have to be undertaken in agricultural soils to ensure sustainable land productivity.

The ***comprehensive risk index (RI)*** for metals can be determined by equation (4), showing the toxicity of the toxic metal to organisms in sediment and water, whether high, low or moderate, as shown in Table 9.

$$RI = \sum_{i=1}^{m} E_r^i \tag{4}$$

The RI enables the determination of the degree of toxic metal pollution in sediments and soils (Hakanson, 1980). The RI provide quantitative value for the combined contamination risk to a particular ecological system based on the toxic metal toxicity and its response to the environment. Based on the RI and E_r^i toxic metal risk index is classified into five classes ranging from low to very high as the status of contamination and associated risks (Table 9).

Despite the fact that the importance of RI, few studies has been conducted in East African agro-ecosystem. The survey conducted by Mungai et al., (2016) in agricultural soils and Olando et al., (2020) in Lake Naivasha sediments observed the overall ecological risk (RI) of the lake sediments and agricultural soils to be low to moderate (RI 36.73–60.51), which were much lower than Hakanson's RI low-risk value of 150 (Hakanson, 1980). This suggested that the concentrations of toxic metals in agricultural soils in the study area posed a low ecological risk to the environment and humans, and the ecological risk level posed by a single factor was low. However, Hg and Cd showed higher values, suggesting this element might pose risk to the environment and humans if not closely monitored. This point out that there is a need to have more studies in the ecological risk index in in agricultural soils and sediments in agro-ecosystem to form a baseline for management strategies to ensure sustainable productivity of land and water aiming to address life in land and water to achieve zero hunger as UN sustainable development goals.

Total toxic metal concentrations: The determination of total toxic metal concentration in agricultural soils and sediments can be used as a simple environmental assessment indicator when the obtained concentrations are compared to the maximum monitoring authorities values which have been put in place as the maximum concentration limits of toxic metals allowed in agricultural soils and water (URT, 2007). In East Africa, many studies have been conducted to analyze the concentration of toxic metals in soils, water, and sediments; however, most of these studies have been conducted in around residential areas and mining areas and not in agro-ecosystem (Almås and Manoko, 2012; Kitula, 2006; Koleleni and Mbike, 2018; Mataba et al., 2016) or around industrial areas (Mahugija and Sheikh, 2018) and very few in agro-ecosystem (Machiwa, 2010). Therefore, toxic metals' risk and contamination status in most agricultural soils in East Africa is unknown. We can not conclude that the system is safe or polluted as there is a lack of supporting evidence because few or no studies have been conducted solely in agro-ecosystem as the focus area. The unavailability of this information hampers management planning and strategies to avoid further contamination. Therefore, sampling of soils, water and sediments from farming areas to characterizing their concentration is a simple and acceptable environmental assessment with regard to toxic metals. For example study conducted by Olando et al., (2020) on concentration of Mn, Zn, Cu, Cr, Co and Pb in lake sediments in Eastern Kenya observed the toxic metal concentration to be Fe 53,655.60 (38, 851.30–64,938.26) mg/kg, Mn 1506.87 (1062.47–2653.43) mg/kg, Zn 231.94 (187.96–334.51) mg/kg, Cu 33.74 (23.05–46.93) mg/kg, Cr 27.44 (2.52–68.83) mg/kg, Co 24.04 (17.82–28.75) mg/kg and Pb 22.11 (14.31–45.93) mg/kg. These high concentrations have potential ecological and environmental impacts on aquatic animals and humans. Therefore further and more studies have to be conducted in agro-ecosystem solely considering the agricultural land as a focal point to ensure high productivity and safe food production.

PTEs Accumulation indicators; The accumulation of PTEs in agricultural soils and sediments can be determined using accumulation and pollution indicators such as the contamination factor (CF) and geo-accumulation index (Igeo), pollution load index (PLI), and enrichment factor (EF) (Malsiu et al., 2020; Suresh et al., 2011). Through determining and calculating the CF values, it is possible to assess the degree of contamination by toxic metals for parameters such as the pollution load index (PLI), the EF enrichment factor (EF), and the index of geo-accumulation (I_{geo}).

(i) **Contamination Factor (CF) and Pollution Load Index (PLI);** The pollution load index (PLI) is the square root of the multiplication of the contamination factor (CF) of metals(Eqn (6)): where CF (metal) is the ratio between the content of each metal and the background value in sediment and water samples of the study area (Eqn (5)). The CF and PLI are important because they are used to evaluate the contamination of PTEs, CF value of less than 1 indicate low pollution, CF 1–3 shows moderate pollution, CF 3–6 means high pollution, and CF above 6 indicates very high pollution (Gashi et al., 2017; Senkondo et al., 2014).

$$CF\ (Metals) = \frac{C(metal)}{C(background)} \tag{5}$$

$$\mathrm{PLI} = (\mathrm{CF1\ \ x\ \ CF2\ \ xCF3\ \ x.......x\ \ CFn})^{1/n} \tag{6}$$

(ii) **Geoacumulation Index (I_{geo});** An assessment degree of contamination by the toxic metals could be determined by the geo-acumulation index (I_{geo}). I_{geo} is calculated as described in equation (7).

$$I_{geo} = \log 2\left(\frac{\mathrm{Cn}}{1.5\mathrm{Bn}}\right) \tag{7}$$

where Cn expresses the content of the toxic metal *n*, Bn expresses background data of the toxic metal *n*, and 1.5 is a factor of possible lithological changes (Gashi et al., 2017; Kersten and Forstner, 1986; Malsiu et al., 2020; Suresh et al., 2011) [9]. The I_{geo} values can be interpreted as follows: $I_{geo} \leq 0$, unpolluted; $0 \leq I_{geo} \leq 1$, unpolluted to moderately polluted; $1 \leq I_{geo} \leq 2$, moderately polluted; $2 \leq I_{geo} \leq 3$, moderately to heavily polluted; $3 \leq I_{geo} \leq 4$, heavily polluted; $4 \leq I_{geo} \leq 5$, heavily to extremely polluted; and $5 \leq I_{geo}$, extremely polluted.

(iii) **Enrichment Factor (EF);** The EF of heavy metals has been commonly used to assess anthropogenic contamination. Element Fe is commonly chosen as the normalizing element for identifying anomalous PTEs contributions (Vemic et al., 2014). The EF values can be calculated by using Equation (8).

$$\mathrm{EF} = \frac{\mathrm{C/Fe(sample)}}{\mathrm{C/Fe(background)}} \tag{8}$$

where C/Fe (sample) and C/Fe (background) represent the PTEs-to-Fe ratios in the study and the background sample, respectively. Generally, values of the EF can be interpreted as follows: <2, minimal; 2–5, moderate; 5–20, significant; 20–40, very high; and >40, extremely high enrichment. For most agro-ecosystem East Africa, information about pollution indices related to sediments is sparse. The study by Nkinda et al., (2020) on levels and associated risk of As, Cd, Cr, Hg, and Pb in sediments collected from four different sites along the Mara River in Lake Victoria Tanzania in 2019 is among few studies that used many pollution indices such as geo-accumulation index (Igeo), enrichment factor (EF), contamination factor (CF), pollution load index (PLI) (Kihampa and Wenaty, 2013; Nkinda et al., 2020). The study found that CF in the study area was below the unit during the dry month indicating low degree of contamination, while during the dry season, CF ranged $1 \leq CF < 3$indicating a moderate degree of contamination. The PLI values determined was above zero but less than 1 indicating minimal deteriorations. The Igeo in most studied sites were observed to be below zero indicating most of the areas were unpolluted; the estimation of enrichment factor observed EF of less than two showing low enrichment of potentially toxic metals or heavy metals in sediments and soils. This is how details of metal accumulation in soils and sediments can be determined when assessing the risk of PTEs in agro-ecosystem. However, for detailed description of pollution indices in agro-ecosystem and related ecosystem, the author refers the reader to Gashi et al. (2017); Kersten and Forstner (1986); Kihampa and Wenaty (2013); Malsiu et al. (2020); Nkinda et al. (2020); Suresh et al. (2011); and Vemic et al. (2014).

9. Conclusion and way forward

Population growth drives increased food demand, requiring increased production per unit area of available arable land. To achieve increased productivity and sustainability of agro-ecosystem, the authors propose the following key research-informed policy to be adopted by the government, educators, scientist, and farmers as follows (i) development of regulation guidelines for agrochemicals use. This will include the amount of fertilizer and other agrochemicals to be applied and application frequencies to ensure high yields while reducing environmental contaminations (ii) Establishment of agro-environmental quality indicators for soils and water to be used by farmers and conservation authorities to monitor any quality changes happening in agro-ecosystem before negative impacts are realized, and (iii) adoption of best farming practices such as split fertilization, cover cropping, reduced tillage, drip irrigation, and biological pest control to increase crop productivity while ensuring agro-ecosystem sustainability. The use of organic fertilizer, split fertilization, reduced tillage, drip irrigation, and biological pest control is suggested as practices that can increase yield per unit area and have less environmental contamination. The split fertilization allows the given amount of fertilizer to be used by target plants and less lost to water bodies. The use of biological pest and weeds control helps reduce the amount and frequency of pesticides and herbicides, which could have increased contaminations. The use of cover crops and intercropping provides soil cover which helps to reduce soil erosion and increase infiltration, reducing the surface runoffs from urban and peri-urban areas, which might be a potential source of toxic metal contaminants in soils and water in agro-ecosystem. Whenever mining or industrial waste has to be deposited, complete treatment should be conducted to avoid possible contaminants to the environment. Realization of these initiatives must be grounded in the robust and representative evaluation of current soil contamination status and a depth understanding of the sources and processes leading to pollution. As monitoring of toxic metal accumulation in soils and water reservoirs is of paramount importance, therefore continuous studies and monitoring of toxic metal accumulation in agro-ecosystem has to be conducted to cover more areas to generate spatial-temporal information, which will help legislation and conservation authorities in setting out specific management in agro-ecosystem for high productivity while ensuring environmental and ecological sustainability.

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Ethics approval and consent to participate

Not applicable.

Consent to participate

Not Applicable.

Consent for publication

Not Applicable.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

Not Applicable.

Author contributions

M.M, P.A.N, T.H.H, and L.K.M; Conceptualization and methodology, M.M, L.K.M and T.H.H; writing—original draft preparation, P.A.N, L.K.M, T.H.H, S.C, and W.B; writing—review and editing, P.A.N, L.K.M, T.H.H, and S.C. Supervision, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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