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Impact of municipal solid waste amendments on molybdenum bioaccumulation in soil and vegetables: Health risk and bioavailability assessment

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Abstract
This study examines the effects of municipal solid waste (MSW) amendments on molybdenum (Mo) concentrations in both soil and vegetables in two growing years. Three MSW treatments were tested, i.e., 25% MSW + 75% garden soil (T1), 50% MSW + 50% garden soil (T2), and 75% MSW + 25% garden soil (T3), with a control treatment of 100% garden soil (T0). Fifteen vegetable species were cultivated to evaluate Mo uptake and bioaccumulation. The Pollution Load Index (PLI) and Bioaccumulation Factor (BCF) values confirmed the impact of MSW on Mo accumulation in both soil and vegetables, with *Allium cepa* and *Mentha arvensis* showing greater sensitivity to Mo contamination. Health risk assessments revealed that vegetables grown in MSW-amended soils, especially *Allium cepa* at T3 Year-1, had higher Daily Intake of Metal (DIM) and Health Risk Index (HRI) values compared to those grown in the control soil. The analysis of molybdenum concentrations in blood samples taken from people of various localities added a human health aspect to the study. This study highlights the potential of MSW compost in increasing Mo bioavailability and the implications for human health through vegetable consumption, emphasizing the need to carefully monitor Mo levels in MSW-amended soils.

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Introduction

Application of organic wastes especially compost may be a strategy to increase the organic matter content of many agricultural soils. Moreover, using waste in agriculture is a cost-effective way

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to dispose of these products (Xu et al., 2024). Agricultural-land will be sustainable when compost is applied and it is also environmentally beneficial as it helps enhance environmental concerns, since it reduces negative environmental effects (Pajura et al., 2024). The success of efficient waste management strategies relies on factors specific to each locality which are influenced by cultural, climatic and socioeconomic factors as well as the institutional capabilities. Principal challenges in waste management involve incorporating the informal waste sector in growing urban areas, decreasing consumption in industrialized cities, enhancing and standardizing the collection and evaluation of solid waste data, and adeptly handling the growing complexity of waste while ensuring the protection of both people and the environment (Vergara and Tchobanoglous, 2012; Mngomezulu et al., 2024).

The most common organic wastes are sewage sludge and manure which can be utilized raw or composted (i.e. humified under regulated conditions). When such wastes are applied to soil, organic matter rises, soil structure improves, and plant nutrient absorption improves (Singh and Agrawal, 2008; Sayara et al., 2020).

Contaminated waste poses a significant concern as heavy metals, especially Mo is introduced in food chain through application of waste tainted with heavy metals to agricultural land. The process begins with the utilization of municipal solid waste (MSW) to the soil which in turn provides the soil with heavy metals (Cao et al., 2023). These heavy metals are subsequently transported to the plant roots and following absorption by the plants, accumulate in various plant parts. Eventually, they are consumed by organisms, and as a result, heavy metals find their way into the human body along with essential nutrients (Witkowska et al., 2021). The rising demand for food further exacerbates the issue of contamination (Sardar et al., 2013; Rai et al., 2019). Huang et al. (2022) reported that undoubtedly, molybdenum (Mo) is essentially required for the normal growth of different organisms including plants, however, its slight excess over normal requirement causes severe toxicity to plants. Moreover, Wang et al. (2024) have recently pointed out that the magnitude of soil molybdenum (Mo) pollution is growing and there is a dire need of proper management of Mo-contaminated soil for the sustainable improvement of soil.

Vegetables have the potential to be the primary means by which heavy metals enter the food chain. The growing demand for vegetables and grains has resulted in peri-urban agricultural practices that amplify heavy metal contamination within the food chain (Gardiner and Harwood, 2017). Consequently, a strong connection was observed between the excessive consumption of heavy metals in soils and vegetables (Khan et al., 2021).

This research aimed to evaluate the transport of Mo from contaminated soil to plants as well as the possible health risks to the surrounding community from consuming such vegetables present in areas irrigated with municipal wastewater that is discharged for agriculture purpose without any treatment.

Materials and Methods

This research focused on a preliminary investigation of peri-urban areas under the impact of municipal solid waste (MSW) contaminated soil.

Study area

The research was conducted in the outskirts of Sargodha, Punjab, Pakistan. Sargodha is a farming town and is densely populated with vegetable growers (Maqsood et al. 2022).

Collection and processing of MSW

MSW is gathered and transferred to recycling facilities by waste pickers. Nevertheless, the biodegradable portion is left along roadways, railway tracks, vacant plots, and streets.

MSW was gathered from a variety of locations within the Sargodha district such as trash disposal sites of vegetable and fruit markets and waste accumulating canals. The composting of MSW involves a two-step process, i.e., degradation and maturation. In the initial phase, aerobic fermentation is employed to break down biodegradable elements, while the subsequent phase targets the decomposition of intricate organic compounds. Plastic fragment stones and roots are segregated from the composted MSW using a 2-mm filter. To ensure uniformity in the samples, the composted MSW is pulverized into fine powder using a crusher and mortar, and then thoroughly blended.

Pot experiment set up and vegetable cultivation

The seeds of different vegetables were collected from peri-urban areas of Sargodha. Each pot of 30 cm height and 30 cm diameter contained one plant. Three hundred pots were used for growing vegetables. All pots were filled with good quality soil and 15 vegetables were grown under four treatments: control with 100% ground soil (T_0), and three treatment groups with various amount of municipal solid waste mixed with ground soil (T_1: 75% ground soil and 25% MSW, T_2: 50% MSW and 50% ground soil, and T_3: 75% MSW and 25% ground soil). Each treatment was replicated 5 times for each vegetable. The pots were watered twice a week and the growing period for vegetables was 2-5 months.

Bottle gourd (*Lagenaria siceraria)* was sown in March and harvested in September. Sowing of round gourd (*Benincasa fistulosa*) was done in March and harvesting at the end of May. In March, bitter gourd (*Momordica. charantia*) was sown and by the end of June it was harvested. Sowing of cucumber (*Cucumis sativus*) was done in February and harvesting in April. Sowing of pumpkin (*Cucurbita pepo*) and ridge gourd (*Luffa acutangula*) was done in February and Mid-February, respectively, and harvesting of both took place in May. Green chillies (*Capsicum annuum*)*,* brinjal (*Solanum melongena*), tomato (*Solanum lycopersicum)* were sown in March and harvested periodically. Okra (*Abelmoschus esculentus*) was sown in February and harvested in April. Mid-February was the time for potato (*Solanum tuberosum*) sowing and it was harvested in May. Onion (*Allium cepa*) was sown in February and harvested in June. Coriander (*Coriandrum sativum*) was sown in late March, while spinach (*Spinacia oleracea*) was sown in mid-February and its harvesting took place in April.

Soil and vegetable samples collection

Soil samples were gathered from the middle portion of the pot. The samples of vegetables were taken when they were ready for human consumption. The collected fresh samples of vegetables were initially washed with tap water and then rinsed thrice with distilled water to extract foreign particles and surface deposition. After this, they were sliced into pieces, air-dried for 2 h and weighed to remove their moisture content. Thereafter, the samples were oven-dried at 65 °C for 90 h and their dry weights measured. The dried vegetable samples were ground properly, filtered through a 0.20 mm screen and preserved at room temperature for further analysis following Harrington et al. (2014).

Serum collection

After obtaining the written permission, 120 volunteers were listed for the study. The same number was chosen from four distinct locations within the Sargodha territory throughout the course of two growing years. The residents of Site 1 (control) consumed vegetables that were irrigated with groundwater. The residents of sites 2 (S_2), 3 (S_3), and 4 (S_4) were chosen because they had inadvertently consumed waste water fed veggies. In that region people have been consuming tainted veggies for a considerable amount of time more than ten years (Ashfaq et al. 2022).

Volunteers' median cubical veins were used to collect 15 mL of human blood and 1% sodium heparin was used as an anticoagulant. To extract the serum, each sample was centrifuged for 10 minutes at 2000 rpm and the serum samples were kept at -20 °C for metal analysis.

Digestion of the sample

A commonly employed acid-based digestion method as outlined by Samuel and Babatunde (2021) was used for the digestion of plant samples. One gram of over-dried plant material was carefully weighed and placed in a 100 mL beaker. Subsequently, 10 mL of concentrated HNO_3 (of analytical grade Merck-Germany) and 2 mL of concentrated $HClO_4$ (Merck-Germany) were added to the beaker. The digestion process was conducted on a hot plate within a temperature range of 150–200 °C. Once the digestion was complete, the samples were removed and allowed to cool down to room temperature. Following this cooling period, the samples were filtered and transferred to volumetric flasks where they were diluted with deionized (DI) water up to a total volume of 100 mL. This resulting 100 mL sample stock solution was subsequently stored in a plastic container for further analysis.

Analysis of the samples

The molybdenum analysis was conducted using an atomic absorption spectrophotometer (Varian AA 240) and the measurements were carried out using a hollow cathode lamp of Mo at wavelengths of 248.3 nm having detection limits of 30.0 µg/L. The sensitivity was regularly verified and upheld by employing standard solutions at intervals (Kalra, 1995).

Pollution load index (PLI)

To measure the extent of harmful pollution of a metal in soil, the PLI index was calculated. PLI was determined following Ashfaq et al. (2022) using the below given equation:

$$PLI = \frac{Metal\ value\ in\ sample\ soil}{Reference\ metal\ value} \quad (1)$$

Bio- concentration factor (BCF)

The BCF was used to investigate the extent to which Mo was moved from the soil to the consumable parts of vegetables. BCF was estimated as described elsewhere (Ashfaq et al., 2022) using the following formula:

$$BCF = \frac{Metal\ value\ in\ edible\ part}{M\ value\ in\ soil} \quad (2)$$

Enrichment factor (EF)

This method is employed to investigate the degree to which human actions have raised the level of a specific element in a sample medium compared to its typical natural occurrence. EF was estimated following Ashfaq et al. (2022).

$$EF = \frac{Plant\ metal\ value / Soil\ metal\ value}{Plant\ standard\ metal\ value / Soil\ metal\ standard\ value} \quad (3)$$

Daily intake of metals (DIM)

DIM was estimated to quantity metal uptake by humans through the consumption of vegetables.

$$DIM = \frac{Mo * F * V}{A} \quad (4)$$

Mo is the plant metal concentration, and F is the conversion factor (0.085) (Jan et al. 2010). V is the daily vegetable intake (0.345 kg/person/day) (Chen et al. 2005). A is the average body weight (60 kg for an adult) (Wang et al. 2005).

Health risk index (HRI)

The HRI index demonstrates the potential risks to health posed by consuming metal-contaminated plants. HRI was estimated by following the description and formula given by Ashfaq et al. (2022).

$$Health\ Risk\ Index = \frac{Molybdenum\ daily\ intake}{Molybdenum\ oral\ reference\ dose} \quad (5)$$

Health Risk Index = Molybdenum daily intake/ Molybdenum oral reference dose

Statistical Analysis

The significant differences between means and interactions were determined using 1 & 2 factorial ANOVA. Tukey HSD all-pairwise comparisons were employed to compare the means of significant variables at the 5% significance level. The means of two years (Year 1 versus Year 2) were examined using a two-sample t-test for each treatment and parameter independently. Minitab 18 SPSS 23 and GraphPad Prism 8 were used to do all statistical analyses and graphics.

Results

Concentration of Mo (mg/kg) in soil modified with different treatments of MSW

A significant effect of treatments was observed in terms of plant treatment and plant × treatment interaction. The lowest value of Mo was found in the soil of *S. oleracea* at control during $Y_{1,}$ while the highest value was found in the soil with *Allium cepa* at T_3Y_2 (**Figure 1**). The concentration of metal differed significantly in *S. melongena* in Y_1 and *C. sativum* in Y_2.

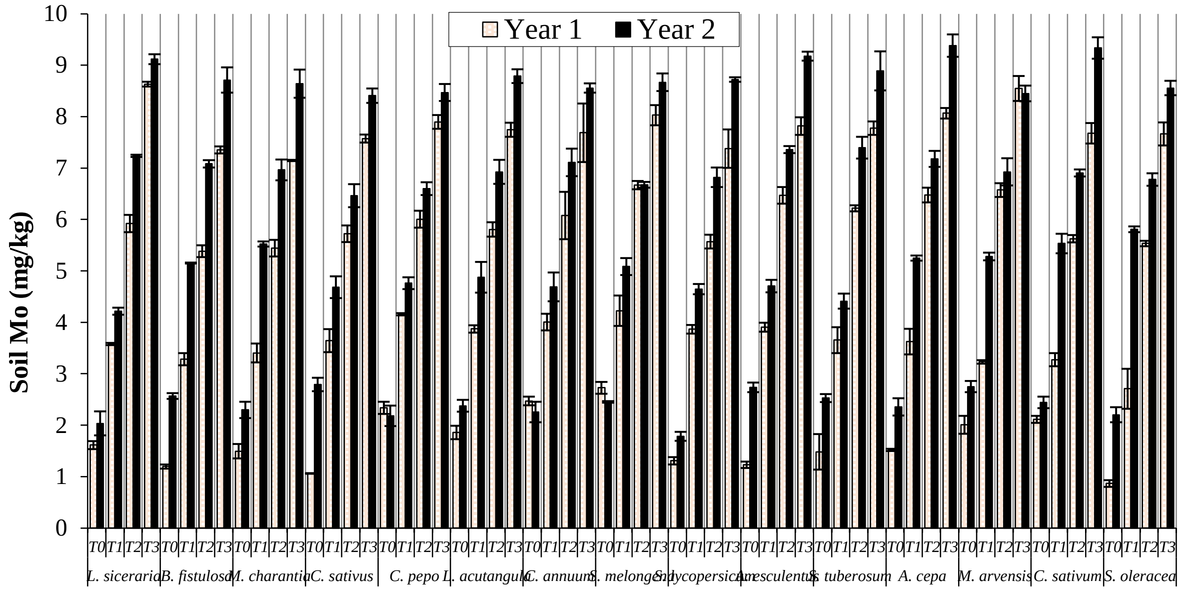

Figure 1. Molybdenum (mg/kg) in soil provided with different treatments of MSW (T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW ; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil)

Molybdenum (mg/kg) in vegetables grown in soil modified with varying treatments of MSW

ANOVA for Mo concentrations in the vegetables depicted a significant ($P \leq 0.01$) effect of plant treatment, the interaction of plants, and among different treatments of solid waste during Year 1. The lowest level of metal (0.096 mg/kg) was present in *C. sativus* under the control treatment. While *A. cepa* possessed the maximum concentration of metal (3.870 mg/kg) at T_3. Overall, the lowest concentration of Mo was found in *C. sativus* (0.260 mg/kg), while the highest in *A. cepa (*1.842 mg/kg).

Tomato exhibited highest metal concentration (1.851 mg/kg) during the second year. while the lowest was present in *C. sativus* (0.365 mg/kg). Spinach had the minimum Mo content (0.098 mg/kg) in T_2, while the maximum was present in tomato (3.78 mg/kg) at T_3 (**Figure 2**).

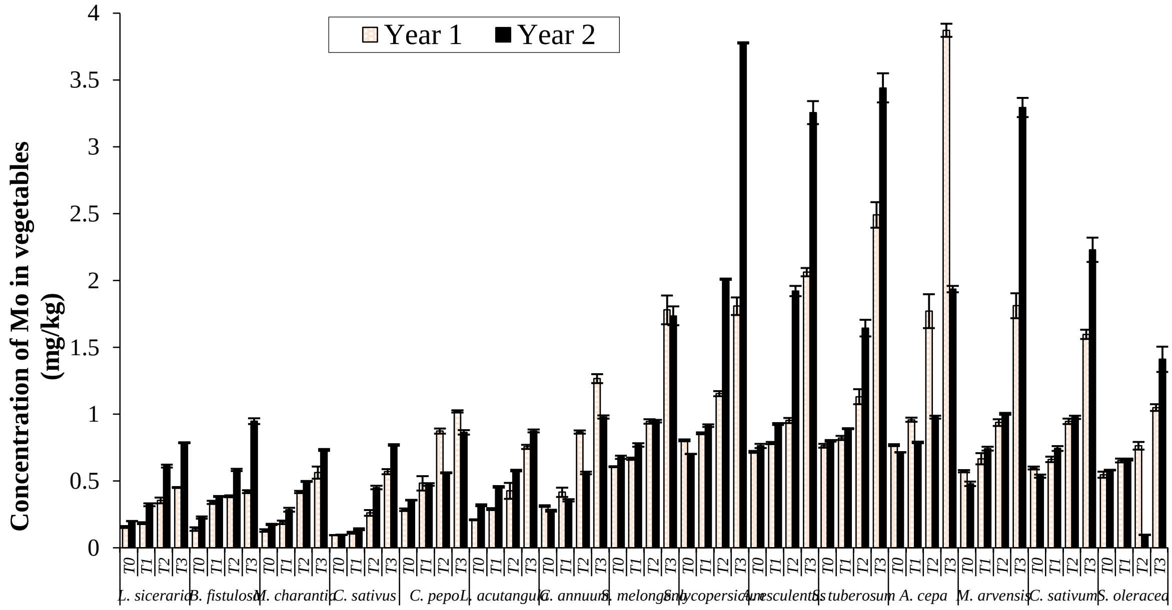

Figure 2. Molybdenum concentration in vegetables provided with different treatments of MSW (T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW ; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil)

Concentration of Mo in serum

In serum, Mo demonstrated highly significant ($P < 0.01$) variations. The results presented in **Figure 3** show that the concentration of Mo varied from 0.042-0.079 mg/L. The highest concentration was found in Y_2 at S_3 while the lowest level was observed in Y_1 at S_0 (**Figure 3**).

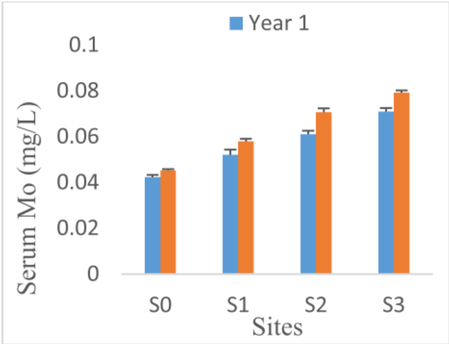

Figure 3. Sites x Mo metal interaction in serum

Pollution load index (PLI) of molybdenum

The minimum value of Mo PLI was observed in the soil containing *S. oleracea* at control and T_1 during both years, however, the soil with this vegetable gained PLI at T_2 and T_3 during both years, and it was as good as those of the other soils with different vegetables. The highest PLI was observed in *A. cepa* soil at T_3 during both years (**Table 1**).

Table 1. Pollution load index (PLI) of molybdenum in the soils modified with MSW treatments

	Year 1				Year 2			
Species	T_0	T_1	T_2	T_3	T_0	T_1	T_2	T_3
A. cepa	0.506	1.208	2.159	2.689	0.785	1.750	2.392	3.127
A. esculentus	0.409	1.302	2.157	2.606	0.912	1.568	2.452	3.059
C. annuum	0.823	1.335	2.026	2.562	0.752	1.563	2.370	2.851
C. pepo	0.779	1.385	2.002	2.632	0.728	1.587	2.200	2.823
C. sativum	0.704	1.091	1.874	2.559	0.814	1.845	2.302	3.112
C. sativus	0.354	1.214	1.908	2.524	0.930	1.561	2.154	2.803
B. fistulosa	0.399	1.094	1.794	2.450	0.856	1.718	2.361	2.904
L. acutangula	0.619	1.291	1.935	2.581	0.792	1.626	2.308	2.929
S. lycopersicum	0.436	1.288	1.856	2.459	0.595	1.548	2.273	2.907
L. siceraria	0.538	1.193	1.974	2.877	0.678	1.405	2.413	3.039
M. arvensis	0.669	1.077	2.191	2.850	0.917	1.761	2.308	2.816
M. charantia	0.498	1.134	1.815	2.383	0.766	1.841	2.321	2.880
S. melongena	0.909	1.408	2.224	2.676	0.817	1.695	2.225	2.889
S. oleracea	0.289	0.903	1.844	2.554	0.734	1.936	2.259	2.852
S. tuberosum	0.494	1.218	2.072	2.591	0.843	1.471	2.465	2.962

T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil

Bio-concentration factor (BF) of Mo

Maximum BF (0.302) was found in *S. oleracea* at control (T_0) during Y_1 and minimum in *C. sativus* (0.0310) at T_1 during the second year (**Table 2**). At the highest treatment (T_3) during the first year, *A. cepa* had the highest BF of all vegetables tested in this study, and during the second year in T_3, *S. lycopersicum* had been superior to all vegetables in terms of BF (**Table 2**).

Table 2. Bio-concentration factor (BF) of Mo in vegetables grown in soils modified with MSW treatments

	Year 1				Year 2			
Species	T_0	T_1	T_2	T_3	T_0	T_1	T_2	T_3
A. cepa	0.507	0.265	0.273	0.479	0.303	0.150	0.136	0.206
A. esculentus	0.585	0.201	0.147	0.264	0.278	0.196	0.261	0.354
C. annuum	0.127	0.104	0.143	0.165	0.123	0.076	0.078	0.114
C. pepo	0.122	0.116	0.145	0.129	0.164	0.099	0.085	0.102
C. sativum	0.283	0.202	0.168	0.208	0.219	0.134	0.141	0.238
C. sativus	0.090	0.031	0.045	0.075	0.035	0.029	0.069	0.091
B. fistulosa	0.118	0.103	0.072	0.057	0.088	0.074	0.082	0.108
L. acutangula	0.114	0.075	0.074	0.098	0.134	0.093	0.083	0.099
S. lycopersicum	0.615	0.222	0.207	0.245	0.393	0.196	0.294	0.433
L. siceraria	0.096	0.051	0.059	0.052	0.099	0.076	0.084	0.086
M. arvensis	0.285	0.206	0.142	0.212	0.174	0.140	0.144	0.389
M. charantia	0.086	0.056	0.076	0.078	0.076	0.051	0.071	0.084
S. melongena	0.223	0.157	0.142	0.222	0.276	0.151	0.141	0.200
S. oleracea	0.630	0.241	0.137	0.136	0.264	0.113	0.014	0.164
S. tuberosum	0.515	0.225	0.182	0.320	0.316	0.202	0.222	0.387

T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW ; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil

Enrichment factor (EF) of Mo

Overall comparison of EF value for Mo in soil of different vegetables showed that maximum value of EF (0.378) was noted in soil with *S. oleracea.* In contrast, the minimum EF (0.009) was noted in soil containing *S. oleracea* (**Table 3**).

Daily intake of metal (DIM) and health risk index (HRI) of Mo

The level of toxicity of Mo to human beings was determined by its daily intake of Mo by vegetable consumption (**Table 4**). The content of DIM ranged 0.0000469-0.001891 mg/kg/day. *A. cepa* showed

Table 3. Enrichment factor (EF) of Mo

	Year 1				Year 2			
Species	T_0	T_1	T_2	T_3	T_0	T_1	T_2	T_3
A. cepa	0.303	0.158	0.163	0.287	0.182	0.090	0.081	0.123
A. esculentus	0.351	0.120	0.088	0.158	0.167	0.118	0.156	0.212
C. annuum	0.076	0.062	0.085	0.098	0.073	0.045	0.047	0.068
C. pepo	0.073	0.069	0.087	0.077	0.098	0.059	0.051	0.061
C. sativum	0.169	0.121	0.101	0.124	0.131	0.080	0.084	0.143
C. sativus	0.054	0.018	0.027	0.045	0.021	0.017	0.041	0.054
B. fistulosa	0.070	0.062	0.043	0.034	0.053	0.044	0.049	0.065
L. acutangula	0.068	0.044	0.044	0.058	0.080	0.056	0.050	0.060
S. lycopersicum	0.368	0.133	0.124	0.147	0.236	0.118	0.176	0.259
L. siceraria	0.057	0.031	0.035	0.031	0.059	0.045	0.050	0.051
M. arvensis	0.171	0.123	0.085	0.127	0.104	0.084	0.086	0.233
M. charantia	0.051	0.033	0.046	0.047	0.045	0.030	0.042	0.050
S. melongena	0.133	0.094	0.084	0.133	0.165	0.090	0.085	0.120
S. oleracea	0.378	0.144	0.082	0.082	0.158	0.068	0.008	0.098
S. tuberosum	0.309	0.135	0.109	0.192	0.190	0.121	0.133	0.232

T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW ; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil

Table 4. Assessment of risk of metal by the uptake of vegetables grown in MSW-modified soil

Year 1	T_0		T_1		T_2		T_3	
Vegetables	DIM	HRI	DIM	HRI	DIM	HRI	DIM	HRI
A. cepa	0.000376	0.041761	0.000469	0.052079	0.000865	0.096121	0.001891	0.210163
A. esculentus	0.000351	0.039046	0.000383	0.042521	0.000465	0.051699	0.001008	0.111978
C. annuum	0.000153	0.016998	0.000203	0.022591	0.000424	0.047083	0.000619	0.068751
C. pepo	0.000139	0.015477	0.000236	0.026230	0.000427	0.047409	0.000499	0.055446
C. sativum	0.000292	0.032421	0.000323	0.035896	0.000463	0.051427	0.000781	0.086726
C. sativus	0.000047	0.005213	0.000552	0.006137	0.000128	0.014228	0.000279	0.031008
B. fistulosa	0.000068	0.007657	0.000167	0.018518	0.000189	0.020962	0.000206	0.022863
L. acutangula	0.000103	0.011458	0.000142	0.015749	0.000208	0.023134	0.000369	0.041055
S. lycopersicum	0.000393	0.043662	0.000419	0.046541	0.000564	0.062614	0.000884	0.098184
L. siceraria	0.000758	0.008417	0.000904	0.010047	0.000174	0.019278	0.000221	0.024546
M. arvensis	0.000281	0.031171	0.000326	0.036168	0.000458	0.050884	0.000885	0.098347
M. charantia	0.000006	0.007005	0.000934	0.010372	0.000204	0.022700	0.000275	0.030574
S. melongena	0.000297	0.033018	0.000326	0.036168	0.000462	0.051319	0.000870	0.096664
S. oleracea	0.000267	0.029705	0.000320	0.035516	0.000373	0.041435	0.000513	0.056967
S. tuberosum	0.000373	0.041435	0.000402	0.044639	0.000552	0.061365	0.001217	0.135221
Year 2	**DIM**	**HRI**	**DIM**	**HRI**	**DIM**	**HRI**	**DIM**	**HRI**
A. cepa	0.000349	0.038828	0.000386	0.042847	0.000478	0.053111	0.000946	0.105136
A. esculentus	0.000373	0.041435	0.000453	0.050287	0.000939	0.104321	0.001591	0.176765
C. annuum	0.000136	0.015097	0.000174	0.019387	0.000274	0.030465	0.000478	0.053111
C. pepo	0.000175	0.019441	0.000232	0.025741	0.000275	0.03052	0.000422	0.046920
C. sativum	0.000262	0.029162	0.000364	0.040403	0.000478	0.053057	0.001090	0.121101
C. sativus	0.000048	0.005376	0.000068	0.007603	0.000220	0.024492	0.000376	0.041761
B. fistulosa	0.000111	0.012327	0.000188	0.020908	0.000285	0.031714	0.000463	0.051427
L. acutangula	0.000155	0.017269	0.000223	0.024763	0.000282	0.031389	0.000427	0.047463
S. lycopersicum	0.000344	0.038177	0.000447	0.049635	0.000982	0.109154	0.001846	0.205112
L. siceraria	0.000098	0.010971	0.000158	0.017541	0.000299	0.033181	0.000385	0.042738
M. arvensis	0.000234	0.026012	0.000363	0.040295	0.00049	0.054414	0.00161	0.178883
M. charantia	0.000085	0.009503	0.000139	0.015477	0.000243	0.02699	0.000358	0.039806
S. melongena	0.000331	0.036765	0.000376	0.041815	0.000463	0.051427	0.000848	0.094274
S. oleracea	0.000284	0.031606	0.000323	0.035896	0.000479	0.005322	0.00069	0.076625
S. tuberosum	0.000391	0.043499	0.000436	0.048495	0.000804	0.089278	0.001681	0.186811

T_0, Control (100% ground soil); T_1, 75% ground soil and 25% MSW; T_2, 50% MSW and 50% ground soil; T_3, 75% MSW and 25% ground soil higher DIM at T_3 during the first year, while the vegetables grown at control during Y_1 showed overall lower content of DIM as compared to those at other treatments (**Table 4**). Health risk index (HRI) of Mo ranged from 0.005213 - 0.210163 and the maximum content was found in *A. cepa* at T_3 during the first year (**Table 4**). However, in contrast, the minimum content was observed in *C. sativus* at control during the first year.

Discussion

In view of the results presented here for Mo levels in soils amended with different levels of municipal solid waste, it is evident that Mo levels increased consistently with increase in the level of MSW. However, different vegetables grown on MSW-amended soils accumulated Mo to a varying extent. Soil, crops and consumers can be affected severely by the release of heavy metals from sources viz factory effluents and contaminated locales (Jaja and Odoemena, 2004; Rai et al., 2019). Analogous to our findings, Wang et al. (2021) have assessed the effects of different soil amendments on the uptake of Mo in monocot (ryegrass) and dicot (alfalfa) plant species and noted that all different amendments such as biosolids, biochar supported nanoscale zero-valent iron (BC-*n*ZVI), drinking water treatment residues (WTR) and ferrous minerals (magnetite and ferrihydrite) improved the extractability of Mo. Significant contents of Mo in the vegetables might have been because of the relationship with different trace elements (Ezebuiro et al., 2018) present in the rhizosphere.

Similar to the Mo uptake pattern in different vegetable crops at varying levels of MSW as observed in the current study, the inhabitants consuming such MSW-contaminated vegetables showed a consistent increase in Mo accumulation in their blood serum. Recently, Mngadi et al. (2024) have investigated the accumulation and distribution of both essential and toxic elements including Mo and several other trace elements in soil and a potential vegetable crop, *Brassica oleracea* collected from 8 polluted sites, and reported a high risk for human health if such metal contimanted vegetable is consumed.

The range of PLI in our study ranged from 0.29 to 3.13. The low value of PLI for Mo was recorded by Ahmad et al. (2016) while investigating the effeccts of polluted water on soil, corriander, and human population consuning this metal-contaminated vegetable grown at different sites within the Sargodha region. However, the PLI for Mo was found to be much lower than that reported elsewhere (Ashfaq et al., 2015). It has also been reported that the properties of rhizosphere affect the absorption of heavy metals by the plants (Yashim et al. 2014; Luo et al., 2023).

In the current research, high BF and EF values were observed at all MSW treatments. It could have been due to the reason that application of municipal solid waste could modify structure of soil and enhance accessibility as well as distribution of metals (Gupta et al. 2012; Meena et al., 2019). In the present findings, all vegetables showed HRI < 1, suggesting that the consumption was safe for humans. HRI defines the hazard of eating metal-polluted edible portions of plants and their impacts on the fitness of humans. The value of HRI of different metals is considered as lethal which exceeds 1 (Karim and Qureshi, 2014; Ratul et al., 2018; Ejaz et al., 2024).

Based on the findings of this research, it was observed that the pollution load index, bioconcentration factor, and health risk index were higher in the MSW-amended soils than those in the non-treated soil. This increase in the values could likely be attributed to the elevated levels of contaminants present in natural additives which are being used as organic soil amendments. However, the study recommends the consistent monitoring of heavy metal (Mo) levels in the potential vegetables as a crucial measure to mitigate the health risks associated with the consumption of contaminated vegetables. Bioaccumulation of Mo in different vegetables was reasonably high at specific sites which requires considerable attention.

Author(s), Editor(s) and Publisher's declarations

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Planning of research: AA, ZIK, KA. Conduction of research: AA, HM, AB, FS, HMN. Data collection, visualization and interpretation: AA, HM, AB, FS, HMN, ZIK. Graphical presentation/visualization: AA, ZIK, KA. Statistical analysis: AA, HM, AB. Preparation of initial draft: AA, HM, AB, FS, HMN. Review of initial draft: ZIK, KA, IRN. Revisions and corrections: AA, ZIK. Proof reading and approval of the final version: AA, ZIK, KA, IRN.

Ethical approval

The Institutional Human Ethics Committee of the University of Sargodha approved all protocols used in this experiment (Approval No. 25-A18 IEC UOS). All experimental methods followed appropriate guidance and regulations including NRC standards. Informed written consent was obtained from all human participants prior to the commencement of the study.

Handling of bio-hazardous materials

The authors certify that all experimental materials were handled with great care during collection and experimental procedures. After completion of the study, all materials were properly discarded to minimize/eliminate any types of bio-contamination(s).

Supplementary material

No supplementary material is included in this manuscript.

Conflict of interest

The authors declare no conflict of interest.

Availability of primary data and materials

As per editorial policy, experimental materials, primary data, or software codes are not submitted to the publisher/Journal management. These are available with the corresponding author (s) and/or with co-author(s) as declared by the corresponding author (s) of this manuscript.

Authors' consent

All authors have critically read this manuscript and agreed to publish in IJAaEB.

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It is declared that the authors did not use any AI tools or AI-assisted services in the preparation, analysis, or creation of this manuscript submitted for publication in the International Journal of Applied and Experimental Biology (IJAaEB).

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