Chromium bio-concentration in soil-plant system: Health risks in Usangu agro-ecosystem

Article *in* Case Studies in Chemical and Environmental Engineering · June 2023

DOI: 10.1016/j.cscee.2023.100398

Marco E. Mng'ong'o
Mbeya University of Science and Technology

Case Studies in Chemical and Environmental Engineering 8 (2023) 100398

Contents lists available at ScienceDirect

Case Studies in Chemical and Environmental Engineering

journal homepage: www.sciencedirect.com/journal/case-studies-in-chemical-and-environmental-engineering

Case Report

Bio-concentration and translocation of chromium in soil-plant system: Health risks in Usangu agro-ecosystem

Marco E. Mng'ong'o [*], Abubakar M. Mshora, Christopher Msigwa, Absalom Komanya, Samwel Shimo

Department of Crop Science and Horticulture, College of Agricultural Sciences and Technology (CoAST), Mbeya University of Science and Technology (MUST), P.O. Box 131, Mbeya, Tanzania

ARTICLE INFO

Keywords:
Chromium
Cr partition
Paddy farming
Bio-concentration factor
Translocation factor

ABSTRACT

Determination and analysis of total chromium (Cr) in soil and plant tissues help estimate the associated health risk; however, this might overestimate the risk because not all Cr from the soil is transported to above-ground plant tissues, mainly the edible part of most plants. Here we present the analysis of Cr partition in soils and paddy rice plant samples which currently missing in Usangu agro-ecosystem. The bio-concentration (BF) and translocation factors (TF) estimating the distribution and partitions of Cr in plant tissues (roots, straws, and grains), and associated environmentally and health risks were determined in Usangu agro-ecosystem. The Cr concentration in soils ranged from 4.58 to 42.76 mg/kg which was within maximum permissible limits (100 mg/kg), with the total Cr in plants samples ranging from 12.88 to 57.34 mg/kg. It was found that straws and roots had higher Cr concentrations than grains indicating a less health risk in edible parts. The BF > 1 was observed in 83.3% of the studied sites indicating higher Cr uptakes by plants. Furthermore, TF < 1 was observed in 67.33% of the studied sites indicating more Cr accumulated in below-ground biomass (roots) than above-ground biomass (straws and grains) (33.33%), thus less risk to edible plant parts. This study indicates that high Cr in agricultural soils may accelerate Cr accumulation in plant tissues or above-ground plant biomass leading to health risks.

1. Introduction

Chromium (Cr) is a toxic metal that at high concentrations have substantial toxicity to plants, soil invertebrates, animals, and human [1, 2]. After the industrial revolution and agricultural modernization, Cr concentration in the environment including the agro-ecosystem has increased dramatically [3], a scenario which increased accumulation of Cr in agricultural soils, water, and plant tissues growing in contaminated areas [4,5]. Furthermore, Cr enters agro-ecosystem as impurities from fertilizer, herbicides, and pesticides but also as aerosols and dust emissions from industries and motor vehicles operating in or near farming areas (Fig. 1). On the other hand, the use of surface water runoffs from urbanized areas as irrigation water in farming areas has accelerated Cr accumulation in agro-ecosystem which consequently increased Cr in plant tissues, thus leading to human health risks [6–9]. Biologically, accumulation of Cr in the plant above acceptable limit causes serious disruption of major biological processes and reactions required for crop growth and yields, thus higher Cr concentration in agricultural soils affect the plant growth and its productivity but also in extreme condition may result in loss of plant biodiversity due to extension of susceptible plant species [4,10]. For plants that can tolerate the increased Cr concentration in plant tissues can potentially be a source and a bridge to transfer excess Cr from plant tissues to food chain and ultimately polluting the entire food system which later causes health risks to animals and humans since Cr is known to be carcinogenic and excess Cr concentration likely to increase cancer cases in the community [6–9,11]. Therefore, increased Cr concentration in the environment will accelerate its levels in plant tissues affecting plant functioning and further threatening food system [4,12]. In developing countries' agro-ecosystems, characterization of Cr accumulation and its partitioning in plant tissues and their implications to human health is limited, the available information is mostly obtained from studies conducted in the distribution and accumulation of Cr in mining areas where more attention is given to concentration in soils and water [13–17] and less attention given to Cr in plant tissues, whenever available just total concentration of the entire plant tissues is determined including edible

---

[*] Corresponding author.
E-mail address: marco.mngongo@must.ac.tz (M.E. Mng'ong'o).

https://doi.org/10.1016/j.cscee.2023.100398
Received 11 May 2023; Received in revised form 9 June 2023; Accepted 10 June 2023

and non-edible plant tissues. However, the obtained information adds to the understanding of Cr concentration and distribution in the food system, their message is very skeptical and of limited use, as does not provide the actual risk which can be induced by that concentrations to the agro-ecosystem actors [18–21]. Therefore, determining Cr accumulation in agricultural soils, their partitions in plant tissues, translocation (TF), and bioconcentration factor (BF), will help to understand the dynamics of Cr concentration in agro-ecosystem, plant tissues and the implication to human health risks, thus providing more evidence and room for monitoring and management of Cr in agro-ecosystem to ensure food quality and safety [22]. The Cr accumulation in agricultural soils, their partitions in plant tissues, translocation (TF), and bioconcentration factor (BF) are rarely studied to estimate Cr-associated health risks to humans in East Africa and other parts of the world especially in developing countries, thus presenting a knowledge gap. Usangu agro-ecosystem (UA) in Southern Highlands Tanzania produces more than 30% of paddy rice (*Oryza sativa* L) consumed in Tanzania. The UA is characterized by the high use of agrochemicals such as fertilizers, pesticides, and herbicides required to achieve higher productivity per unit area. Which consequently can increase the level of toxic metals including Cr in agricultural soils, water (Fig. 1), and plants [23,24]. High Cr levels in the soil increase its concentration in plant tissues later to feed, fodder and food system leading to health risks [16]. Therefore, a better understanding of Cr accumulation, distribution, and partitioning in paddy rice plant tissues is essential in estimating the human health risk of Cr accumulation in agricultural soils and plant tissues, the information which currently missing in most Tanzanian agro-ecosystems. This study investigates chromium (Cr) accumulation, partitioning, translocation, and bioconcentration factors in paddy rice plants and soils of the Usangu agro-ecosystem in Tanzania. This study was conducted to characterize: (i) Cr accumulation in soils and plants, (ii) Cr partitions in plant tissues, (iii) their translocation and bioconcentration factors, (iv) and their implications in human health using Usangu agro-ecosystem and paddy rice plants as a case study. The study fills a knowledge gap in East Africa by examining the specific Cr concentrations in plant tissues and their implications for human health, providing valuable insights for monitoring and managing Cr contamination in agricultural systems to ensure food safety.

2. Materials and methods

2.1. Study area and sample collection description

This study was conducted in six irrigation schemes in Usangu agro-ecosystem located in Southern Highland Tanzania in Mbeya region and Mbarali district. Geographically, the study area was between latitudes 7°41′ and 9°25′ south and longitudes 33°40′ and 35°40′ east, covering the about 20,800 km^2 (Fig. 2). The area has annual average precipitation ranging from 700 mm to 1600 mm. The basin receives rain from December to March and it does not rain for seven months [23]. As a result, the basin is warmer with a temperature range of 19–29 °C with a mean value of 25 °C. The area is famous for irrigated paddy rice farming producing more the 30% of rice consumed in Southern Highland Tanzania. A total of 168 soil samples (0–30 cm) and 68 paddy rice plant samples were collected from six irrigation schemes in Usangu agro-ecosystem and processed based on the standard procedures as described in Mng'ong`o et al. (2021).

During soil and plant sampling a Y design strategy (Fig. 3) was used where a sampling point was selected and from the selected point three-meter diagonal was made to collect soil and plant samples and composited to one sample.

2.2. Chromium extraction and determination in soil and plant samples

The concentration of Cr in soil and plant samples was extracted by acid digestion mixture (*aqua regia* (AQ)) of concentrated hydrochloric acid (HCl) and Nitric acid (HNO_3) in a 3:1 ratio for 3 hours [25]. "About 0.2 g of soil and plant samples were added into a 25 ml beaker, followed by 1 ml of HNO_3 and allowed digest at room temperature (20 °C) for 1 h, after 1 hour, 3 ml of HCl and 1 HNO_3 were added and heated for 3 hours in a hot plate (90–180 °C) to ensure complete digestion" [26]. "The sample was cooled and filtered into 25 ml using 0.42 μm filter paper. The filtrates were diluted to 25 ml by diluting with 2% $HNO_{3,}$ ready for analysis. A blank was also prepared for each digestion with an equal volume of acid without the sample" [26]. The Cr extraction in each sample (soil and plants) was conducted in triplicates, and the final concentration was determined by ICP-OES and ICP-Ms based on

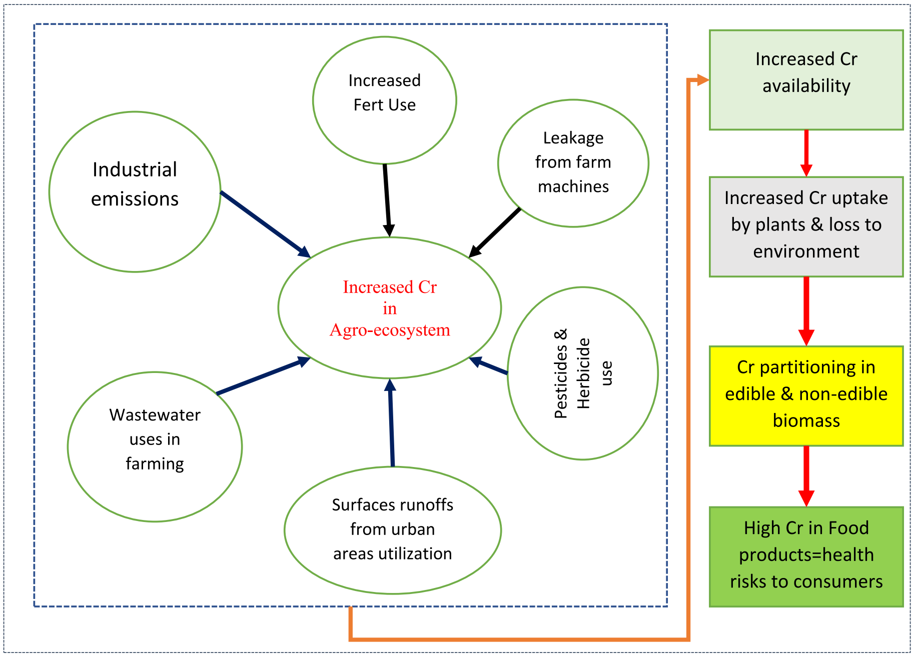

Fig. 1. The diagrammatic portrayal of Cr sources in an agro-ecosystem and how the increased Cr concentration in an agro-ecosystem can lead to elevated Cr levels in food products leading to health risks to consumers (Source: Authors).

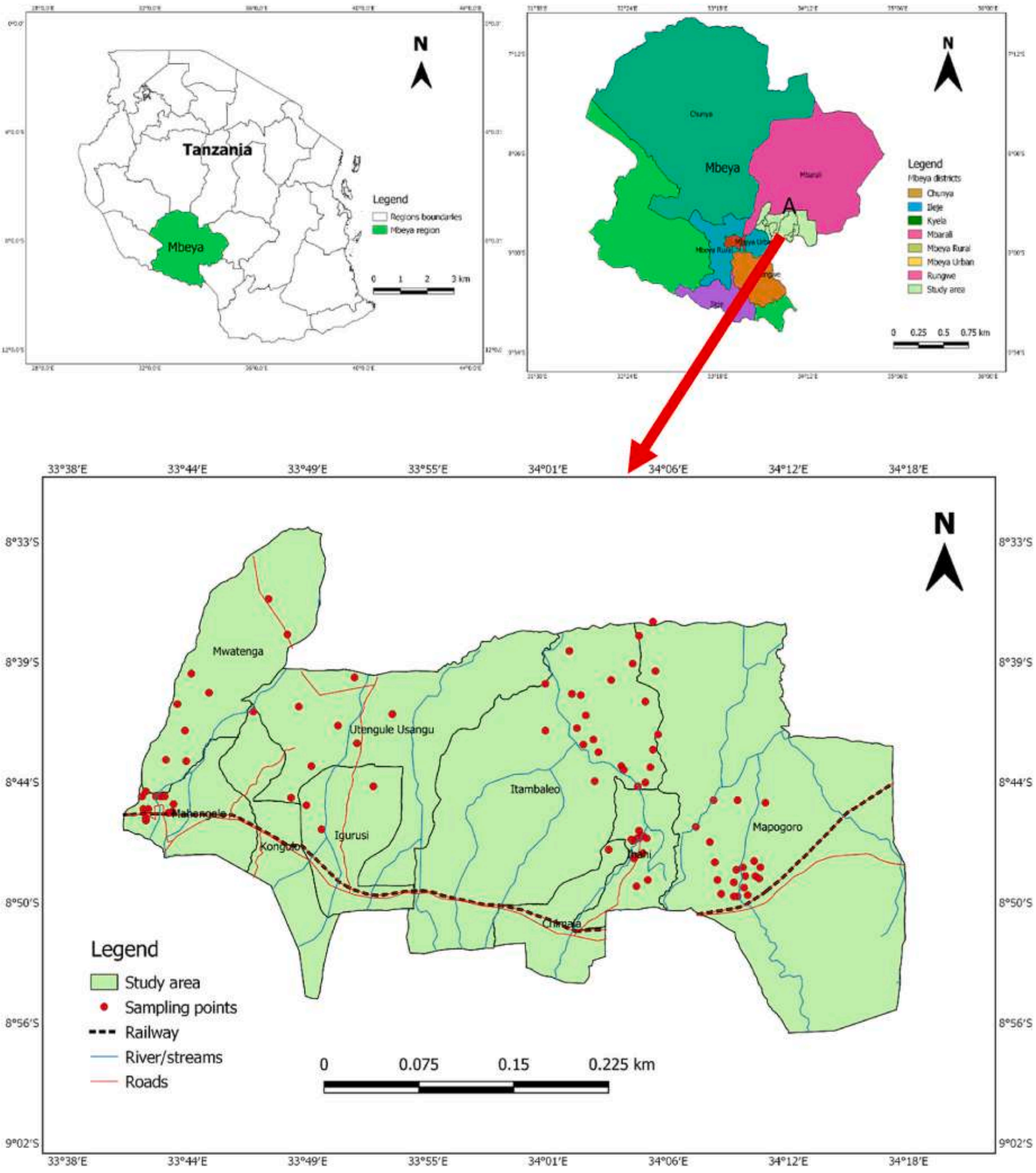

Fig. 2. Soil and paddy rice plant sampling points in Usangu agro-ecosystem-Mbeya, Tanzania [23].

manufacturers' instructions.

Bio-concentration factors (BF) and translocation factor (TF) were estimated based on the Cr concentration determined in soils and plants by equations (1) and (2), respectively.

$$\text{Bio}-\text{concentration factor (BF)} = \frac{[\text{Cr}-\text{Plants}]}{[\text{Cr}-\text{soil}]} \tag{1}$$

$$\text{Translocation factor (TF)} = \frac{[\text{Cr}-\text{Shoot}]}{[\text{Cr}-\text{roots}]} \tag{2}$$

Where [Cr-plants]; [Cr-soil] represent Cr concentration in soil and plant extracts, whilst the [Cr-roots], and [Cr-shoot] represents Cr concentration in roots and shoots respectively.

The BF > 1 indicates more Cr uptake by plants than those in soils, BF < 1 indicates more Cr is available in soils than those in plants, and BF $=$ 1 indicates equal Cr concentration in soils and plant samples. But also, TF > 1 indicates that there is more Cr translocation from root (below-ground biomass) to above-ground biomass (straws and grains), TF < 1 indicates that there is less Cr translocation from below-ground biomass (roots) to above-ground biomass, and TF $= 1$, indicates equal Cr accumulation in below- and above-ground biomass, proposing a non-preferred Cr transfer from soil to plants.

2.3. *Statistical analysis*

All collected Cr data in soil and plant samples were analyzed by Jamovi 1.2.25, while all plots were generated in Minitab 14. The analysis of variance and Tukey post hoc analysis was conducted to determine differences between sampling points, schemes, and plant parts ($P < 0.05$). The Cr concentrations determined in soil and plant samples were

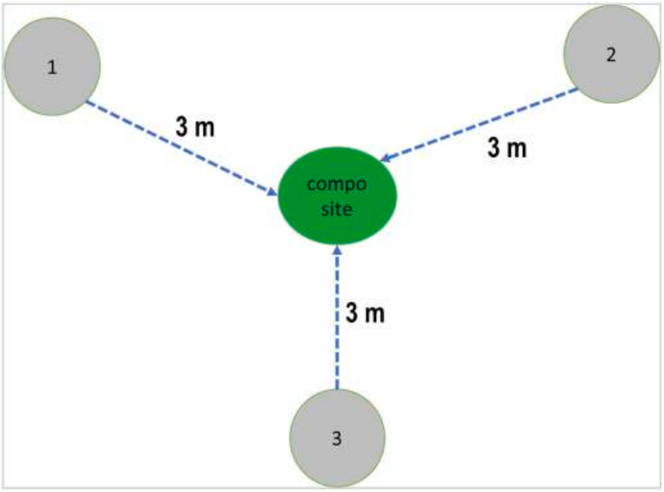

Fig. 3. The soil and plant sampling strategy used in the present study.

compared to the maximum permissible limits for contamination analysis. The maximum Cr permissible concentration for agricultural soils (100 mg/kg) and plants (1 mg/kg) were obtained from WHO and Tanzania Environmental Management regulation guidelines [27,28].

3. Results and discussion

3.1. The Cr spatial distribution in agricultural soils

It was observed that the Cr concentration in agricultural soils over the entire Usangu agro-ecosystem ranged from 2.5 to 15.39 mg/kg, where all determined values were within the maximum permissible limits (100 mg/kg) for Cr in agricultural soils and natural habitats [27]. This indicates Cr concentration in the Usangu agro-ecosystem are at a concentration that can not pose serious environmental and health risk to food products produced in the area, however, the determined concentration can conciliatory agro-ecosystem quality and food chain if allowed to continue at a current pace. The determined Cr concentration is sufficient to trigger minimal harmful effects on invertebrates, animals, and humans [29].

The Cr distribution among irrigation schemes was observed to be significantly different ($P < 0.001$), whereas lowland schemes (elevation not shown) such as Kapunga, Mubuyuni, and Mabadaga (Fig. 4) were observed to have high Cr concentrations. The scenario could be influenced by upstream surface runoffs and agricultural intensification. Highly intensive schemes such as Kapunga, Mubuyuni, and Mabadaga had higher Cr concentrations in agricultural soils (Fig. 4), which could be exacerbated by increased use of agrochemicals such as pesticides and fertilizer as the same scenario reported by Wang et al. [30]. Chimala, Ilaji, and Mabadaga irrigation were observed to have significantly higher Cr which might be caused by their location as they were close to residential areas and along the busy TAZAM highway (Fig. 4); the higher Cr in these schemes might be associated with urban runoff, sewage waste, and household waste (Shemdoe, 2010). Based on this study, the system investigated was uncontaminated with respect to Cr however, it is necessary to implement a management strategy to maintain low Cr levels in soils to ensure environmental quality and safety.

3.2. Cr accumulation and distribution in paddy rice parts

The Cr accumulation in plants and their parts can health risks to consumers. To estimate the risk of Cr that may be directed to humans, soil invertebrates, and animals in the food chain, the determination of total Cr concentration and its partitions in paddy rice plant parts is paramount because it determines the environmental and health risks associated with soil micro-organisms, animals, and humans [22,31]. Total Cr and its fractions in paddy rice plant parts (roots, straws, and grains) were determined were measured (Fig. 5 and Table 1). The total concentration of Cr determined in the whole plant sample was observed to range from 12.88 to 57.34 mg/kg (Fig. 5). The determined Cr was higher than that determined in soil samples indicating preferred accumulation in paddy rice plant samples (Fig. 3). Cr among plant samples varied suggestively between irrigation schemes ($P < 0.001$) where Kapunga, Ihahi, Igalako, and Mubuyuni were observed to have higher total Cr concentrations (20.90–37.03 mg/kg) in paddy rice plant samples (Fig. 5). The total Cr concentration was above 1 mg/kg, an FAO and WHO guidelines allowable Cr in food products [28,32], thus might be associated with health risks to soil inhabitants, animals, and humans [33]. However, Cr concentration in paddy rice grain, which is an edible part, is lower than that of other parts of the plant, thus more Cr is accumulated in non-edible parts, henceforth less health risks to consumers. However, the risk can be experienced by animals such as cattle, goats, and wild animals which are observed to feed on paddy rice straws,

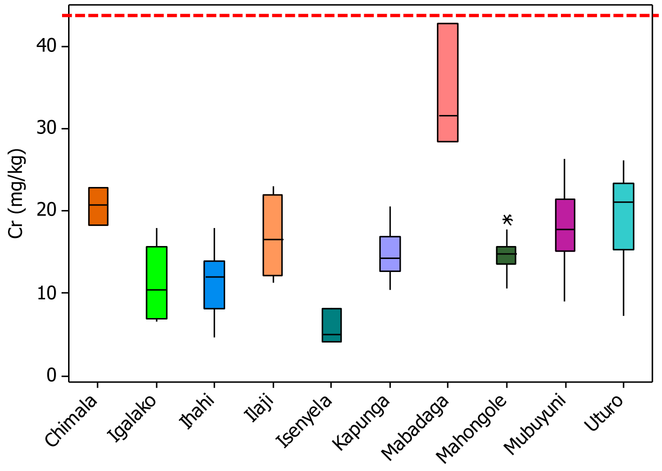

Fig. 4. The Cr distribution in agricultural soils among various irrigation schemes of Usangu agro-ecosystem. Values above the red dotted lines represent exceedance of FAO maximum permissible limits (1 mg/kg). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

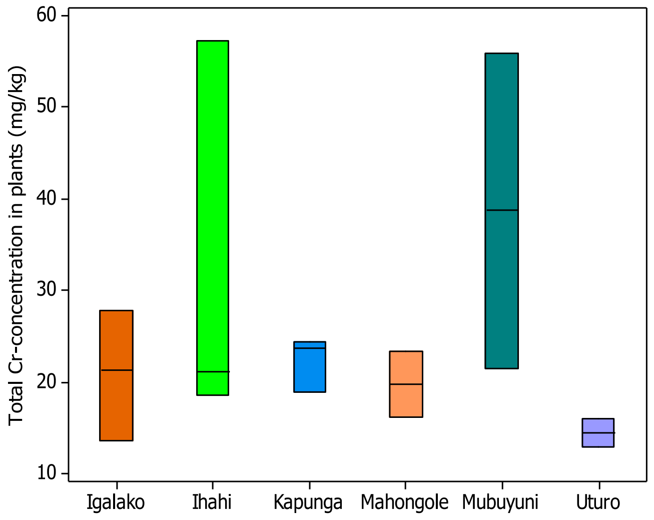

Fig. 5. The Cr accumulation (mg/kg) in paddy rice plants in six irrigation schemes in the Usangu agro-ecosystem (this includes Cr in roots, straws, and grains).

Table 1
The Cr concentration and partitions in different paddy rice plant tissues in six irrigation schemes.

Scheme	Cr (mg/kg)			
	Roots	Straws	Grain	Total
Igalako	9.36	5.35	6.19	20.90
Ihahi	6.87	15.89	9.58	32.34
Kapunga	6.58	2.05	11.47	20.10
Mahongole	9.75	2.97	11.52	24.24
Mubuyuni	6.20	21.05	9.78	37.03
Uturo	5.09	2.14	10.99	18.22
Mean	**7.31**	**8.24**	**9.92**	**25.47**
SD	**1.85**	**8.18**	**2.01**	**7.54**

especially after harvesting [34]. Overall Cr trends distribution in paddy rice varies significantly among schemes, where higher Cr was observed in Igalako (20.90 mg/kg), Mahongole (24.24 mg/kg), Ihahi (32.34 mg/kg), and Mubuyuni (37.03 mg/kg) (Fig. 4 and Table 1). Anthropogenic activities such as the use of pesticides and the outflow from semi-urbanized settlements available in agricultural areas might be associated with increased uptake of Cr in soils and plant tissues as is a potential source of Cr contamination [4,5,11,35].

3.3. The Cr distribution in paddy rice plant tissues or parts

Determination of total Cr in plant samples as a whole including edible and non-edible parts tends to overestimate associated risk because not all fractions are available for animals and humans. Therefore, the determination of Cr partitions among plant parts such as roots, straws, and grains is very important in estimating the health risk associated with an elevated level of Cr. The Cr in contaminated grains and fodders can be transported to a far distance and cause negative effects on animals and humans who are not even directly connected to a particular agro-ecosystem pose a health risk to humans through consumption. Cr concentration in roots is available to soil decomposers, and Cr in straws are available to animals through the feed while Cr in grains is available to animals and human through contaminated grain consumption. This study found that Cr concentration among paddy rice tissues/parts varied significantly (Table 1 and Fig. 6). Where Cr ranged from: roots (5.09–9.75 mg/kg), Straws (2.05–21.05 mg/kg), and grains (6.19–11.52 mg/kg) (Table 1 and Fig. 5). It was found that the Cr concentration values in roots and straws were higher than that determined in paddy rice grains (Table 1 and Fig. 6). High Cr levels in straws pose a risk to animals grazing in paddy rice straws after harvesting. On the other hand, the incorporation of paddy rice straws in agricultural soils could significantly return Cr in agricultural soil, thus increasing Cr availability to soil micro-organisms and invertebrates [5,29,35]. The Cr generally observed was higher for straws and roots, however, at some schem4es higher Cr concentrations were observed in paddy rice grains such as Mahongole (11.52 mg/kg), Kapunga (11.47 mg/kg), and Uturo (10.99 mg/kg) (Table 1 and Fig. 6). In general, it was observed that the Cr concentrations followed the same tendency of higher values in roots and straws than those in paddy rice grains. The Cr concentration in the rice grain as the edible portion of paddy rice was lower than that of the rest of the plant but was observed to be close to the maximum tolerance of WHO, exceeding the WHO limit in some plant samples. The Cr concentration (mg/kg) in paddy rice plant parts can be arranged in the order of decreasing as follows; Straws > Roots > Grains. Therefore, it is necessary to manage Cr concentration in agricultural soils to ensure that lower Cr concentrations accumulate in plant tissues, especially in the edible parts of plants such as grains.

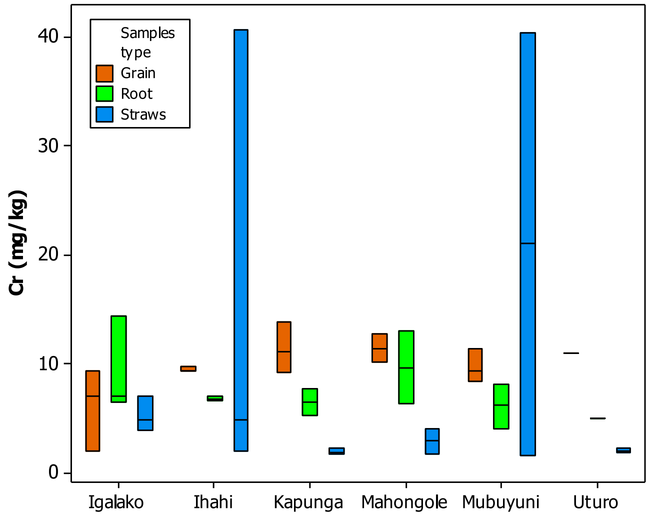

Fig. 6. The chromium (Cr) distribution in different paddy rice plant parts (roots, straws, and grains) in six irrigation schemes in Usangu agro-ecosystem.

3.4. Translocation and bio-concentration factor for TMs in plant samples

The bio-concentration factor (BF) describes the Cr accumulation from soil to plant tissues, while the Translocation factor (TF) describes Cr movement from soils through roots to above-ground biomass (shoot and straws); all these describe the availability of Cr for plant uptakes and associated risk [22]. The BF > 1 signifies greater Cr uptake by crops than those in soils, while BF < 1 signifies less Cr uptakes by plants, and more Cr is expected to be accumulated in agricultural soils [22]. The determined BF among plant samples from Usangu were significantly different ($P < 0.05$) among schemes, where it was found that BF ranged from 0.7 to 2.7 (Table 2). The study found that it was found that 83.3% of the study schemes had BF greater than 1 indicating more Cr was accumulated in paddy rice plant tissues, or the concentration of Cr determined was higher in plant samples compared to Cr in soil samples. This indicates plants had higher Cr uptake, polluting the grain and fodders, which could lead to ecological and health risks to humans and animals. Furthermore, some schemes (16.7%) below 1 (BF < 1) such as Uturo indicate less Cr accumulation in plant sample tissues compared to soils (Table 2). This indicates that the plant had a high Cr affinity that's why low Cr was observed in soils that might be affected by management practices [35]. Higher BF (BF > 1) is an indication of Cr enrichment in food systems which can result in potential health risks to humans and animals [29].

Based on the TF, a large concentration of Cr was accumulated more on below-ground biomass (roots) than the above-ground biomass (straws). This study found that TF values for Cr were 0.27 to −2.33 (Table 2). It was observed that 33.33% of the studied schemes had TF values above 1 for Cr indicating that more Cr was in above-ground biomass (Table 2 and Fig. 7). This indicates that the translocation of Cr was high shoots or straws than roots which shows more transportation of Cr from roots to straws. It was observed that Mubuyuni and

Table 2
The bioconcentration (BF) and translocation (TF) factor for Cr estimated in paddy rice plant samples from Usangu agro-ecosystem.

S/N	Scheme	Cr	
		Bioconcentration factor (BF)	Translocation factor (TF)
1	Igalako	1.9	0.68
2	Ihahi	2.7	2.33
3	Kapunga	1.5	0.27
4	Mahongole	1.3	0.55
5	Mubuyuni	2.1	3.34
6	Uturo	0.7	0.47
% BF or TF > 1		**83.3**	**33.33**

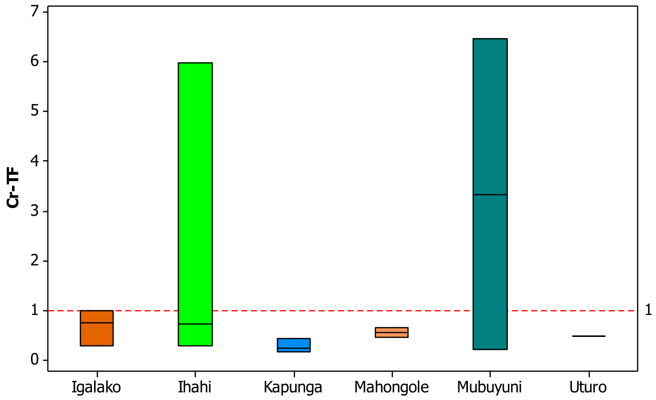

Fig. 7. The Cr translocation factor shows more Cr accumulation in below-ground biomass (roots) than above-ground biomass (straws) except for Ihahi and Mubuyuni irrigation schemes which were observed to have higher Cr in above-ground biomass.

Ihahi irrigation schemes had TF values greater than 1 such as Mubuyuni (3.34) and Ihahi (2.33), this might be associated with farming management practices that involve extensive use of agrochemicals such as fertilizer and pesticides which are usually associated with Cr impurities [35,36].

On the other hand, the TF values for Cr in 66.67% of the studied scheme (Igalako (0.68), Kapunga (0.27), Mahongole (0.55), and Uturo (0.47)) and plant samples were observed to have TF values of less than 1 (TF $<$ 1) indicating that the Cr concentration was higher in below-ground biomass (roots) than above-ground biomass (straws and shoots) (Table 2 and Fig. 7). The general trend for Cr TF in this study found that TF values in most irrigation studied (66.67%) were below 1 (TF $<$ 1) indicating that there was less Cr translocation from roots to straws, or in other words, more Cr was found to be accumulated in below-ground biomass (roots) than above-ground biomass (straws and grains). Considering the Cr-determined TF, it is clear that paddy farming areas of the Usangu agro-ecosystem have minimal risks of Cr accumulation in edible plant parts. Thus using total Cr and bio-concentration alone to estimate the risk of Cr in an agro-ecosystem is not adequate and may result in an overestimation of associated risks. Combined determination of BF and TF provides a better understanding of Cr distribution in plant parts and related risks.

4. Conclusion and recommendations

The assessment of Cr concentration in soil and paddy rice samples within the Usangu agro-ecosystem revealed potential health risks associated with the accumulation of Cr in soil and different parts of plants. The bioconcentration factor analysis indicated a higher accumulation of Cr in the plants compared to the soil, considering roots, straws, and grains. However, the translocation factor estimation revealed that the majority of Cr within the plants was concentrated in the roots. Moreover, the study found that more Cr accumulated in below-ground biomass (roots) than in above-ground biomass (straws and grains). As a result, the associated health risk to animal and human health appears to be minimal. It is important to note that this conclusion may be subject to change in the near future due to factors such as increased agricultural intensification, the rising use of agrochemicals, and urbanization in the area. These factors could potentially alter the distribution and accumulation of Cr in the soil and plant tissues, thereby impacting the health risks associated with consumption. Continued monitoring and assessment of Cr levels in the agro-ecosystem are crucial to ensure the long-term safety of agricultural products and mitigate potential health hazards.

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.

Data availability

Data will be made available on request.

References

[1] N. Abdu, J.O. Agbenin, A. Buerkert, Geochemical assessment, distribution, and dynamics of trace elements in urban agricultural soils under long-term wastewater irrigation in Kano, northern Nigeria, J. Plant Nutr. Soil Sci. 174 (2011) 447–458, https://doi.org/10.1002/jpln.201000333.
[2] W. Addis, A. Abebaw, Determination of heavy metal concentration in soils used for cultivation of Allium sativum L.(garlic) in East Gojjam Zone, Amhara Region, Ethiopia, Cogent Chem 3 (2017), 1419422, https://doi.org/10.1080/23312009.2017.1419422.
[3] N. Kazakis, N. Kantiranis, K. Kalaitzidou, E. Kaprara, M. Mitrakas, R. Frei, G. Vargemezis, D. Vogiatzis, A. Zouboulis, A. Filippidis, Environmentally available hexavalent chromium in soils and sediments impacted by dispersed fly ash in Sarigkiol basin (Northern Greece), Environ. Pollut. 235 (2018) 632–641, https://doi.org/10.1016/j.envpol.2017.12.117.
[4] A. Ertani, A. Mietto, M. Borin, S. Nardi, Chromium in agricultural soils and crops: a review, water, Air. Soil Pollut. 228 (2017), https://doi.org/10.1007/s11270-017-3356-y.
[5] N. Xie, C. Kang, D. Ren, L. Zhang, Assessment of the variation of heavy metal pollutants in soil and crop plants through field and laboratory tests, Sci. Total Environ. 811 (2021), 152343, https://doi.org/10.1016/j.scitotenv.2021.152343.
[6] A. Alkenani, T.A. Saleh, Synthesis of amine-modified graphene integrated membrane as protocols for simultaneous rejection of hydrocarbons pollutants, metal ions, and salts from water, J. Mol. Liq. 367 (2022), 120291, https://doi.org/10.1016/j.molliq.2022.120291.
[7] T.A. Saleh, M. Mustaqeem, M. Khaled, Water treatment technologies in removing heavy metal ions from wastewater: a review, Environ. Nanotechnol. Monit. Manag. 17 (2022), 100617, https://doi.org/10.1016/j.enmm.2021.100617.
[8] T.A. Saleh, Nanomaterials: classification, properties, and environmental toxicities, Environ. Technol. Innov. 20 (2020), 101067, https://doi.org/10.1016/j.eti.2020.101067.
[9] T.A. Saleh, Protocols for synthesis of nanomaterials, polymers, and green materials as adsorbents for water treatment technologies, Environ. Technol. Innov. 24 (2021), 101821, https://doi.org/10.1016/j.eti.2021.101821.
[10] C. qing Su, L. qing Li, Z. hui Yang, L. yuan Chai, Q. Liao, Y. Shi, J. wei Li, Cr(VI) reduction in chromium-contaminated soil by indigenous microorganisms under aerobic condition, Trans. Nonferrous Met. Soc. China (English Ed. 29 (2019) 1304–1311, https://doi.org/10.1016/S1003-6326(19)65037-5.
[11] A. Kazemi, M. Esmaeilbeigi, Z. Sahebi, A. Ansari, Health risk assessment of total chromium in the qanat as historical drinking water supplying system, Sci. Total Environ. 807 (2022), 150795, https://doi.org/10.1016/j.scitotenv.2021.150795.
[12] Y. Xu, Y. Wu, J. Han, P. Li, The current status of heavy metal in lake sediments from China: pollution and ecological risk assessment, Ecol. Evol. 7 (2017) 5454–5466, https://doi.org/10.1002/ece3.3124.
[13] Å.R. Almås, M.L.K. Manoko, Trace element concentrations in soil, sediments, and waters in the vicinity of geita gold mines and north mara gold mines in northwest Tanzania, Soil Sediment Contam. 21 (2012) 135–159, https://doi.org/10.1080/15320383.2012.649372.
[14] R.S. Shemdoe, Heavy metal concentrations in soils and leachetes of Mtoni dumpsite bordering the Indian Ocean in Dar es salaam, Tanzania, Sci. Res. Essays 5 (2010) 2143–2147.
[15] J.F. Machiwa, Heavy metal levels in paddy soils and rice (oryza sativa (L)) from wetlands of lake victoria basin, Tanzania, Tanzania, J. Sci. (2010).
[16] F. Simon, K.M. Mtei, M. Kimanya, Heavy metals contamination in agricultural soil and rice in Tanzania: a review, Int. J. Environ. Protect. Pol. 4 (2016) 16, https://doi.org/10.11648/j.ijepp.20160401.13.
[17] G.R. Mataba, V. Verhaert, R. Blust, L. Bervoets, Distribution of trace elements in the aquatic ecosystem of the Thigithe river and the fish Labeo victorianus in Tanzania and possible risks for human consumption, Sci. Total Environ. 547 (2016) 48–59, https://doi.org/10.1016/j.scitotenv.2015.12.123.
[18] J. Liu, M. Qian, G. Cai, J. Yang, Q. Zhu, Uptake and translocation of Cd in different rice cultivars and the relation with Cd accumulation in rice grain, J. Hazard Mater. 143 (2007) 443–447, https://doi.org/10.1016/j.jhazmat.2006.09.057.
[19] M. Chabukdhara, A.K. Nema, Heavy metals assessment in urban soil around industrial clusters in Ghaziabad, India: probabilistic health risk approach, Ecotoxicol. Environ. Saf. 87 (2013) 57–64, https://doi.org/10.1016/j.ecoenv.2012.08.032.
[20] N.M. Phuong, Y. Kang, K. Sakurai, K. Iwasaki, C.N. Kien, N. Van Noi, L.T. Son, Levels and chemical forms of heavy metals in soils from red river delta, Vietnam, Water, Air. Soil Pollut. 207 (2010) 319–332, https://doi.org/10.1007/s11270-009-0139-0.

[21] N.M. Phuong, Y. Kang, K. Sakurai, K. Iwasaki, C.N. Kien, N. Van Noi, L.T. Son, Arsenic contents and physicochemical properties of agricultural soils from the Red River Delta, Vietnam, Soil Sci. Plant Nutr. 54 (2008) 846–855, https://doi.org/10.1111/j.1747-0765.2008.00312.x.

[22] E.H. Lugwisha, Heavy metal levels in soil, tomatoes and selected vegetables from morogoro region, Tanzania, Int. J. Environ. Monit. Anal. 4 (2016) 82, https://doi.org/10.11648/j.ijema.20160403.13.

[23] M. Mng'ong'o, L.K. Munishi, P.A. Ndakidemi, W. Blake, S. Comber, T. H. Hutchinson, Accumulation and bioconcentration of heavy metals in two phases from agricultural soil to plants in Usangu agroecosystem-Tanzania, Heliyon 7 (2021), e07514, https://doi.org/10.1016/j.heliyon.2021.e07514.

[24] C.H. Tseng, I.H. Lee, Y.C. Chen, Evaluation of hexavalent chromium concentration in water and its health risk with a system dynamics model, Sci. Total Environ. 669 (2019) 103–111, https://doi.org/10.1016/j.scitotenv.2019.03.103.

[25] UoP, Hotplate Digestion for Soils/Sediments: ISO900, 2015, p. 9001.

[26] M. Mng'ong'o, L.K. Munishi, S. Comber, P.A. Ndakidemi, W. Blake, T. H. Hutchinson, Land use patterns influence the distribution of potentially toxic elements in soils of the Usangu Basin, Tanzania, Chemosphere 284 (2021), 131410, https://doi.org/10.1016/j.chemosphere.2021.131410.

[27] URT, The Environmental Management (Soil Quality Standards) Regulation, 2007, United Republic of Tanzania, 2007.

[28] Y.Y. Choi, International/National Standards for Heavy Metals in Food, 2011, pp. 1–13.

[29] R. Tang, X. Li, Y. Mo, Y. Ma, C. Ding, J. Wang, T. Zhang, X. Wang, Toxic responses of metabolites, organelles and gut microorganisms of Eisenia fetida in a soil with chromium contamination, Environ. Pollut. 251 (2019) 910–920, https://doi.org/10.1016/j.envpol.2019.05.069.

[30] B. Wang, Z. Xie, J. Chen, J. Jiang, Q. Su, Effects of field application of phosphate fertilizers on the availability and uptake of lead, zinc and cadmium by cabbage (Brassica chinensis L.) in a mining tailing contaminated soil, J. Environ. Sci. 20 (2008) 1109–1117, https://doi.org/10.1016/S1001-0742(08)62157-9.

[31] V. Srivastava, A. Sarkar, S. Singh, P. Singh, A.S.F. de Araujo, R.P. Singh, Agroecological responses of heavy metal pollution with special emphasis on soil health and plant performances, Front. Environ. Sci. 5 (2017) 1–19, https://doi.org/10.3389/fenvs.2017.00064.

[32] Y.I. Koleleni, S.A. Mbike, Analysis of heavy metals in soil and maize grown around namungo gold mine in ruangwa district, lindi region in Tanzania using X-ray fluorescence, Chem. Sci. Int. J. 24 (2018) 1–18, https://doi.org/10.9734/csji/2018/44976.

[33] D.K. Patra, C. Pradhan, H.K. Patra, Chromium bioaccumulation, oxidative stress metabolism and oil content in lemon grass Cymbopogon flexuosus (Nees ex Steud.) W. Watson grown in chromium rich over burden soil of Sukinda chromite mine, India, Chemosphere 218 (2019) 1082–1088, https://doi.org/10.1016/j.chemosphere.2018.11.211.

[34] A. Ordóñez, J. Loredo, E. De Miguel, S. Charlesworth, Distribution of heavy metals in the street dusts and soils of an industrial city in Northern Spain, Arch. Environ. Contam. Toxicol. 44 (2003) 160–170, https://doi.org/10.1007/s00244-002-2005-6.

[35] S. Adhikari, J. Marcelo-Silva, N. Rajakaruna, S.J. Siebert, Influence of land use and topography on distribution and bioaccumulation of potentially toxic metals in soil and plant leaves: a case study from Sekhukhuneland, South Africa, Sci. Total Environ. 806 (2022), 150659, https://doi.org/10.1016/j.scitotenv.2021.150659.

[36] F.C.F. Santos, C.A.M. Van Gestel, M.J.B. Amorim, Impact of chromium on the soil invertebrate model Enchytraeus crypticus (Oligochaeta) in standard reproduction and full life cycle tests, Chemosphere (2021), 132751, https://doi.org/10.1016/j.chemosphere.2021.132751.