



Review Article

Preliminary review of mine air pollution in Zambia

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ABSTRACT

Zambia is endowed with mineral wealth that includes copper, cobalt, gold, nickel, lead, silver, uranium, zinc, and numerous precious and semi-precious stones. Mining activities are predominantly found on the Copperbelt and North-Western Provinces, although these minerals are dotted all over the country. Copper mining in Zambia dates back to the 1900s and this period witnessed massive investment in mine development with concomitant increase in support facilities including building of new towns, roads and other commercial infrastructure. The mining sector has therefore evoked considerable national attention for its potential to contribute towards economic growth, job creation and poverty alleviation. However, mining and mineral processing by its very nature comes with environmental costs and the effects can continue long after the mining has stopped. The aim of this article was to review the relevant publications on the impacts of air pollution arising from mining operations with respect to human health, plants, animals and infrastructure and synthesize the views of researchers and suggest any additional research required to inform policy and remedial actions. This review has revealed that there is a paucity of studies on mining-related air pollution in Zambia. The main identified air pollutants were SO₂ and particulate matter (PM), both fine and ultrafine (PM₁₀, PM_{5.0}, PM_{2.5} and PM_{0.1}). The main sources of these pollutants were flue gases from smelter operations and dusts within the mines and those blown from both operational and abandoned waste rock, overburden and tailings dump sites. The identified occupational diseases for miners in Zambia were silicosis and tuberculosis, which have been compounded by the prevalence of HIV/AIDS. In the hotspot townships of air-borne exposures from smelter emissions in Mufulira, ambient air SO₂ levels exceeded the 'safe' limits of international and National standards. Moreover, the top soils have turned acidic and have become laden with heavy metals (Pb, Zn, Cu, Co and Fe). These metals were also found in the dust deposited on leaves of crops. There were also visual signs of impaired vegetation cover and corroded housing infrastructure in the affected areas. In the vicinity of the abandoned Pb–Zn mine in Kabwe, the soils have been contaminated by heavy metals and pathological lead poisoning of children and wild mammals have occurred. The review article has further examined study gaps and suggested areas that need further research in order to address the challenges arising from the legacy of copper mining in Zambia. These include comprehensive PM characterization from mining environments, extent of occupation exposure to air pollutants, efficiency and efficacy of airborne control technologies, health risks and epidemiological studies in mining towns, and the influence of exposure to PM on pulmonary tuberculosis and HIV/aids among miners.

1. Introduction

Zambia is located on the Southern African sub-continent between 8° and 18° south, and 22° and 34° east. It covers an area of 752, 614 km², with a population of about 15 million persons, and is landlocked, surrounded by eight countries which include the Democratic Republic of Congo, Tanzania, Malawi, Mozambique, Zimbabwe, Botswana, Namibia

and Angola. Administratively, it is divided into ten provinces, namely, Central, Copperbelt, Eastern, Luapula, Northern, North-Western, Southern, Western, Muchinga and Lusaka (the capital city). The climate is subtropical and in general, the year in Zambia can be divided into two distinct halves, a dry half from May to October and a wet half from November to April. The annual rainfall ranges from 700 mm in the extreme southwest to 1,400 mm in the north and is 1,001 mm on

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average. The average temperature is 21.0 °C. July is the coldest month and the cold temperature ranges from 3.6 °C to 12.0 °C with an average of 8.1 °C. The hottest month is October and the recorded hot temperature range is 27.7–36.5 °C with an average of 31.8 °C. Air-masses are predominantly light easterly to southeasterly most of the year. However, during the rainy season air-masses become more variable and westerly and northwesterly in the northern and western parts of the country (YEC, 1995). Fig. 1 below shows GIS location map of the study area.

Zambia has been predominantly a mining country and the copper industry has dominated the mining landscape for more than eight decades since the first commercial mine was opened in the early 1900s (RCCM, 1978; Simutanyi, 2008). To date, the mining sector is still the major foreign exchange earner for the country and the increase in the mining activities in the last decade has seen an increase in the sector's contribution to Gross Domestic Product (GDP) from around 8% in 2000 to 11% in 2011 (MoF, 2014), employing over 50,000 people. Zambia plays an important role in the global mining industry and the country

contains the largest known reserves of copper in Africa, holding 6% of known copper reserves in the world (CTPD, 2012). Zambia's mining sector has continued to register strong performance over the last decade with growth averaging 11% per annum (MoF, 2014). At present, five companies own holding of about 80% of all copper output and these are Swiss (Glencore Limited – majority owners of Mopani Cooper Mine), Canadian (First Quantum Minerals Limited – majority owners of Kansashi Mine), Indian (Vedanta – majority owners of Konkola Copper Mine), Barrick Gold (Lumwana Mines Plc) and Chinese (NFC Africa). According to the Zambia extractive industries transparency initiative report, covering the 2015 fiscal year, there were more than 30 companies operating in Zambia who provided information on their contribution to the Government of the Republic of Zambia's revenues arising from the extractive industrial activities (ZEITI, 2016). Besides, copper, Zambia is endowed with mineral wealth that includes cobalt, gold, nickel, lead, silver, uranium, zinc and numerous precious and semi-precious stones. These minerals are dotted all over the country, although mining activities

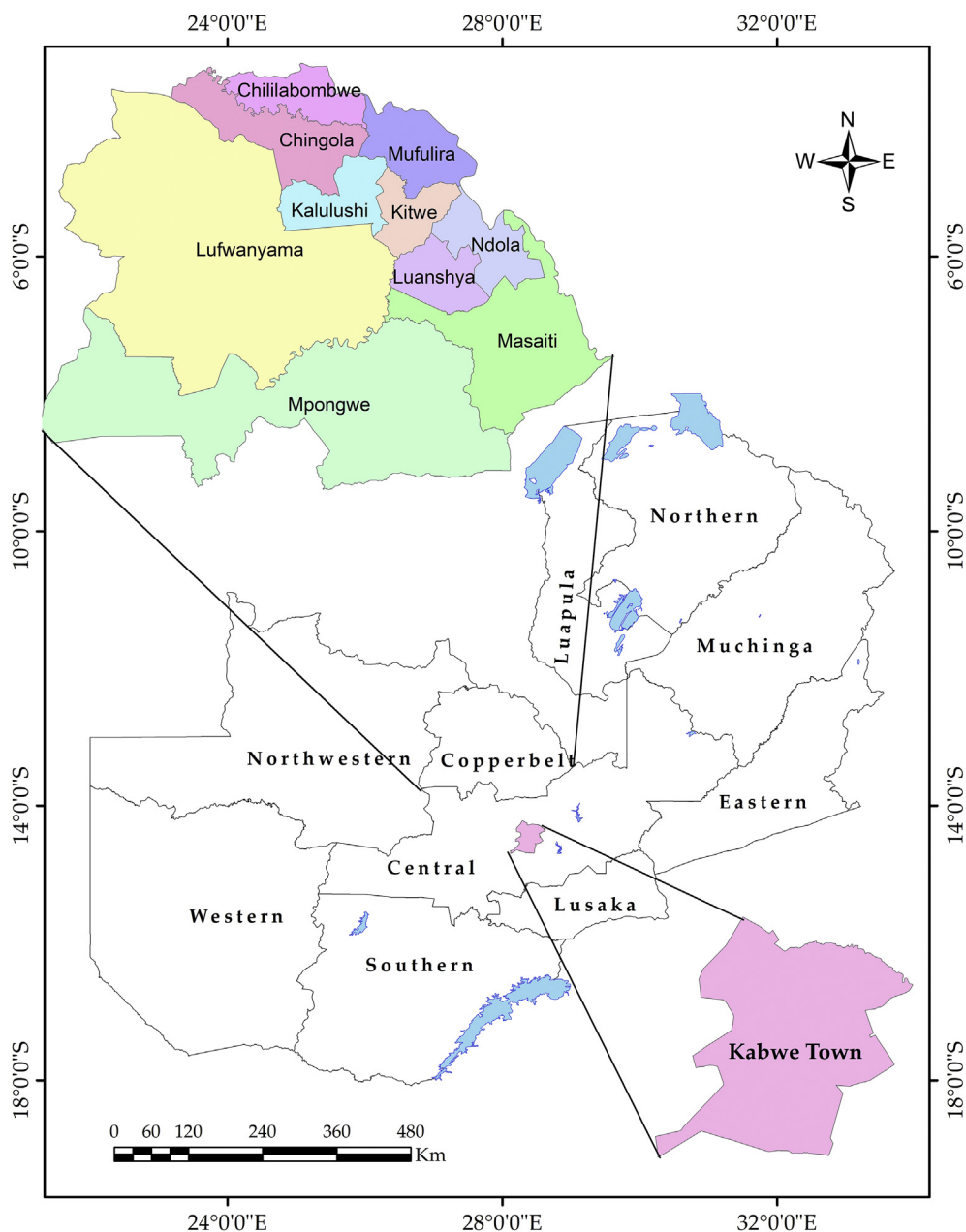


Fig. 1. GIS map showing location of study area.

are predominantly found on the Copperbelt and North-Western Provinces.

The copper mine operations on the Copperbelt have had a history of poor environmental management from inception. The poor environmental stewardship has continued irrespective of whether the mining companies were privately or public owned. Over the years, sadly, this environmental mismanagement has compromised the health of the local people, vegetation, animals and has led to the destruction of infrastructure. According to some recent studies (World Bank, 2012; ZIEM, 2012; OAG, 2014; Fraser and Lungu, 2006), there are three prominent environmental problems arising from the mining operations namely sulphur dioxide (SO₂) and particulate matter (PM) emission from smelters, heavy-metal effluents released into water streams and rivers and siltation of local rivers and water bodies.

Mine air pollution in Zambia, which is largely due to SO₂ and PM, both fine and ultrafine (PM₁₀, PM_{5.0}, PM_{2.5} and PM_{0.1}) emissions has been a topical issue since commercial mining started in the 1920s in the Copperbelt region of Zambia. However, very few studies have been undertaken to chronicle the extent of damage to the environment and harm to human health. The studies showing extent of widespread pollution have been undertaken in the recent past. For instance, in 2000, the Air Pollution Information Network for Africa (APINA) conducted a study to ascertain the levels of air pollution in Zambia. The results of this study showed that the highest total emissions in Zambia where PM₁₀ emissions which recorded 406.8 kilotonnes/year (kt/yr) and accounted for 35% of the total emissions that year. This was followed by SO₂ which recorded 359.6 kt/yr, accounting for 31%, while PM_{2.5}, NH₃ and NO_x were at 252.7 kt/yr, 75.8 kt/yr and 72.8 kt/yr, respectively (ECZ and ZEOR 3, 2008). An audit report from the Office of the Auditor General on mine operations (OAG, 2014) revealed that SO₂ and PM emissions for most of the 5 large scale mines with smelters and other discharge licences were outside the national set limits by between 155% to 111% higher than the Zambia Environmental Management Agency (ZEMA) standard during the 2013 reporting year.

SO₂ is the most critical air pollutant that continues to be emitted from the mining companies. The main source of SO₂ pollution from the Zambian mines is from the roasting and refining of copper bearing sulphide ores, chalcopyrite (CuFeS₂) (Simukanga, 1999). The first stage in most processes is roasting or smelting the ore in air which oxidizes some of the copper and produces SO₂. The increase in SO₂ emissions has always been observed to increase at the same rate as copper production, primarily due to old smelting processes that are inefficient (Olli, 2014).

However, in the last two decades, partly as a result of pressure from international NGOs and Banks (CTPD, 2012) and the strengthening of the implementation of air pollution legislation by ZEMA, serious efforts by mining companies in modernizing their smelters has led to significant reduction in SO₂ emissions. For instance, 4 of the 5 major mining companies in Zambia that have a holding of 80% copper output as mentioned earlier, have modern smelters with improved efficiency of SO₂ capture.

Whilst there is some noticeable improvement in the reduction in SO₂ emissions, the control of particulate pollutants from mining environments especially PM_{2.5} and PM₁₀ still remain a major concern (Fig. 2). Tao et al. (2003) classified PM as coarse (2.5–10 µm aerodynamic diameter, PM₁₀), fine (0.1 ≤ 2.5 µm aerodynamic diameter, PM_{2.5}) and ultrafine (≤0.1 µm aerodynamic diameter). According to Tao et al. (2003), fine and ultrafine PM are produced by combustion that include motor vehicles and power plants, whereas PM₁₀ are generated by mechanical processes that produce fugitive dusts from non-combustive sources. Kumari et al. (2011) noted that all production oriented mining operations such as cutting, breaking, crushing, drilling, grinding or abrasive blasting contribute to fine PM generation, while tailings dump sites are responsible for the emission of coarse PM. The other pollutants such as NO_x and CO, including secondary pollutants like ozone are generated from mining related activities. However, the impacts of these pollutants are not as significant on the local communities as that of SO₂ and PM, whose devastations are quite evident on the Copperbelt



Fig. 2. Air pollution from the Mufulira Mine.

Province.

1.1. Historical background to air pollution and control on the copperbelt

Considering the long period of mining on the Copperbelt it is important to look at the historical background to mine air pollution and control efforts. From the beginning of large scale commercial mining in 1928 on the Copperbelt, the mines with smelters received protection from the law against liability as they were indemnified from liability through Smoke Damage (prohibition) Act of 1935. This act declared smelter areas like Nkana, Luanshya and Mufulira Mine areas as Smoke Areas. So during the colonial times under the British rule the mine operators were thus not liable for any damage to human health and property as a result of air pollution from these smelters. Therefore, there was no incentive to control the emissions but rather a licence to pollute.

Upon Zambia getting independence and nationalization of the private mines, this law still remained on the statute books of law. The then government-owned Zambia Consolidated Copper Mines (ZCCM) also enjoyed indemnity from liability resulting from air pollution. When Zambia returned to multi-party democracy and the liberalization of the economy in the 1990s, the Smoke Damage Act was found to be repugnant and was thus repealed in 1996 in the Act No. 21 of 1996 CAP. 205 of the Laws of Zambia.

However, during privatization of the mines in the late 1990s-2000 the spirit of the Smoke Damage Act found its way in the development agreements, as the new investors sought indemnity for acquiring and operating polluting mine operations for the so called stability period (OAG, 2014), in which period the government or its agencies will not take any action to enforce or penalize the new owners of the mines for any pollution during the stability period. During this period the mines environmental management was only regulated within the scope of their approved Environmental Management Plans (EMP).

2. Main text

2.1. Effects of mine air pollution on human and animal health

Studies elsewhere have revealed that air pollution can have devastating effects on human health (Bernstein et al., 2004; Tao et al., 2003). According to the World Bank (2005), urban air pollution is estimated to cause 250,000 deaths and millions of cases of respiratory illnesses every year. Kapungwe et al. (2001) revealed in their study that toxicological data collected worldwide suggests that human fatalities can arise from short-term exposure to atmospheric SO₂ levels in excess of 1000 µg/m³. Such levels were common, especially in the mining towns of Kitwe and Mufulira.

Zambia Environmental Outlook Report 3 (Environmental Council of

Zambia, 2008), indicated that the major source of SO₂ were from industrial processing which contributed 346,700 tonnes/year, accounting for 98% of the total emission and these were mainly from metal processing, mostly copper smelting. Ncube et al. (2012) carried out a study that measured the concentration of SO₂ from the converters and the smelter in Chambishi and the results showed a concentration of 1402 µg/m³ and 369 µg/m³ SO₂ from the converters and the smelter, respectively. Furthermore, this study also showed that the levels of SO₂ in ambient air, several kilometers from emission sources still exceeded the permissible Zambian annual ambient value of 50 µg/m³ by between 2–3 orders of magnitude.

The Occupational Health and Safety Institute of Zambia (OHSIZ) is a statutory body in the Ministry of Health, mandated to carry out occupational medical surveillance, occupational hygiene and occupational health and safety research in the Zambian mines and miners with particular emphasis on silicosis, tuberculosis and silico-tuberculosis.

Silicosis has been described (Michael et al., 2007) as a potentially fatal, irreversible, fibrotic pulmonary disease that develops subsequent to the inhalation of large amounts of silica dust over time. This has a long latency period and develops subsequent to substantial occupational exposures. It clinically presents as an acute, accelerated, or chronic disease.

Few studies have been done on silicosis prevalence in Zambia. Paul (1961), while at OHSIZ, undertook the first published descriptive epidemiological study of Zambian copper miners that reported a low silicosis incidence of <0.5%. However, Paul's analysis lacked age stratification of the cohort. By the early 1970s, this weakness was obvious to OHSI scientists who corrected it by reporting age stratified silicosis risk that showed a prevalence of 5% in older in-service miners (Hayumbu, 2012).

Sitembo (2012) conducted a retrospective study that reviewed 476 randomly selected records of Zambian former copper mineworkers who underwent medical examinations at OHSIZ for the period of 1st January 2004 to 31st December 2008. The results showed a silicosis prevalence of 8.8%. The silicotics were found to have worked in the mining industry for a median 26 years while the non-silicotics' median service stood at 21 years.

Tuberculosis (TB), though typically not restricted to miners, presents another disease burden in Zambia that has been associated with exposure to respirable silica dust in underground mines. Silica-related TB has become a menace among silicosis-afflicted mineworkers. Mulenga et al. (2005) examined medical records of 2114 Zambian miners for the period 1945 to 2002. They found that 22.7% had silicosis, 65.4% had TB, while 11.9% suffered from silico-tuberculosis. Analysis of data from OHSIZ of a sample of copper miners by Chanda-Kapata et al. (2016) revealed that the weighted average incidence rate of bacteriologically confirmed pulmonary TB (PTB) within the Zambian mines for the period 1994–2014 was 658 per 100,000 persons. It was also found that the Copperbelt Province, a region with the highest concentration of mines in Zambia, had a notification rate of 415 per 100,000 people in 2013, which was more than 10-fold the national TB notification rate.

Human exposure to air pollutants from mining and ore processing operations can also occur through the food chain. A study by Kr̄ibek et al. (2014) found substantial chemical contamination of the surface of leaves of cassava (second staple crop after maize in Zambia) grown near the smelters located in the Copperbelt region of Zambia. The leaves of cassava cultivated in the immediate vicinity of smelters were found covered with tiny particles of dust that contained potentially toxic levels of heavy metals. The presence of these metals in the fallout dust was confirmed when their concentrations in washed and unwashed cassava leaves were compared (Table 1). Overall, using the highest tolerable weekly ingestion limits established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2007), this study concluded that dietary exposure to metals through the consumption of uncooked cassava leaves and tubers posed a moderate hazard to human health. It was further noted that as the surfaces of leaves were strongly contaminated by metalliferous dust in the polluted areas of the Copperbelt, there was still a potential hazard

Table 1

Concentrations (mg kg⁻¹) of metals in unwashed and thoroughly washed cassava leaves from contaminated area of the Copperbelt region and the amount of chemical elements removed by washing (% of concentrations in unwashed leaves). MED = median value, MAD = median absolute deviation, number of samples: 5 (Kr̄ibek et al., 2014).

Element	Unwashed leaves MED ± MAD	Washed leaves MED ± MAD	% of element removed
As	0.08 ± 0.01	0.07 ± 0.01	12.0
Co	1.30 ± 0.05	0.60 ± 0.03	53.8
Cu	35.95 ± 5.74	20.12 ± 1.12	44.0
Fe	800.20 ± 51.0	183.00 ± 0.0	77.1
Pb	0.71 ± 0.11	0.61 ± 0.11	14.3
Zn	345.20 ± 6.16	316.27 ± 4.43	8.4

of ingesting dangerous levels of copper, lead and arsenic if dishes were prepared with poorly washed foliage.

Another lesson that has been learnt from the legacy of mining in Zambia is the fact that human exposure to toxicants can persist for decades, long after the closure of mining operations at any given locality. This situation pertains to Kabwe town (Fig. 1), the provincial capital of Zambia's Central Province that has had a long history of open-pit Pb-Zn mining. The mine opened in 1902 and ceased operations in 1994. Apart from Lead (Pb) and Zinc (Zn), Cadmium (Cd) was produced as a by-product of processing zinc-containing ores. Yabe et al. (2018) analysed Pb and Cd concentrations in blood, feces and urine of children from three townships near the abandoned lead-zinc mine in Kabwe. They found that faecal Pb (up to 2252 mg/kg, dry weight) and urine Pb (up to 2914 mg/L) were extremely high. Concentrations of Cd in blood (Cd-B) of up to 7.7 mg/L, fecal (up to 4.49 mg/kg, dry weight) and urine (up to 18.1 mg/L) samples were also elevated. In an earlier study by the same authors (Yabe et al., 2015) of the same townships and children in Kabwe, it was found that all the 246 sampled children exhibited indications of lead poisoning, with blood lead levels (BLL) exceeding the 5 µg dL⁻¹ "level of concern" set by Centre for Disease Control (CDC) (Betts, 2012). The mean BLL was 59.4 µg dL⁻¹ for all the sampled children, with a range of 5.4–427.8 µg dL⁻¹. Children living in townships which were close to and in the direction of the prevailing winds from the abandoned mine dumps recorded the highest concentrations of metals in their bodies. Therefore, polluted dust was the main exposure route for the affected townships. The study described the above-stated levels of lead and cadmium in children as alarming and prescribed immediate medical intervention for the affected children.

The study of lead poisoning in Kabwe has also been extended to terrestrial wildlife, in the form of small wild mammals. Nakayama et al. (2011) analysed the lead and other heavy metal concentrations in soil and wild rat (*Rattus* sp.) samples collected from around the abandoned Pb – Zn mine in Kabwe and Lusaka (the capital city of Zambia). Lusaka served as the control as it was not a mining town. The results revealed that concentrations of Pb, Zn, Cu, Cd, and As in Kabwe soils were much higher than those for Lusaka and that metal concentrations and distance were negatively correlated in all directions from the abandoned mine.

Of particular interest was the finding that both liver and kidney from rats in Kabwe had significantly higher lead concentrations than those from Lusaka (Table 2), indicating that polluted soil caused metal accumulation in wild rats.

It is also evident from Table 2 that the levels of Pb in Kabwe rats

Table 2

Body weight (g), age (months) and Pb concentrations (mg kg⁻¹ dry-wt) in liver and kidney of wild rats (Nakayama et al., 2011).

Locality	Body weight (g)	Age (months)	Pb concentration (mg/kg)	
			Liver	Kidney
Kabwe	21–170	0.9–20	0.009–7.3	0.3–22.1
Lusaka	28–213	0.9–15	0.003–0.5	0.08–1.9

exceeded the histopathological threshold of 2.5 mg kg^{-1} dry-wt. Additionally; a significant negative correlation between body weight and renal Pb was found, suggesting that wild rats from Kabwe have been chronically exposed to Pb, and that Pb might have affected growth of these rats. A reduction in body weight is a known typical toxic effect of Pb in rats (Nakayama et al., 2011).

2.2. Effects of mine air pollution on infrastructure

The damage due to air pollution on materials is of serious concern as it affects the service life of buildings and hence the economy of the affected community (Zhang et al., 2017; Rao et al., 2014). In Zambia, due to the nature of the mined copper ore, chalcopyrite, the predominant air pollutants include SO_2 and PM. These anthropogenic pollutants can cause building degradation through soiling, corrosion and erosion. Although the effects of air pollution on materials may easily be seen in terms of discoloration, material loss and soiling, the structural failing and economic losses may not always be visible to everyone.

Though sulphur dioxide can fall both as wet and dry deposition, it frequently falls as dry deposition even up to 30 km of its source (Rao et al., 2014). Wet deposition of acids occurs when the pollutants are released into the atmosphere and react with water vapor present in clouds to form dilute acids. Besides sulphur dioxide, nitrogen dioxide and carbon dioxide can also cause damage to the materials and infrastructure.

In Copperbelt Province, sulphur dioxide emissions are chiefly responsible for the acid rain which deteriorates the houses of inhabitants in mining communities. For instance, the Kankoyo Township near the Mufulira Mine is one of the classic examples where paint on houses has been peeling off and the corrugated iron roofs are corroded by the sulphur acidity (Simpere, 2010), as shown in Fig. 3.

This review was unable to find scientific literature that directly linked air pollution in Kankoyo township of Mufulira to acid rain and the resultant damages to housing infrastructure. However, the potential or probability for acid rain occurrence could be gleaned from the historical atmospheric concentrations of sulphur dioxide (SO_2) recorded in the area.

Leif and Simukanga (2005), compiled data from four SO_2 monitoring stations which were installed by the mining company at different clinics of the residential areas of Mufulira town. They found that the SO_2 concentrations were very high at Clinics 3 and 5, representing the townships of Kantanshi and Kankoyo respectively, which were located in the vicinity of the smelter as well as in the downwind direction of the smelter. On the other hand, the other clinics which were located further away, and either upwind of the plant (Clinic 8 in a low-density neighbourhood of Mufulira town) or not directly in the path of the dominant winds (Clinic 7 of Butondo township) recorded relatively reduced levels of SO_2



Fig. 3. Roofs and paints corroded by sulphur acidity in Kankoyo.

(Table 3).

The data in Table 3 further show that the SO_2 levels at Clinics 3 and 5 exceeded the annual guidelines significantly and even exceeded the daily guideline value for most of the years. Clinic 7 is located relatively far away downwind of the smelter but its SO_2 levels often exceeded the annual guideline value. It is only at Clinic 8, on the upwind side of the smelter, where the SO_2 levels were below the guideline values.

2.3. Effects of mine air pollution on soil and vegetation

Research elsewhere (Rai, 2016; Darrel, 1989) has shown that ambient air pollutants can adversely impact the physiological and biochemical parameters of plants, which can lead to a reduction in the overall growth and development of some plants species. Usually as observed by Darrel (1989) the greatest effects occurs when plants are exposed to mixtures of pollutants, whose effects can even manifest at lower threshold levels at which effects for each individual pollutant cannot be detected. Thus in case of the copper mine air pollution effects, other minor pollutants such as oxides of nitrogen, including the secondary pollutant like ozone become significant as they can contribute to poor plant growth.

The particulate matter effects on the growth and development aspects of plants are dependent on the physical and chemical nature of PM. Besides, the presence of heavy metals, the pH of PM can adversely affect soils making plant growth intolerable (Rai, 2016).

The SO_2 emitted in the air may form acid rain especially in the rain season and this contributes to the deterioration of the soils which become unfit for farming and inhibit growth of vegetation. The effect of mine air pollution is clearly visible in the vegetation of some townships near the mine areas. For instance, the Kankoyo area in Mufulira has open spaces without vegetation and only selected shrubs and trees like cactuses, mango and avocado are able to grow (Fig. 4). Thus according to Simpere (2010), some areas of Mufulira are considered as wasteland.

The direct cause and effect relationship between air pollution and failure of the soils in Kankoyo to support plant life, as witnessed by the residents of Kankoyo and the surrounding townships in Mufulira town, has yet to be scientifically established. However, a study by Konečný et al. (2014) revealed that the soils in Kankoyo Township and other surrounding areas which were located downwind of the Mufulira smelter had undergone acidification. Moreover, these soils recorded excessive amounts of metals in the ranges of 37–8980 mg Cu/kg, 3–46 mg Co/kg, <2.5–42 mg Pb/kg, and 16–83 mg Zn/kg; with the lowest values corresponding to topsoil from the reference sites located at 24 km upwind from the smelter (Table 4). When these soils were tested for biotoxicity, it was found that reproduction of *Enchytraeus crypticus* (worms) was fully inhibited in the soils with the highest Cu concentration of 8980 mg Cu/kg (Table 4). Overall, the number of reproduced enchytraeids correlated negatively with total Cu and Co concentrations ($r = -0.97$ and -0.94 at $p < 0.001$, respectively). No reproduction was possible in soils with Cu levels of $>5000 \text{ mg/kg}$. The median effect concentration (EC50) values were calculated for total Cu and Co and corresponded to 351 mg/kg and 7.8 mg/kg, respectively. Additionally, the number of reproduced enchytraeids also negatively correlated with total sulphur ($r = -0.80$, $p < 0.05$) in these soils.

Enchytraeid worms are critical soil biome components that contribute to organic matter decomposition by fragmenting organic debris, changing its properties and structure, and regulating soil microbial processes that are vital for normal plant growth (Tosza et al., 2010). They are, therefore, used as indicators to assess the biotoxicity or ecological health of contaminated soils.

The study by Ncube et al. (2012) examined the extent of damage of mine air pollution to vegetation in Mufulira and noted that SO_2 emissions from the mines caused physical damages such as necrotic spot, yellowing of leaves, defoliation (Fig. 5) and die-back on trees which were closer to the emission source.

Table 3
Average daily SO₂ concentrations (µg/m³) at monitoring stations in Mufulira town (Leif and Simukanga, 2005).

YEAR	SAMPLING STATIONS				Zambian annual SO ₂ guideline	Zambian, EU and WHO 24-hour SO ₂ guideline
	Clinic 3	Clinic 5	Clinic 7	Clinic 8		
1995	145	427	63	29	50	125
1996	189	485	74	41	50	125
1997	149	342	41	22	50	125
1998	103	407	50	34	50	125
1999	141	480	74	45	50	125
2000	76	247	44	35	50	125
2001	131	377	81	-	50	125
2002 (April to December only)	707	447	55	-	50	125
2003	400	388	66	-	50	125
2004	369	514	82	-	50	125



Fig. 4. Only resistant plants to air pollution are able to grow in some Mufulira townships.



Fig. 5. Effects of air pollution on plant species.

2.4. Discussion

This review has revealed the possibility of mine-derived air pollution in Zambia. The few studies that are available are not contemporary, but they have revealed the occupational and environmental effects of airborne hazard exposures associated with mining and ore-processing operations in Zambia.

In the mining workplaces, exposure to PM, in the form of silica dust, has created a pool of former and in-service silicosis-afflicted mine-workers. However, the actual prevalence or incidence rates for silicosis amongst miners are not exactly known as they change from one study to another. The reported rates are mainly based on restricted sample sizes, making it difficult to derive population-based rates. Moreover, according to Hayumbu et al. (2008), the reported rates could substantially underestimate total silicosis cases in Zambia. This is because the OHSIZ's (institution that is responsible for silicosis screening in Zambia) radiological diagnosis procedures of occupational respiratory diseases have not been updated in the last 30 years and the institute reports silicosis

morbidity as annual counts of silicosis cases instead of succinct silicosis parameters such as prevalence or incidence. The OHSIZ has also a limitation of poor follow-up of retired miners who are usually repatriated to their distant places of origin around Zambia. These miners usually undergo socio-economic destitution due to the debilitating effects of silicosis, for which, currently, there is no cure or effective treatment available. Tuberculosis (TB) has also emerged among Zambian miners as an additional occupational disease. TB being an airborne disease entails that enclosed areas such as mining sites with poor ventilation create favorable environments for TB transmission. The higher TB incidence rates in the mines have been attributed to higher rates of exposure to silica dust and silicosis (silicosis increases risk of tuberculosis by up to three times), the HIV/AIDS epidemic (HIV/AIDS increases risk of tuberculosis by up to ten times) and the environmental factors associated with the mines (Chanda-Kapata et al., 2016).

This review has also shown that apart from occupational exposures, the mining industry in Zambia has subjected residents, fauna and flora of

Table 4
Location and properties of the studied soils in Mufulira (Konečný et al., 2014)*.

Distance to Smelter (km)	Description of location and sampling depth	pH	Cu (mg/kg)	Co (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
3.6	Grassland, downwind, 0–1 cm	5.46	8980 ± 60.5	45.8 ± 0.48	41.6 ± 1.85	63.2 ± 0.14
3.6	Forest area, downwind, 0–1 cm	5.39	2830 ± 39.6	21.0 ± 0.06	21.3 ± 0.14	64.8 ± 0.52
3.6	Forest area, downwind, 1–3 cm	6.30	1140 ± 7.50	20.0 ± 0.23	23.2 ± 2.10	55.0 ± 0.95
3.6	Forest area, downwind, 3–10 cm	6.70	1020 ± 5.52	19.9 ± 0.13	21.5 ± 0.22	51.4 ± 0.58
8.0	Grassland, downwind, 0–1 cm	5.34	5480 ± 22.0	25.2 ± 0.10	39.1 ± 0.29	83.3 ± 1.41
8.0	Grassland, downwind, 10–20 cm	5.15	530 ± 448	14.2 ± 3.37	14.7 ± 6.62	49.0 ± 7.06
8.0	Forest area, downwind, 0–1 cm	6.85	3320 ± 58.2	23.5 ± 0.07	17.9 ± 0.02	50.8 ± 0.80
8.0	Forest area, downwind, 3–15 cm	5.78	694 ± 24.4	5.41 ± 0.08	10.0 ± 0.03	28.5 ± 0.93
24	Grassland, upwind, 0–1 cm	6.55	37.4 ± 0.22	2.70 ± 0.05	2.5	25.1 ± 0.12

* Metal concentrations expressed as means ± standard deviations.

surrounding communities to environmental exposures of air-borne pollutants. The main exposure hazards are SO₂ and metal-laden PM emanating from smelter emissions and wind-blown dust from both operating and abandoned tailings and mining-waste dumps.

The ambient air SO₂ and PM concentrations reported in this review were in most cases above the international and Zambian permissible guideline limits. The effects of SO₂ on humans are well documented. According to Bernstein et al. (2004), SO₂ in high concentration with or without exercise is a respiratory irritant, provoking airflow limitation. In some studies SO₂, sulfates and acid aerosols have been associated with increased emergency visits and hospitalizations for asthma (Kampa and Castanas, 2008). Besides SO₂, PM is another environmental issue of great concern to both the miners and the residents living near the mine sites. It has been established that elevated concentrations of PM induces protective but injurious cellular response (Li et al., 2003). Bernstein et al. (2004) further stated that PM on humans can cause oxidative stress. The other health impacts on PM include procoagulant activity by ultrafine particles after access to the systemic circulation and the suppression of the normal defense mechanisms e.g. suppression of the alveolar macrophage functions. Tao et al. (2003) also indicated that exposure to ambient air pollution particulates has been associated with increased cardiopulmonary morbidity and mortality, particular in individuals with pre-existing diseases.

Both in vivo and in vitro studies of the health effects of ambient PM have identified the generation of oxidative stress as one of the major mechanism by which air pollution particles exerts adverse biological effects (Li et al., 2008). Among particles of different sizes, it has also been established that ultrafine particles (UFP), which have an aerodynamic size of PM_{0.1}, are potentially the most dangerous due to their small size, large surface area, deep penetration and ability to be retained in lungs and content of redox – cycling organic chemicals.

Pope et al. (2004), carried out a review study on the relationship between air pollution and both morbidity and mortality involving short-term and long-term effects. They found out that short term exposure air pollutants are directly linked to increased morbidity. They also showed that an increase in PM₁₀ level by 10 µg/m³ was associated with 1.27%, 1.45% and 2.00% increase in hospital admissions for heart disease, chronic obstructive pulmonary disease, and pneumonia respectively.

In the mining towns of the Copperbelt Province, miners and residents have endlessly been exposed to elevated concentrations of SO₂ and PM. According to Burnett (2015), residents of mining towns, particularly Mufulira, complain of an array of diseases including pulmonary tuberculosis (PTB) and other respiratory complications associated with mine air pollution. Whilst these complaints were likely to be a reflection of what people have endured in these mining towns for a long time, the absence of research based evidence makes it difficult for government to take any remedial action.

When SO₂ is released into the atmosphere, it can react photochemically or catalytically with other pollutants to form sulphur trioxide (SO₃), sulphuric acid (H₂SO₄) and various sulphuric acid salts which represent the main constituents of acid precipitation, also known as acid rain. Therefore, the potential or propensity for acid rain occurrence in Mufulira town of the Copperbelt Province is quite high and cannot be ruled out, despite the absence of direct research based scientific evidence.

Acid rain speeds up the natural chemical weathering and corrosion of exposed material in a variety of ways like ferrous metals are attacked by SO₂ and rust more quickly (Singh and Agrawal, 2006). According to Anon (1984), steel buildings, rail tracks and other structures built of iron can be adversely affected by air pollution with extensive economic losses. Singh and Agrawal (2006) further observed that corrosion rate was about two to ten times higher in polluted urban and industrial air in India especially in the presence of high concentration of SO₂ than the countryside.

Despite the visible effects of mine air pollution on infrastructure in the Copperbelt Province, there has not been any research to quantify the

economic loss. Elsewhere, studies have shown the extent of economic damage caused by air pollution to infrastructure. For instance, according to Zhang et al. (2017), the material loss caused by acid deposition in China was about 5 billion US dollars in 2013. Rao et al. (2014) reported that India was losing about 45 billion US dollars annually due to corrosion of infrastructure. Whilst the pressure from international NGOs and Banks have helped in forcing copper mining companies to reduce air pollution, mainly for human health and environmental perspectives, the weight of evidence on the economic argument needs to be part of the dialogue.

Exposure to wind-blown dust from the abandoned Pb-Zn mine dump site in Kabwe has been shown to affect lead poisoning in children, with blood lead levels (BLL) exceeding the reference value of 5 µg/dL. Environmental lead exposure is a known risk factor for neurodevelopmental impairment such as decreased intelligence quotient (IQ), abdominal pain, encephalopathy, blindness, deafness convulsions, coma and death in children (Yabe et al., 2018). Overall, in human beings, higher concentrations of lead in blood have been associated with hypertension, electrocardiographic abnormalities, peripheral arterial disease, left-ventricular hypertrophy, and cardiovascular disease mortality. In fact recent findings by Lanphear et al. (2018) have shown that concentrations of lead in blood lower than 5 µg/dL (<0.24 µmol/L) were also associated with all-cause mortality, cardiovascular disease mortality, and ischaemic heart disease mortality in the USA. The Pb-Zn Kabwe Mine has been in existence for over 100 years and yet the prevalence of all these lead-induced diseases has not been studied, let alone initiation of interventions for lead exposure prevention.

Wind-blown dust from the abandoned Kabwe Pb-Zn Mine dump site has also been shown to contaminate soils in the area. This soil contamination has resulted in lead-poisoning of wild rats (Table 2). On the other hand, in the Copperbelt region of Zambia, wet and dry deposition of smelter emissions have caused heavy metal contamination of both crops (Table 1) and soils (Table 4). In Mufulira town on the Copperbelt, the metal-contaminated soils were found to be toxic to worms. The fact that contaminated soils were toxic to rats and worms indicated that the heavy metals (Pb, Zn, Cu, Cd, As, Co and Fe) were bioavailable and bio-accessible to fauna and flora in the affected areas. Therefore human exposure to heavy metals can occur through dietary uptake of metal-contaminated foods. Excessive uptake of dietary heavy metals may induce toxic (acute, chronic or sub-chronic), neurotoxic, carcinogenic, mutagenic or teratogenic effects in humans (European Union, 2002). Intake of food contaminated with heavy metals can deplete some essential nutrients in the body and cause a weakening of immunological defenses, intrauterine growth retardation, disabilities associated with malnutrition and a high prevalence of upper gastrointestinal cancer (Amin et al., 2013). Additionally, Cd and Pb have been associated with a number of cardiovascular, kidney, nervous system, blood and bone diseases and have even been considered potential carcinogens (Liu et al., 2017). Recently, studies have found that long-term exposure to air pollution was associated with increased risk of diabetes (Yang et al., 2018) and that exposure to air pollution induced changes to fetal and neonatal DNA repair capacity, suggesting that these mutations could have a role in carcinogenic insults later in life (Neven et al., 2018). It is clear that exposure to pollutants, due to soil and atmospheric contamination from mining activities in Zambia, poses a serious threat to the quality and safety of life in the affected regions. The situation is further compounded by the fact that the pieces of research on the effects of mine air pollution in Zambia are inadequate and not comprehensive enough for providing the scientific basis upon which policy and technical interventions could be formulated for protection of human and ecosystem health.

It is known that heavy metal pollution not only reduces the yield and quality of crops but also threatens ecosystem functioning (Liu et al., 2017). Heavy metal pollution of soils has been shown to suppress the growth and root development of some herbaceous and woody plant species in other regions of the world which have been equally

contaminated by mining and ore processing wastes (Shi et al., 2011). It is thus not far-fetched to suggest that air pollution, in the form of wind-dispersed slag dusts and smelter flue dusts, is responsible for the visually observed sparse vegetation and failure of soils to support crop production in the affected townships of Mufulira.

Some of the studies in China (Weijie et al., 2017) have estimated crop yield losses, due to air pollution, for wheat, rice, maize, and soybean amounting to 9.9, 2.5, 0.3 and 2.2%, respectively, of total yields for each of these crops. In fact residents of Kankoyo Township and surrounding areas in Mufulira have for years been publicly complaining about the failure of soils there to support the growth of vegetables and other crops. They have actually demanded to be relocated to other areas that still have productive soils.

Despite, the visual evidence of the adverse effects of air pollution on vegetation in the affected areas of Zambia, there is paucity of data not only on the extent of damage, but also on the loss of agricultural production. On the other hand, no study has yet examined the changes in physiological and biochemical changes to the vegetation that does not show any physical manifestation of damage within the proximity of the mine areas. Mine-related air pollution, therefore, if left unchecked, constitutes a serious threat to agricultural prosperity and biodiversity sustainability in Zambia.

Air pollution from the copper mines has produced visible impacts on human lives and the physical environment on the Copperbelt. In terms of regulatory framework, air pollution in Zambia is regulated by ZEMA through a Statutory Instrument No.141, called the Air Pollution Control (Licensing and Emission) Regulations. This piece of legislation calls for self-regulation among polluters by submitting their bi-annual returns (reports) to ZEMA for assessment and ensure that they emit below the statutory limits. However, as indicated by Lindahl (2014), this system has some inherent weaknesses as ZEMA lacks the human and technical capacity to verify the reports received and consequently mining companies continue to emit SO₂ and PM in excess of both national and international limits.

This review has shown that mine air pollution has been a thorny issue since the beginning of commercial copper mining in Zambia, in the 1900s. The advent of the Smoke Damage Act of the 1935, which provided indemnity against any liability resulting from Smelter emissions, explains the current state of environmental devastation. Thus the legacy of mine air pollution in Zambia has its genesis in the Smoke Damage Act which continued to provide indemnity to the mining companies until 1996 when this Act was repealed. However, according to the OAG (2014), even after the privatization of the mines, the spirit of this Act still protected the mines from any liability through development agreements. The extent to which the Smoke Damage Act has contributed to the stifling of research on various issues relating to the impact of SO₂ and PM on human and environmental health and the concomitant economic losses is unknown.

Research elsewhere (Kampa and Castanas, 2008) has indicated that mine air pollution (SO₂ and PM) can have serious human health adverse effects. With emissions of these pollutants in excess of national and international limits, it is not known, as to what extent the mine air pollution has contributed to the disease burden of the local residents. PM, particularly, ultrafine, which is predominantly emitted from smelters (Tao et al., 2003) can induce significant adverse effects to exposed organisms (Oberdorster, 2001). As observed by Li et al. (2003) PM composition is critical in assessing the impact it may have on exposed individuals. However, in the Zambian mine air pollution, there are no studies conducted to characterize the physical and chemical composition of the PM emissions, to which residents within the proximity of mine areas are exposed.

Traditionally, Zambian miners were required by law to undergo annual pneumoconiosis screening as a way of monitoring the impact of the occupational exposure to silica in dust. Interestingly, however, as Hayumbu et al. (2008) pointed out, for a long time (over 50 years), Zambian mine dust control regulations have only utilized total dust occupational exposure limits, which do not take into account the

quantitative silica content in dust to which miners are exposed. Furthermore, even in cases where the total dust to which miners were exposed exceeded the statutory Zambian limit of 1.75 mg/m³, little or no practical measures were taken, except providing the affected miners with “dust masks” whose pore size could have no bearing to the dust characteristics, as no studies have ever been conducted to ascertain the physico-chemical characteristics of the mine PM (dust).

In the last decade, efforts have been made by the mining companies, albeit partly due to pressure from international NGOs and Banks (CTPD, 2012) and partly due to the strengthening of implementation of regulation by ZEMA, to minimize the emission of SO₂ and PM from the copper smelters and converters.

For instance in 2009 the Nkana Copper Smelter which has been a source of SO₂ pollution for over six decades was closed and this has improved the quality of air in Kitwe, despite the damage caused to property and vegetation still remain unmitigated. Interviews with residents of this area bear testimony to the fact that respiratory related complaints have drastically reduced. Unfortunately, records from two hospitals, Wusakile and Sino-Zam, within the proximity of the Nkana Smelter, which would have availed documentary evidence to the nature of frequent cases related to air pollution, are not accessible.

Similarly, the Mufulira Copper Smelter which is well known for polluting the environment especially the Kankoyo Township where some areas have been declared a wasteland, has undergone some modernization and the SO₂ emissions have been reduced. The smelter upgrade project that started in 2005 was completed in 2016. In Chingola, The Nchanga Smelter in Chingola is a modern facility with little known episodes of SO₂ pollution. According to the design parameters, it was expected to capture about 95% of the SO₂ and feed to the modern and fully fledged sulphuric acid plant.

Finally, both the Kansanshi Mine and The Chambishi Copper Smelters in Solwezi and Chambishi, respectively, are equally new and as such low levels of SO₂ emissions are expected. Despite the installation of new and modern smelters, it is only the stringent monitoring of SO₂ emissions at these facilities that will help avoid the age long legacy that has been endemic in the Zambian mines.

2.5. Identified research areas/gaps

Based on the reviewed literature and the current state of mine air pollution in Zambia, the following are some of the possible research areas:

- Critical studies on comprehensive characterization of PM from the mine environments are required, as these will help in understanding the possible long and short term adverse health and ecological effects PM has on the communities in the mining areas. In Mufulira and other affected regions, there is need for studies on the effects of mining-derived acid rain, dust deposition on leaves and soil heavy metal contamination on plant/crop growth and related abiotic and biotic processes in the soil. These ecological impact assessments must include the identification of resistant species that may have the potential for bioremediation of metal-contaminated soils or sites.
- Though silicosis is an occupational health issue in the Zambian miners, there is need for research to understand its influence on pulmonary TB and establish the link between silicosis, TB cases and the prevalence of HIV/AIDS among Zambian miners. Surveillance/monitoring and epidemiological studies covering retired and in-service miners are required for determining the actual prevalence rates of mining-related illnesses and diseases in Zambia and the appropriate interventions for control, prevention and compensation.
- The current occupational exposure limits (OEL) in Zambia do not take into account the silica content in the ore dust. This situation suggest that many miners maybe exposed to levels of total respirable dust and respirable crystalline silica that are higher than Occupational Safety and Health Administration (OSHA) Personal Exposure Limit (PEL) for

respirable dust containing crystalline silica. There is need for research to establish the relationship between silica exposure and silicosis occurrence in miners. In this regard, it is imperative that national institutions, mandated to regulate, monitor and screen miners for silica exposure and silicosis prevalence, acquire contemporary state of the art equipment and attain international certification for both personnel and laboratories. This responsibility should be shared with mining firms in Zambia. Data from these monitoring and screening activities should be analysed to set appropriate occupational personal exposure limits and supporting policies and legal instruments.

- Health risk assessments and epidemiological studies in mining towns are required to determine the mining-related environmental air pollution exposure levels, sources, routes and risk factors, so that interventions could be developed to protect human and ecosystem health in the affected communities. In the mining-based air-borne hazard hotspots of Kabwe and Mufulira towns, it is necessary to conduct prospective and retrospective longitudinal cohort studies to establish the short- and long-term health impacts and the socio-economic implications of environmental exposure to mining-related air pollution.
- Mining companies and the mandated regulatory institutions must institute intervention research to determine the efficiency and efficacy of air-borne hazard control technologies and other measures employed in protecting the health of miners.
- Research on the effects of current and past air pollution on agricultural productivity and costs in affected areas of the mining towns requires attention.
- Baseline scientific investigation using Remote Sensing and GIS Tools to confirm the absence of environmental degradation (land cover and land use changes) and human health issues prior to mining activities in Zambia.

3. Conclusion

Despite the paucity of data on the extent of the impacts of mine air pollution in Zambia, its effects are visible particularly on vegetation and infrastructure. In some towns of the Copperbelt, for instance, Mufulira, the impact there is so severe that an area like Kankoyo Township has been declared a “wasteland”. In terms of human health, insufficient studies have been conducted to corroborate the numerous complaints from residents in the mining towns about respiratory complications associated with air pollution. In order to have a comprehensive understanding of the extent of adverse impacts of mine air pollution on human health and the economic costs, future research involving interdisciplinary research groups is recommended.

Whilst much investment has been made by mining companies towards reducing SO₂ emissions, vigilance on the part of ZEMA is critical. The reviewed literature has shown that the current state of environmental degradation arising from mine air pollution has its genesis from the Smoke Damage Act of 1935. Furthermore, it has also been observed that the academic and research institutions in Zambia have not provided leadership in the area of research and potential areas of research have been highlighted. Nevertheless, based on this review it can be concluded that there is a strong link between human health, animal health, and environmental degradation and mine air pollution in Zambia.

Declarations

Author contribution statement

Phenny Mwaanga: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mathews Silondwa: Analyzed and interpreted the data; Wrote the paper.

George Kasali: Analyzed and interpreted the data; Contributed

reagents, materials, analysis tools or data.

Paul M. Banda: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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