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Trace Metal Deposition on Soil and Accumulation in Plants around a Coal Power Station in Pretoria, South Africa

ABSTRACT

Combustion of coal in power stations is one of the main sources of environmental pollution due to the generation of trace metals. This study investigated levels of trace metals from five different plants and soils around a coal-fired power station in Tshwane, South Africa. Plants and soil samples were collected from different points (10, 500 and 750 m) along different directions (North West, North East, South West and South East) and analyzed for metals contents using Inductive Couple Plasma–Optical Emission Spectrophotometer (ICP-OES). A significant increase in the concentration of trace metals was detected from the stack pointing to the effect of the long stack in depositing more trace metals at a distance of 750 m away from the power station. Digitaria diagonalis and Tagetes minuta have significantly higher concentrations of trace metals than other plants collected around the area ($p < 0.05$). The soil pH was in the range 5.13 ± 0.11 to 6.01 ± 0.12. The concentrations for all elements in soil were recorded in the following descending order: Fe > Al > Mg > Cr > Zn > Cu > Pb >Ni > Co.

Key words: *Trace metals, Coal-fired plant*

Mandla W. Xaba[1*]
Joshua O. Olowoyo[1]
Gregory Scott[2]

[1] Sefako Makgatho Health Science University, Department of Biology, P.O Box 139, Pretoria, South Africa
[2] Department of Environmental Affairs, Private Bag X447, Pretoria, 0001, South Africa

*Corresponding author: xabamandla@gmail.com

INTRODUCTION

According to the statistical review of world energy submitted by British Petroleum, South Africa produces more than 255 MT of coal, about three quarters is used up locally (*BP Review 2012*). The coal usage for electricity generations in Africa is anticipated to increase from the year 2004-2030 at a yearly rate of 2.3%, whereas the average coal usage in the first-world countries is projected to increase at a rate of 1.4% yearly (*Scott 2011*).

Most of the energy requirements in South Africa are directly derived from coal and a greater percentage of the African countries rely on South Africa for the supply of coal (*Meij and Winkel 2006*). The use of coal in South Africa is an old practice; charcoal was used to melt iron and copper for commercial purposes (*Scott 2011*). The mining weekly magazine recently reported that “new coal mines are urgently needed in South Africa and provision of infrastructures must begin just to keep the lights on” (*Mining Weekly Magazine 2014*).

Over the years, trace metal availability in the environment have been associated to the burning of coal from coal power stations (*Pushan et al. 2008*). The release of trace metals as pollutants from coal power stations depends on the original concentration of each element in the coal, on the precise chemistry of the coal ash, the elements of the removed ash, combustion conditions and the removal efficiency of air pollution control devices. Toxic trace metal, which occurs naturally in the environment, becomes part of the coal structure through the coalification process (*Moumakwa and Marcus 2004*). Trace metals can be carried over long distances by wind and ultimately have a negative impact on the soil, water and plants (*Baba and Kaya 2004*).

Soil is the ultimate and most important sink of trace elements in the terrestrial environment. Previous studies have shown that plants growing in the nearby zone of industrial area, waste dump sites or those at close proximity to vehicular emissions usually display an increased concentration of trace metals, thus serving in many cases as biomonitors of these pollutants (*Olowoyo et al. 2012*).

Trace metals act as micro-nutrients to certain plants but become toxic at enhanced levels in the soil (*Mukherjee and Nag 1997*). Plants may take up large quantities of trace metals and translocate them into vegetative and generative organs at various rates depending on the level of these trace metals in the nearby environment (*Kovács et al. 1993*). Furthermore, the uptake of trace elements by plant varies and depends largely on several factors, such as soil pH and organic matter content (*Logan et al. 1997*). Through the uptake of trace metals into plants, the food chain may also be negatively impacted as many of these elements can accumulate in organisms. Trace metal incorporation in some parts of cultured plants used for human consumption is of particular concern. Metal transfer through natural food chain, extending finally to humans can be a threat to human health. The released trace metal in soil in excessive amounts may pose a serious threat to human health when taken up in the food chain (*Li et al. 2001*).

Over the years, most attention on the effect of coal power station had been largely concentrated on the release of uranium to the environment. The level of Polycyclic Aromatic Hydrocarbons (PAHs) has been reported around some of the coal power stations in South Africa (*Okedeyi et al. 2013*). Stack emissions from various industries may contain trace metals that can be carried over long distances and negatively impact ecosystems. Little to no work was carried out to investigate the nature and concentration of trace metals around most of the coal power stations in South Africa. Little attention has so farbeen given to the effect of distance and wind direction on the dispersion of trace metals originating from coal burning processes. This study therefore investigated the composition and trace metal composition and concentration in soils and plants collected around a coal power station in Tshwane, South Africa.

METHODOLOGY

Study site

The study was carried out in and around Rooiwal coal-fired power station, situated in Gauteng Province, North of Tshwane, South Africa (latitude 25° 33’ 0S and longitude 28° 10’ 60E) (**Figures 1** to **3**). The primary fuel is bituminous coal of grade E and F, with an installed capacity of 300 MW. The power station has smoke stacks equipped with efficient pollution control devices. The altitude of the area is 1,251 m with an average rainfall of about 674 mm. The average annual temperature ranges from -6°C to 28°C.

Sampling and laboratory analysis of soil samples

Soil samples were collected at between 0-20 cm depth from twelve sites along four directions namely; South-West, South-East, North-East and North-West using soil auger. From each direction, the soil samples

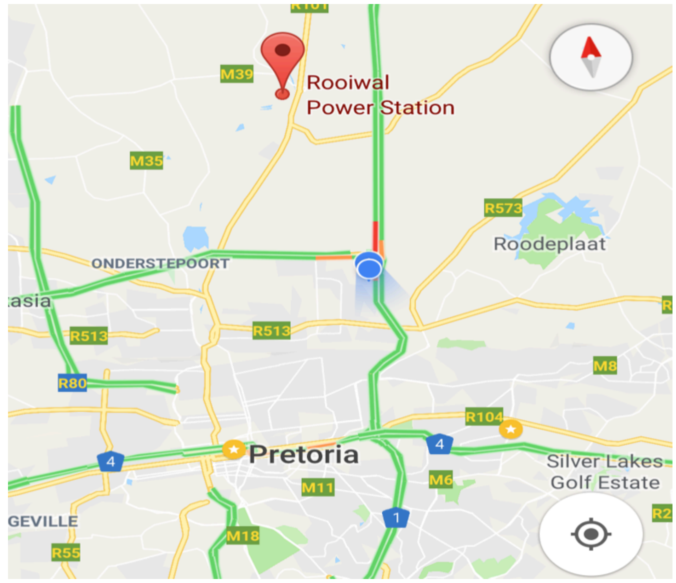

Figure 1. Map illustration of Pretoria, Rooiwal coal power station location. (source: “Rooiwal, Pretoria,” Map. Google Maps. Google, 24 December 2018. Web. 24 December 2018.)

Figure 2. Study site around the coal power station.

Figure 3. Illustration of the coal power station.

were collected at distances of 10 m, 500 m and 750 m with starting point from the stack of the coal-fired power station. All the soil samples were collected with the aid of a soil auger of 7.0 cm in diameter. The soil samples were allowed to dry by spreading it on laboratory table grounded in a closed environment and sieved using a mesh of < 60 µm.

The soil pH was determined in 0.01M $CaCl_2$ (1:2 soil-solution ratio) and in distilled water using a pH meter fitted with glass electrode (Jenwal Model 3015 digital). For trace metals analysis, 0.5 g of the ground soil samples was weighed and the total metal content of the soil was determined by digesting the sample with a mixture of HNO_3 (5 ml) (65% Supra pure Merck), HCl (5 ml) (65% Supra pure Merck), H_2O_2 (2 ml) (65% Supra pure Merck) and $HClO_4$ (2 ml) (65% Supra pure Merck) and the resulting solutions were analysed for trace metal content with the use of an ICP-OES Inductive Couple Plasma-Optical Emission Spectrophotometer. Certified reference material and triplicate analysis were used to ascertain the validity of the results obtained from the analysis.

Sampling and laboratory analysis of plant samples

Fresh plant materials were collected at the sites from which the soil samples were collected. Plant species were identified to species level wherever possible in the field and those that could not be identified were preserved for identification in the Department of Biology using reference materials. The collected plant samples intended for metal analysis were oven dried at 80°C for 48 hours. The plants were then separated into roots, stems and leaves. Samples were carefully pulverized and sieved using a mesh < 60 µm. Approximately 0.5g of the fine powdered leaves, stem and roots samples were weighed into the TFM microwave vessels. Plant total metal content was determined by digesting the sample with a mixture of HNO_3 (7 ml) (65% Supra pure Merck) and H_2O_2 (3 ml) (65% Supra pure Merck) acid digestion. The resulting solutions were analysed for trace metal content with the use of an ICP-OES (Inductive Couple Plasma-Optical Emission Spectrophotometer).

Statistical analysis

The statistical analysis was carried out using SPSS 21.0. Differences in the concentrations of trace metals between the soil sampling sites were determined using the analysis of variance (ANOVA). Duncan multiple range test was used to ascertain the significant differences from the mean values.

The plants identified around the coal power station included, *Digitaria diagonalis*, *Amaranthus hybridus*, *Panicum repens*, *Tagetes minuta* and *Urochloa mosambiscensis*. Of all the plants collected, *Tagetes minuta* was the most abundant plant around the study area, followed by *Urochloa mosambiscensis*. The pH of the soils in the study site varied from 5.13, to 6.70 while the soil organic matter varied from 1.10 to 1.98 %. The concentration of Al from all plants ranged from 0.10 ± 0.01 µg g^{-1} - 7.15 ± 0.32 µg g^{-1} (**Table 1**). The highest mean concentration for this element was recorded from the roots of *T. minuta*. The differences in the concentrationof Al from the different plants and parts were significant ($p < 0.05$).

Table 1. Trace metal concentration (µg g^{-1}) in plants and grasses collected around the study site.

Plant species	Parts	Trace Metals						
		Fe	Al	Cr	Mg	Zn	Co	Pb
A. hybridus	Roots	16.70±0.01	0.34±0.11	0.67±0.02	37.83±1.23	0.03±0.00	ND	0.01±0.00
	Stem	1.10±0.01	BDL	0.27±0.04	32.75±0.54	0.44±0.02	0.34±0.01	0.03±0.01
	Leaves	5.22±0.12	BDL	0.52±0.11	29.95±0.98	0.38±0.21	0.34±0.08	0.03±0.01
U. mosambiscensis	Roots	16.66±0.11	0.10±0.01	0.55±0.02	45.46±1.65	0.34±0.08	0.30±0.03	0.02±0.00
	Stem	1.09±0.67	ND	0.27±0.03	32.12±2.34	0.43±0.04	0.35±0.08	0.08±0.02
	Leaves	7.47±0.23	0.16±0.03	0.52±0.02	45.28±3.67	0.20±0.01	0.25±0.05	BDL
T. minuta	Roots	25.63±1.45	7.15±0.32	27.02±0.08	27.0±2.12	0.58±0.21	6.61±0.04	9.10±1.01
	Stem	4.06±0.89	0.88±0.08	ND	41.12±1.32	4.27±0.64	8.71±0.89	11.34±1.05
	Leaves	17.29±0.64	0.12±0.03	0.58±0.05	46.36±2.34	0.33±0.32	0.29±0.11	0.03±0.01
P. repens	Roots	15.36±0.23	0.46±0.03	0.69±0.12	69.34±3.32	0.04±0.01	0.22±0.09	0.01±0.00
	Stem	10.74±1.11	0.32±0.01	0.91±0.08	48.46±3.21	0.29±0.03	0.31±0.07	0.13±0.05
	Leaves	11.16±1.34	0.35±0.01	0.94±0.06	50.72±2.32	0.30±0.02	0.31±0.04	0.16±0.09
D. diagonalis	Roots	14.58±0.78	0.41±0.08	0.69±0.03	66.8±3.11	0.02±0.01	0.23±0.03	0.02±0.01
	Stem	10.91±1.22	0.21±0.06	0.55±0.12	44.33±2.12	0.18±0.01	0.24±0.08	0.13±0.03
	Leaves	10.78±0.24	0.20±0.02	0.54±0.17	44.44±2.34	0.18±0.02	0.25±0.03	0.13±0.04

BDL: Below the detection limit. ND: Not detected

The Concentration of Cu from all the plant parts ranged from 0.11 ± 0.03 μg g-1 to 7.15 ± 0.01 μg g^{-1}. From most of the plants collected, Cu was only determined from the roots of *Digitaria diagonalis, Panicum repens* and *Tagetes minuta*. The stem of *Tagetes minuta* also presented a value of 0.88 ± 0.02 μg g^{-1} of Cu. Zinc (Zn) concentrations was significantly higher in the stem and roots of *Tagetes minuta* with a value of 4.27 ± 0.64 μg g^{-1} and 0.58 ± 0.21 μg g^{-1}. The values recorded for *P. repens* were significantly lower ($p < 0.05$).

The maximum concentration of Fe in the plants was measured from the roots of *T. minuta* with a value of 25.63 ± 1.45 μg g^{-1}; 17.29 ± 0.64 μg g^{-1} and 4.06 ± 0. l89 μg g^{-1} were measured from the leaves and stem, respectively (**Table 1**). The stem of *U. mosambiscensis* recorded the lowest value for Fe with a value of 1.08 μg g^{-1} (**Table 1**). Concentration of Cr from the plant parts ranged from 0.27 ± 0.03 μg g^{-1} to 27.02 ± 0.08 μg g^{-1}. The highest concentration for this element was recorded from the roots of *Tagetes minuta*.

The concentrations for Mg ranged from 27.02 ± 2.12 μg g^{-1} to 69.34 ± 3.32 μg g^{-1}, with the lowest and highest levels occurring from the roots of *Tagetes minuta* and *Panicum repens*, respectively (**Table 1**). The differences in the concentration of Mg from the different plant parts were significant ($p < 0.01$). Cobalt (Co) recorded low concentrations in most of the plants after Pb. However, the concentration of both Pb and Co were significantly higher ($p < 0.05$) in the stem and roots of *Tagetes minuta* as compared to all the other plants (**Table 1**).

The roots of all the plants in this study recorded the highest concentration of Fe. The sequence of trace metals concentration in roots in this study is *D. diagonalis* < *P. repens* < *U. mosambiscensis* < *A. hybridus* < *T. minuta*. Fe concentration in the stem is highest in the *D. diagonalis* and lowest in the *U. mosambiscensis*. The leaves of *T. minuta* recorded the highest concentration of Fe while *A. hybridus* recorded the lowest concentrations of Fe (**Figure 1**).

The concentration of Chromium (Cr) was highest in the root of *T. minuta* and lowest in *U. mosambiscensis*. Also, Cr concentration was highest in leaves of *P. repens*. The stem of *P. repens* recorded the highest concentration of Cr in this study (**Figure 2**). The concentration of Crwas highest in the leaves of *P. repens* as compared with other plants in the study. The stem of *T. minuta* recordedthe lowest Cr concentration from this study (**Figure 2**).

Panicum repens recorded the highest concentration of Mg in the root and stem among all the plants in this study closely followed by *D. diagonalis* in the roots (**Figure 3**). The lowest concentration of Mg in the leaves was recorded in *A. hybridus* in this study (**Figure 3**). The *U. mosambiscensis* recorded the lowest concentration of Mg in the stem in this study (**Figure 3**).

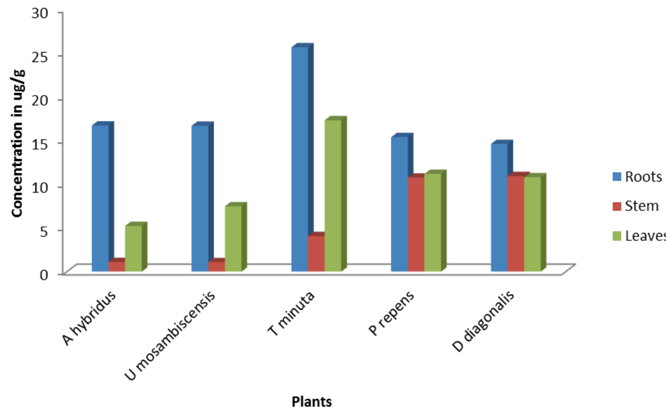

Figure 1. Concentration of Fe (μg g^{-1}) in roots, stem and leaves of all plants.

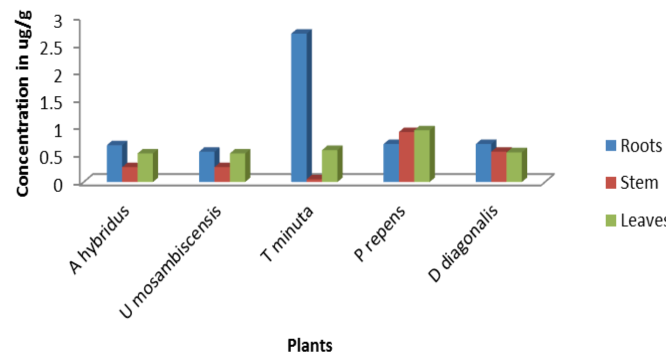

Figure 2. Concentration of Cr (μg g^{-1}) in roots, stem and leaves of all plants.

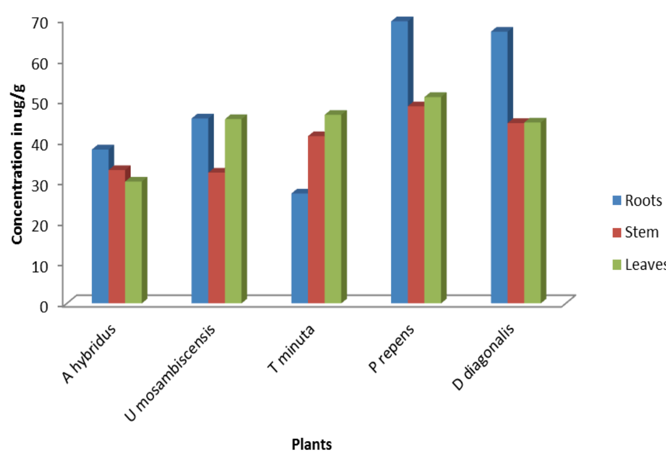

Figure 3. Concentration of Mg (μg g^{-1}) in roots, stem and leaves of all plants.

The highest Fe concentration in the soil was recorded at 1.65 ± 0.32 mg g^{-1} from the top soil collected at the South West direction at a distance of 750 m (**Table 2**). The difference in the concentration of Fe from the soil was significant for both the direction and the distance ($p < 0.05$).

The highest concentration of Al from soil samples was recorded as 19.51 ± 3.21 mg g^{-1} from the North Western direction at a distance of 750 m and the lowest value was at the South Eastern part of the power plant with values of 0.19 ± 0.03 mg g^{-1} at a distance of 10 m (**Table 2**). The difference in the concentration of Al from the soil was significant both from the different directions and sites as well ($p < 0.05$). From the soil samples, the concentrations of Mg ranged from 16.71 ± 2.11 mg g^{-1} - 44.68 ± 2.31 mg g^{-1}. The highest concentration for Mg from all the soil samples was obtained from the South Western direction at a distance of 750 m away from the coal power station (**Table 2**).

The difference in the concentration of Cr from the soil was significant ($p < 0.05$). The highest concentration of Cr from soil samples was recorded at a distance of 500 m in the South Eastern direction from the top soil (6.06 ± 0.12 mg g^{-1}). The lowest concentration for Cr from the soil sample was recorded at a distance of 10 m away from the plants at the North West direction of the coal powered station (**Table 2**).

DISCUSSION

The observed pH level (5.13 to 6.70) recorded from the study revealed that some of the trace metals might become easily accessible to plants. At a relatively low pH, the mobility of trace metals is significantly enhanced due to the acidic nature of the soil and the displacement of transferable cation from the exchange site (*Olivia and Espinosa 2007*). Most agronomic crops require soil-water pH values between 5.7 and 7 (*McKenzie 2003*). Some plants, such as blueberries and azaleas, require acidic soil conditions with soil-water pH below 5 (*Megan et al. 2008*).

The permissible limit for trace metals as recommended by World Health Organization (WHO) for Cd in plant is 0.03 mg l^{-1}, Cr - 0.05 mg l^{-1}, Zn - 3.00 mg l^{-1}, Hg - 0.5 mg l^{-1}, Mn - 0.50 mg l^{-1}, Ni - 0.02 mg l^{-1}, Fe - 63.55 mg l^{-1} and Cu - 1.89 mg l^{-1} (*WHO 2001*). The concentrations of trace metals from the plants may become a very serious issue especially those plants used for human consumption.

Concentrations of Zn and Cu exhibited a similar pattern with those found in Lead (Pb) from all the sites. A similar trend in the accumulations of Pb and Ni was observed in this study. Concentrations of Pb and Ni from *Tagetes minuta* were significantly higher than all other plants. *Tagetes minuta* accumulated more of the Pb and Ni than any other plants collected from the coal power area.

Specifically, trace metal concentrations for *A hybridus* exceeded the acceptable limit set by WHO (*Adewuyi et al. 2010*). It was observed that the elemental concentrations varied from site to site around the coal-fired power station. Distance affected the concentrations of trace metals around the study site both in the plant and the soil. It was observed that at a distance of 750 m in all the directions, a significantly higher ($p < 0.05$) concentration of trace metals were recorded from all the sites both in the plant and the soil.

It was evident from the study that the North Western direction had more concentrations of trace metals from all the sites where soil samples were collected (10 m, 500 m and 750 m). The differences recorded from all the

Table 2. Trace metal concentration (μg g^{-1}) in soil samples collected around the study site.

Site	Trace Metals (μg g^{-1})							
	Fe	Al	Cr	Mg	Zn	Co	Pb	Ni
NE 10m	1.10±0.76	9.18±1.32	4.01±1.32	28.74±0.32	1.94±0.21	3.54±0.11	1.99±0.02	0.93±0.03
NW 10m	1.05±0.65	15.74±2.32	0.15±0.12	BDL	BDL	BDL	BDL	BDL
NW 500m	1.56±0.34	7.82±1.36	6.06±0.21	38.43±2.33	3.30±1.11	3.16±0.21	3.63±0.34	1.50±0.05
NW 750m	1.64±0.32	19.51±3.21	4.92±0.11	40.98±1.22	2.39±0.86	2.61±0.12	3.02±0.43	1.15±0.02
SE 10m	0.45±0.12	0.19±0.03	2.38±0.21	40.31±0.21	0.35±0.03	1.25±0.02	0.29±0.01	0.62±0.01
SE 500m	1.56±0.45	7.82±0.65	6.06±0.12	38.43± 2.32	3.30±0.20	3.16±0.11	3.63±0.11	1.49±0.11
SE 750m	1.44±0.23	18.21±0.21	2.75±1.03	16.71±2.11	0.53±0.11	0.86±0.07	1.84±0.05	0.25±0.03
SW 10m	0.02±0.01	0.64±0.11	0.68±0.22	37.50±3.42	BDL	BDL	BDL	BDL
SW 500m	0.39±0.03	13.41±0.12	2.30±0.56	40.32±3.23	0.85±0.21	2.25±1.01	0.69±0.07	1.46±0.05
SW 750m	1.65±0.32	15.77±0.34	4.14±1.21	44.68±2.31	1.00±0.04	1.08±0.23	2.24±0.11	1.51±0.23

BDL: Below the detection limit. * Values are recorded in mgg^{-1} due to high values sites were significant ($p < 0.05$). *Gur and Yaprak* (*2011*) reported a similar observation with the use of lichens. It was reported from the study that the most polluted areas were found to be those in the vicinity of the coal-fired power plant, particularly along the direction of predominant wind and in the corridor which runs from west to southeast direction due to topographic conditions.

According to *Bari et al.* (*1998*) climatic factors most probably play an important role in the bioaccumulation of heavy metals. Prevailing wind and its direction is a critical factor for the determinant of pollutants level around an industry (*Conti 2008*). Observation from this study where trace metals were found to be significant in the leaves of the plants, suggested other sources such as atmospheric deposition of these trace metals from the coal power station. *Digitaria diagonalis* and *Tagetes minuta* bioaccumulated more heavy metals, which may be from atmospheric sources and from the soil, because the concentration is higher in the root region than any other part of the plant. *Krause and Kaiser* (*1977*) reported that the accumulation of heavy metals in plants may follow two different absorption pathways which may be through the roots or by deposition on leaf surfaces.

In a separate study, *Armando et al.* (*2009*) demonstrated that the ability of plants to bioaccumulate trace metals may differ. The study established the ability of *E. mollis* to accumulate metal more than all other plants and this was ascribed to the effect of atmospheric deposition. It was evident from this study that the bioaccumulative properties of plants could vary depending on the plant species and sizes. Plant abilities and capacities to bioaccumulate dust particles and by extension trace metals through the leaf stomata depends on factors such as the size, nature, and shapes of the leaves, and the size and abundance of stomata in the leaves may also affect the levels of trace metals in plants (*Tomasevic et al. 2005*).

High concentrations of some elements such as Fe, Cr and Mg in the soil might be due to the long term burning of coal for electricity generation since there are no industries found around the coal-fired power station. This is in agreement with the report of *Jasim et al.* (*2010*), where trace metals such as Fe, Mg and Cr was remarkably higher than other trace metals in their study. Similarly, the result of the findings of this study agrees with the report by *Bajpai et al.* (*2010*), where Fe, Cr and Mg were reportedly higher in their study around a mining site. Fe was also discovered to have the highest concentration with a maximum of 1498.4 ± 2.0 ug g^{-1} which suggested other possible sources.

CONCLUSION

The levels of trace metals and their distribution from the study sites in both plants and soil around the vicinity of the coal-fired power station varied from site to site. The distribution pattern of some metals and relationship with distance from the coal power plant showed that the pollution of trace metals might be from a local source. *Digitaria diagonalis* and *Tagetes minuta* bioaccumulated more of these trace metals, respectively, than other plants collected around the power station. Distance and direction relative to the col power station also affected the level and concentrations of trace metals. From the study, it can be suggested that the Rooiwal coal-fired power station might have affected the concentrations of trace metals in the soil and plants around the Rooiwal area.

Future studies should also attempt to check on the effect of the seasons and other bioaccumulators in order to establish the source of these traces metals around the power station.

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