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Impact of municipal solid waste compost on *Spinacia oleracea* L. (Spinach) Yield: Health risk assessment and dosing optimization

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ABSTRACT

The increasing demand for effective Municipal Solid Waste (MSW) management stresses the importance of sustainable disposal approaches. Composting biodegradable solid waste offers such a solution, but it raises concerns about contamination with xenobiotics. This study evaluates the impact of Municipal Solid Waste Compost (MSWC) sourced from open landfills on agricultural soils and the yield of *Spinacia oleracea* L. (Spinach). The suitability of MSWC as a soil amendment was characterized using the Fertilization Index (FI) and Cleanliness Index (CI), while the risk of trace metal (TM) contamination was assessed through the Pollution Index (PI), Pollution Load Index (PLI), and Enrichment Factor (EF). The results show that MSWC application improved soil health but did not significantly enhance plant performance. Higher MSWC concentrations in amended soil increased TM levels, including Cu, Cr, Cd, Pb, and Ni, often exceeding permissible thresholds for soil and plant safety. At a 25% application rate, PI and PLI values indicated low to moderate pollution, while EF suggested no significant accumulation of Cu, Cr, Cd, or Ni but moderate enrichment of Pb. The study infers that while MSWC can condition soil, its use must be carefully managed to mitigate toxicity risks. This research highlights the dual potential and challenges of using MSWC in agriculture, emphasizing the need for optimized application strategies to balance soil improvement with food safety.

Introduction

The management of Municipal Solid Waste (MSW) is one of the prominent challenges throughout the globe [1]. Factors like rising population density, socio-economic conditions, and local climate directly influence the generation and attributes of MSW [2]. The diminishing quantity of land in emerging countries is a serious fear that underlines the need for the management of waste [3]. Research in the field of waste management is encouraged in developed nations, and increased stakeholder accountability is a result of economic and technological advancements [4]. Insufficient handling of waste in emerging nations, including Cambodia [5], Thailand [6], and several countries from Southeast Asia, such as Bangladesh, India, and Pakistan [7], pose a

growing threat to public health. The primary emphasis lies on India's shift from being primarily agrarian to becoming a nation focused on the industrial and service sectors. As of February 2022, with several megacities and other cities with populations greater than one million, India is home to an estimated 1.40 billion people [8]. According to the Ministry of Housing and Urban Affairs, India produces over 50 million tons of MSW annually [9]. Solid waste production per person has increased dramatically from 0.26 kg per day to 0.85 kg per day as a result of cities' fast growth and rising emigration rates [10].

Landfills often lack suitable and cost-effective waste processing technologies, leading to unscientific dumping practices [11]. Inappropriate disposal of waste in non-regulated areas near urban centers has significant environmental impacts, including the emission of gases

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responsible for global warming [12,13] ultimately disrupting ecological balance [14]. India's efforts to manage the vast amounts of generated MSW are slow and insufficient [15].

In the area of waste management, composting emerged as a viable solution for handling organic waste to enhance its quality and environmental stability [16,17]. Nonetheless, the improper segregation of waste and incorrect composting practices can result in the production of low-grade compost, limiting its effectiveness as soil amendment [18]. Important micronutrients for plant growth, such as iron (Fe), copper (Cu), and zinc (Zn), as well as important macronutrients like nitrogen (N), potassium (K), and phosphorus (P), are provided by compost [19]. By improving soil aeration and water retention, adding decomposed organic matter to the soil improves its properties [20]. The making of Municipal Solid Waste Compost (MSWC) poses a significant challenge in its utilization for sustainable agricultural practices due to higher operational and maintenance costs compared to landfilling [21]. Despite the implementation of quality control standards in continents like South Asia, Europe, and North America, there remains a need to classify compost quality for various applications such as cultivating high-quality crops, soil conditioning, non-food fibre growth, and land restoration [22]. The application of MSWC to agricultural soil has shown potential for boosting crop productivity, both in traditional farming [23,24] and hydroponic systems [25]. However, concerns remain regarding the risk of trace metal (TM) concentration. To mitigate these risks and further enhance soil physicochemical properties and nutrient availability, the incorporation of inorganic and organic by-products, including animal and sewage sediments, as well as poultry manure has been proposed as a sustainable strategy for improving soil fertility and agricultural productivity. These results emphasize the importance of proper waste management and composting in promoting sustainable agriculture, while also highlighting the need for further research and robust guidelines to ensure the safe and effective use of compost across various applications.

It was observed that a variety of vegetables grown in cropland could experience positive effects from the application of MSWC [24,25,26]. A study on the use of MSWC supplemented with 92 kg N ha⁻¹ increased spinach fresh yield by up to 109 %, reaching 3.86 kg m⁻², comparable to conventional fertilization. The study also reported that soil organic matter increased from 1.1 % to 2.0 % in acidic soil, and pH increased from 5.5 to 7.3. Shoot uptake of key nutrients like N, P, and K also improved significantly, while Mn concentration was reduced by over 50 %, highlighting MSWC's effectiveness in enhancing soil health and crop productivity sustainably [27]. However, compared to MSWC-amended soil, a study on greenhouse grown spinach reported that the application of co-composted MSWBC containing 10 % pigeon pea biochar significantly reduced the concentrations of Cu, Cd, Pb, Cr, Ni, and Zn in spinach leaves by 20.62 %, 28.95 %, 36.02 %, 41.88 %, 41.50 %, and 41.23 %, respectively [28]. Moreover, significantly increased amounts of Cd, Zn, Cu, and Pb were found in edible parts of the vegetables with higher MSWC application rates (0 %, 20 %, 40 %, and 60 %) [29]. However, even at lower rates, the application of MSWC led to TM accumulation in the edible parts of the plants and exceeded permissible limits. It was also observed that spinach had a higher buildup of Pb and Cd compared to beans, and with increasing MSWC application rates, there was a substantial increase in leaf count, height, dry mass, and productivity for both beans and spinach [29].

Spinach, a popular green leafy vegetable crop grown in many areas, is scientifically known as *Spinacia oleracea* L., with substantial dietary benefits [30]. Its ability to thrive in cool weather with a short maturation period makes it a valuable vegetable [31]. The popularity of spinach is on the rise globally due to its exceptional nutritional qualities. Spinach can be eaten raw, boiled, in salads, or as an ingredient in blended dishes. China, the US, Turkey, and Japan produce 30.1 million tonnes of

spinach annually, with China producing 27.52 million tonnes (91 % of global production) [32]. Reduced in calories, spinach is high in flavonoids, proteins, minerals, and vitamins, as emphasized by numerous studies [33]. Amazingly, spinach is rich in iron, vitamins, lutein, folate, minerals, antioxidants, and different kinds of phenolic and carotenoid chemicals [34,35]. A fantastic way to improve overall health is by incorporating spinach into your diet. Sprouted leaves contain significant amounts of antioxidants that are essential for protecting cells against oxidative stress caused by free radicals [36]. Furthermore, a spinach-rich diet may offer potential benefits such as better management of blood glucose levels in individuals with diabetes, reduced susceptibility to cancer, and increased intake of essential minerals and vitamins.

Given its advantageous characteristics and widespread use in Indian cooking, Spinach was chosen as the subject for evaluating the impact of applying MSWC. Moreover, the study aimed to determine the most effective proportion of MSWC to urban soil for farming to reduce potential health hazards during the cultivation of this crop. Consequently, this investigation was carried out with the following objectives: (1) characterization of MSWCs generated in Delhi, (2) Introducing the categorization of compost quality according to its Fertilizing Index (FI) and Clean Index (CI), (3) assessment of TM contamination when MSWCs are incorporated in varying ratios with agricultural soil for safer application, (4) evaluation of the effect of diverse combinations of soil and MSWCs on the morphology and development pattern of spinach, and (5) the concentrations of TM in spinach for its safer consumption by humans.

Methodology

Collecting and preparing samples

The MSWC samples were obtained from two waste management companies in New Delhi, India, namely Delhi MSW Solutions Limited (DMSWSL) in the Bawana Industrial Area and IL&FS Environmental Infrastructure & Services Ltd. (IEISL) in Okhla.

Characterized samples, each weighing 100 g, were collected, ensuring thorough mixing, and then kept safely and properly labelled in sealed polythene bags. The samples were stored in the laboratory at a temperature of 4 °C for future analysis. Following this, they underwent ambient temperature dehydration before being homogenized and ground until they reached a fine texture suitable for passing through a sieve with a 2 mm mesh size. Subsampling of these processed samples was performed for future investigations.

Study design and treatment regime

The research was carried out at Amity University in Noida, India, by conducting experiments in clay pots with a volume of 8.23 L (diameter 8 in., height 10 in.). Soil samples were obtained from the university's organic farm and underwent thorough blending to remove dead leaves, plant clippings, and weeds before adding MSWCs. Compost samples were then integrated into the soil in proportions of 25 %, 50 %, and 75 % relative to the soil weight, with each mix replicated three times per pot (as detailed in [Supplementary data Table 1](#)). Pots without any MSWC addition were used as the control. Subsequently, all soil samples, including the controls, were analyzed using PI methods. Furthermore, compost samples were examined for FI and CI to observe variations in fertilization effect and TM content.

Analysis of samples

A hot air oven set at 40 °C was used to dry the collected compost, soil, and treatment samples. Additionally, the desiccated sections were

filtered by a 4 mm sieve using a sieve shaker for further investigation. Using a digital pH meter (Systronics, pH meter 361), the pH values of the soil, compost, and treatment samples were measured by preparing a combination of soil/compost plus water in a proportion of 1:2 (w/v), following the standard method [37]. Furthermore, a digital EC meter was utilized to measure electrical conductivity (EC). The amounts of nitrogen (N), phosphate (P), potassium (K), and organic carbon (OC) content were measured analytically. The OC was examined utilizing a standard approach [38]. After the samples had been completely digested, the total nitrogen (TN) content was calculated using concentrated H_2SO_4 and a catalyst mixture in a Kjeldahl flask. The Nitrogen concentration was then determined in the resulting digested solution using steam distillation and titration [39]. Total phosphorus (TP) and total potassium (TK) were estimated based on standard procedures [40,41].

To detect TMs (Cu, Cr, Pb, Ni, and Cd), all soil and compost sample treatments were dried at 105 °C and subsequently broken down using the triple acids method. The aqua regia + HF digestion method was engaged to assess the elemental substance in the treatments. Post completion of this procedure, the samples were subjected to treatment with a combination consisting of six milliliters Hydrochloric acid (HCl), two milliliters Hydrogen Fluoride (HF), and two milliliters of Nitric acid (HNO_3) [42]. Using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) technology, namely the Analytik Jena PQ 9000 model, TMs were estimated in the liquid samples. The IV-STOCK-4 TM standard, which was supplied by Inorganic Ventures, was used in the analysis. Initially, the equipment was used to examine multiple concentration standards for each metal to create a calibration curve. Using a comparable method, the concentration of the desired elements in all samples was evaluated to determine their unknown values.

Fertilization and pollution potential of MSWC

The evaluation of the basic features of compost derived from MSW can be conducted by utilizing fertilization and pollution potential as quantifiable parameters [22]. The standard values of the “weighing factor” for fertility and TM limits, along with the “score value” for compost samples are provided [43] (Supplementary data Tables 2 & 3).

Fertilizing Index

“The C:N ratio, NPK status” and carbon and respiration activity play an important role in determining the fertilizing potential of composts and their impact on soil productivity. These fertility factors are assessed based on both a “score value” and a “weighing factor” (Supplementary data Table 2). The FI for compost collected is computed with help of Equation (1), where “Si” represents the score value and “Wi” signifies the weighing factor assigned to each fertility parameter within the analytical data [22]. Higher index values indicate the compost’s significant capacity to effectively fertilize soil when applied appropriately. Therefore, both the compost samples were assessed for fertilizing potential.

$$FI = \frac{\left(\sum_{i=1}^{j-1} S_i W_i \right)}{\left(\sum_{i=1}^{j-1} W_i \right)} \quad (1)$$

Clean Index

Each analytical value of TM and every metal was assigned a score value and a weighing factor (Supplementary data Table 3). The CI for each composition was computed using equation (2), where S_j denotes the score value and W_j resembles the weighing factor of the j^{th} trace metal of analytical data. The higher value of CI denotes fewer TM components in compositions.

$$CI = \frac{\left(\sum_{j=1}^{n-1} S_j W_j \right)}{\left(\sum_{j=1}^{n-1} W_j \right)} \quad (2)$$

Methods for assessing pollution indices

The assessment of soil sample contamination levels and the methods used involved the application of different measures, such as the Pollution Index (PI), the Pollution Load Index (PLI), and the Enrichment Factor (EF) (Supplementary data Table 4) [44,45,46] and [47].

Pollution Index and pollution load Index

The PI and PLI in soil amended with MSWC were calculated using equations (3) and (4).

$$PI = \frac{C_{ems}}{C_{bgv}} \quad (3)$$

$$PLI = (PI_1 \times PI_2 \times PI_3 \times PI_4 \times \dots \times PI_n)^{1/n} \quad (4)$$

In this research context, the term C_{ems} signifies the metal concentration in the soil samples, measured in $mgkg^{-1}$. Meanwhile, C_{bgv} denotes the background value concentration, also measured in $mgkg^{-1}$. Additionally, n represents the number of TMs under consideration.

Enrichment factor

The EF for a particular TM was calculated by dividing its proportion to the normalizing element by the corresponding proportion identified in the selected baseline [48]. In general, reference metal concentration is commonly employed for normalization purposes. Iron (Fe) is predominantly chosen as the reference element due to its natural presence in soils and minimal interaction with other trace metals [49,50]. EF in soil and compositions is calculated using Equation (5) [51].

$$EF = \frac{\left(\frac{C_n}{C_{REF}} \right)}{\left(\frac{B_n}{B_{REF}} \right)} \quad (5)$$

C_n represents the observed concentration of TMs in soil, while C_{REF} stands for the reference element used for normalization in soil. B_n refers to the concentration of the TM under examination, and B_{REF} represents the background concentration of the reference TM. A higher EF value indicates a greater degree of enrichment and potential anthropogenic input.

The five identified categories of EF are discussed below [52,53] (Supplementary data Table 4).

Preparation of crops for pot experiments

The crop seeds were obtained from the National Seeds Corporation, Indian Agriculture Research Institute, Pusa, New Delhi, India. Spinach seeds were planted in pots during the winter months of December 2020 and December 2021. These pots were filled with various soil and MSWC mixtures.

Before sowing, the soil in the pots was carefully tilled to ensure thorough blending of MSWCs and to mitigate soil compaction and composting. The seeds were evenly spread in rows, with a spacing of approximately 7–8 cm, creating deep furrows, each containing 3–4 seeds. In instances where initial germination was insufficient, additional seeds were sown in January 2021 and 2022. Each pot accommodated four evenly distributed seedlings. Upon germination, all seedlings were closely monitored for their development patterns. Every morning, pots were watered, and meticulous care was taken to maintain the pots and observe crop growth throughout the experiment. The growth of Spinach plants was observed for 60 days. Additionally, crops were treated with neem oil spray to mitigate any potential fungal infections in the leaves [54]. Since no substantial differences in results were observed between the two years, the results from both years were combined or pooled together. Fig. 1 illustrates the experimental design employed for conducting the pot experiments.

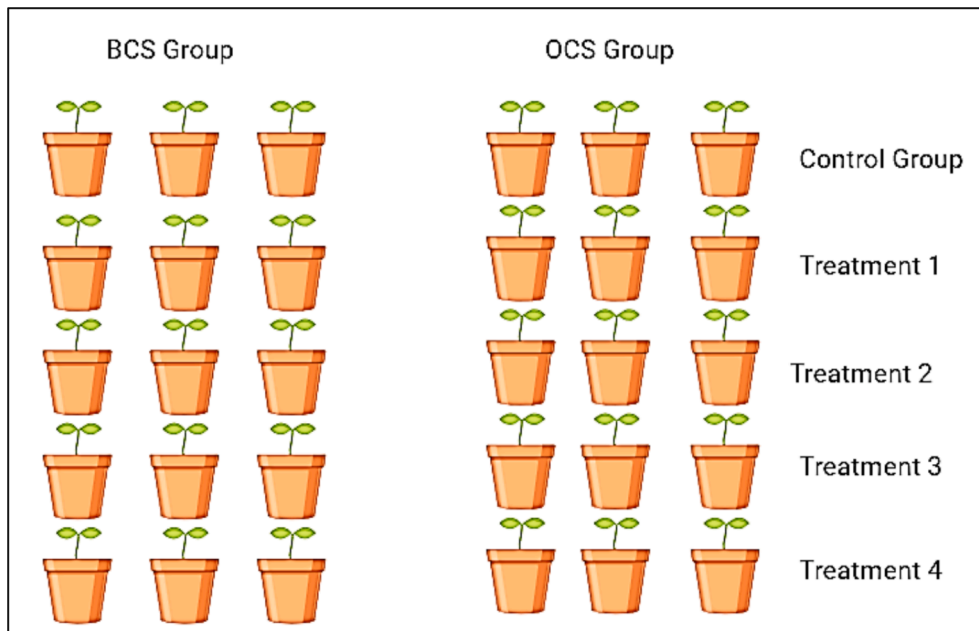


Fig. 1. Experimental design used for crop growth experiments.

Crop analysis

Plant health and yield assessment

The growth of crops under each treatment was carefully monitored, focusing on various morphological parameters. These included plant height (PH), leaf width and leaf length (LW and LL), leaf count per plant (LN), root length (RL), shoot fresh and dry weight (SFW and SDW), root dry and fresh weight (RDW and RFW), Relative Water Content (RWC), and yield. Visual observations were made to evaluate overall plant quality and growth.

LN was tallied every 15 days. LW and LL were measured using a Vernier caliper at 15-day intervals and post-harvesting, respectively. A vernier caliper was used to measure the PH and RL. Fresh weight (FW) was measured with a TLISMI TS500 standard analytical weighing scale. To determine Dry weight (DW), plant samples were dried for 24 h at 220–230 °C and 80 °C in a hot-air oven made by SISCO India. The growth performance of crop plants was monitored from germination through the phenological stages. PH was monitored from the vegetative stage to the fruiting stage (up to 13 weeks of growth), and productivity was evaluated based on fruit biomass after harvest.

Sampling of crops

After reaching maturity, the leaves and roots of each crop were harvested and carefully labelled. Each plant sample underwent a meticulous cleaning operation to eliminate any traces of dust particles. This involved giving them three tap water rinses before giving them a final rinse with distilled water. After that, the samples were dried in a hot-air oven set at 80 °C. Following drying, a blender was used to grind them into a fine powder. The resulting powder was run through a screen with a 2 mm mesh size. Following that, it was either kept for later use or subjected to further processing for chemical analysis.

Trace metal analysis of crops

A tri-acid combination was applied to digestion tubes that contained 0.5 g of dried vegetable sample (15 mL; 70 % HNO₃, 65 % HClO₄, and 70 % H₂SO₄ (5:1:1)) [55]. The tests were subjected to heating at 120 °C until they became transparent. Using Whatman No. 42 filter paper, the samples were filtered after cooling, and the filtrate was then diluted to make 50 mL using Distilled Water (DW). Subsequently, a similar procedure as discussed above was used to analyze the liquid samples for

TMs.

Computation of health risk

The probable health risks associated with consuming spinach cultivated in soil amended with MSWC were evaluated in humans using internationally recognized markers, i.e.,

- Bioconcentration factor (BCF),
- Daily trace metal intake (DMI), and
- Health Risk Index (HRI)

Estimating BCF

The BCF indicates the ratio of TMs found in the plant components to those in the soil. Accumulation of TMs within the roots and leaves of the plant was calculated using equations (6) and (7), respectively [56].

BCF for roots,

$$BCF = \frac{C_r}{C_{soil}} \quad (6)$$

BCF for the plant's leaves,

$$BCF = \frac{C_e}{C_{soil}} \quad (7)$$

In this equation, C_r and C_e denote the concentration of TMs in the roots and leaves of the crops being investigated, respectively, while C_{soil} represents the concentration of TMs in the soil used for plant growth.

Evaluating DMI

Equation (8) was used to calculate the DMI (mgkg⁻¹ day) of TMs for each spinach crop for each treatment.

$$DMI = \frac{DIV \cdot C}{BW} \quad (8)$$

In this case, “C” stands for the metal content, expressed in mgkg⁻¹, that is found in the edible vegetable parts.

For children and adults, the daily intake of vegetables (DIV) is 0.232 kg and 0.342 kg, respectively. The assumed body weight, denoted by “BW,” is 16.2 kg for children and 70 kg for adults [57].

Determining HRI

The HRI was evaluated to identify any potential health risks associated with eating TM-polluted vegetables, which were cultivated with different MSWC ratios. The ratio of the suggested oral dosage to the DMI was calculated using Equation (9).

$$HRI = \frac{DMI}{ROD} \quad (9)$$

Representing ROD as the recommended oral dose ($\text{mgkg}^{-1} \text{d}^{-1}$).

For the metals under study, namely Ni (0.02), Cd (0.001), Pb (0.004), Cr (1.5), and Cu (0.04), ROD was utilized (US EPA IRIS, 2011) [58].

Analytical statistics

Duncan's test, a one-way ANOVA, was employed to search for noteworthy alterations in the metal concentrations between the control and treatments of soil and compost. We used a significance level of $p < 0.05$ for these methods. Bar graphs and pie charts were used to display the data as arithmetic means with standard deviation. Microsoft Excel 2010 and IBM SPSS 23.0 were used for all statistical analyses. The figures are created using Origin Version 8.5 from OriginLab Corporation, Northampton, MA, USA.

Discussion

After conducting experiments, the collected data was examined, and the outcomes were interpreted and are described below.

Characterization of compost samples

The findings show an analysis of MSWC and its evaluation against the Fertilizer Control Order (FCO) standard established by the Ministry of Agriculture and Rural Development, Government of India. The compost samples were odorous and brown-colored (Table 1). The compost needs to maintain optimal levels of moisture and oxygen to prevent clumping caused by excessive moisture content. The average pH of the compost samples (8.36 & 8.21) was noted to be slightly alkaline. The research findings indicate that elevated pH levels were found to speed up the emission of ammonia gas from the compost piles. Moreover, the compost piles temperature rose as a result of microbial activity throughout the breakdown process. It was discovered that the composts' EC was below the FCO standard's permissible limit, and the average concentration of TOC for both samples was within acceptable limits. TN, TP, and TK concentrations were also within considerable limits. Furthermore, the C: N ratio for BCS (10.32) and OCS (13.09) was lower than the recommended value of maximum 20, contrary to the high C: N ratios found in a few cities across India according to the report by CPCB 2005.

According to the results, the concentrations of the TMs under investigation in BCS surpassed the permissible thresholds established by

FCO standards. Specifically, Cu, Pb, Cd, Cr, and Ni surpassed the standards by 32.6 %, 42 %, 40 %, 231.2 % and 86.4 %, respectively. Similarly, in OCS, Cu, Cr, Cd, Pb, and Ni exceeded the standard permissible values by 36 %, 250.4 %, 44 %, 37.3 %, and 97.2 %, respectively. The findings hold great importance and call for deeper examination and exploration within the framework of environmental and public health impacts. Results disclosed that OCS had higher average metal concentrations compared to BCS, except for Pb. Additionally, larger cities were found to have a higher volume of waste containing more metals compared to smaller city areas [59]. The existence of elevated levels of TMs in compost limits its appropriateness for use in agricultural settings. It was also noted that the impact of compost rich in TMs differs based on the kind of plant species and the condition of the soil [60].

Categorization of MSWC based on its market potential and utilization across various sectors, using CI and FI values is revealed in Supplementary data Table 5. MSWC is divided into classes A, B, C, and D, representing high-quality compost suitable for agricultural soil use in the market. Meanwhile, RU-1, 2, and 3 classes have limited applications and are commonly used as soil conditioners or for gardening purposes. Classes A and C, which possess the highest FI value, are suitable for high-value crops. Classes A and B, with the highest CI values, indicate lower levels of TMs and minimal environmental pollution impact. The FI value for BCS ranged from 4.20 to 4.73, with the CI value ranging from 1.50 to 1.85 (Fig. 2). Similarly, FI and CI values for OCS were identified ranging from 4.13 to 4.46 and 1.92 to 2.14, respectively. Despite showing signs of contamination potential (CI value < preferred value) due to increased TM concentrations, the results showed that the compost made in Delhi had a good fertilizing potential (FI value > 4) [21].

Characterization of the treatments

In Table 2, the analysis presents the characterization of soil before and after the application of MSWC, with a comparison to the standards set by Awasthi et al. [61], also mentioned by Selvi et al. [62]. Soil pH was observed to undergo slight changes due to the addition of MSWC, shifting from neutral to slightly basic with higher MSWC ratios. The EC showed a positive correlation with the increasing MSWC dosage, with the maximum EC observed in T3 compared to the control. Similarly, few studies observed the influence of EC following MSWC application [63]. The soil's OC content experienced a significant increase following the incorporation of MSWC, ranging from 2.22 (T1-O) to 11.25 (T3-O), indicating a direct correlation between MSWC addition and OC content. The addition of MSWC or organic manures is found to increase the macronutrients in the soil, as mentioned by number of studies [64]. As per our research, TN was positively influenced by the amendments, with the maximum increase observed in T3-O (1.42) compared to the control (0.17). TN increased gradually with the increasing MSWC ratio. Similarly, TP and TK showed a positive correlation with the MSWC ratio, with the highest enhancement observed in T3-B (0.85 and 1.55) compared to the control (0.18 and 1.14).

On the contrary, the TM presence in the soil increased post-MSWC amendments. The control soil has the detected metals within the Standard Permissible Limits (SPL), with the trend being $\text{Cd} < \text{Cr} < \text{Pb} < \text{Ni} < \text{Cu}$. The soil was observed to be rich in Cu, an essential micronutrient. Organic soils usually lack Cu or may have it in excess [65]. The local and regional geology is primarily responsible for the geographical distribution of copper (Cu) in soil [66]. Post-amendments, the metal concentration was significantly improved and was correlated with the MSWC applied ratio.

An increase in metal concentration was observed in soil with increasing doses of applied MSWCs, except for Ni, which exhibited no correlation with MSWC application. The distribution of TMs based on PI and PLI across different treatments revealed a moderate pollution load at the 25 % application rate and a high pollution load at the 75 % application rate. Pb showed significant enrichment compared to other TMs, with the highest EF value of 2.59 at 75 %. Therefore, MSWC

Table 1
Nutrient status and trace metal content (Mean $\pm$ S.D.) of the compost samples.

	BCS	OCS	FCO Standards
pH	8.36 $\pm$ 0.16	8.21 $\pm$ 0.09	6.5—7.5
EC (ds/m)	3.18 $\pm$ 0.07	3.25 $\pm$ 0.04	< 4.0
TOC (% DM)	14.5 $\pm$ 0.17	14.6 $\pm$ 0.1	$\geq$ 16
TN	1.32 $\pm$ 0.08	1.82 $\pm$ 0.02	$\geq$ 0.5
TP	1.61 $\pm$ 0.11	1.76 $\pm$ 0.15	$\geq$ 0.5
TK	0.91 $\pm$ 0.03	1.06 $\pm$ 0.05	$\geq$ 1
C/N	10.32 $\pm$ 0.08	13.09 $\pm$ 0.15	
Trace metals (mgkg^{-1} DM)			
Cu	398 $\pm$ 6	408.3 $\pm$ 6.39	$\leq$ 300
Cr	165.6 $\pm$ 3.48	175.2 $\pm$ 5.52	$\leq$ 50
Cd	6.98 $\pm$ 0.57	7.2 $\pm$ 0.77	$\leq$ 5
Pb	142 $\pm$ 6.78	137.3 $\pm$ 2.90	$\leq$ 100
Ni	93.2 $\pm$ 5.89	98.6 $\pm$ 5.61	$\leq$ 50

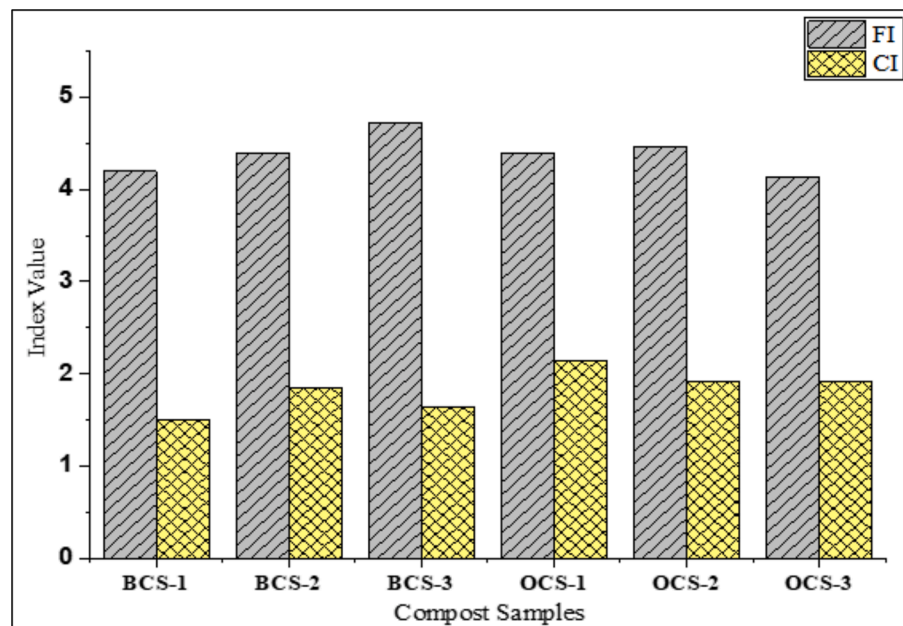


Fig. 2. FI and CI values of the studied MSWC samples.

Table 2

Nutrient status and trace metal contents (Mean $\pm$ SD) of the treatments.

Parameters	T0	T1-B	T1-O	T2-B	T2-O	T3-B	T3-O	Standards
pH	7.19 $\pm$ 0.06	7.33 $\pm$ 0.11	7.34 $\pm$ 0.09	7.36 $\pm$ 0.05	7.31 $\pm$ 0.03	7.12 $\pm$ 0.10	7.47 $\pm$ 0.05	
EC (ds/m)	0.10 $\pm$ 0.01	0.25 $\pm$ 0.03	0.27 $\pm$ 0.04	1.10 $\pm$ 0.10	1.3 $\pm$ 0.02	2.96 $\pm$ 0.18	2.31 $\pm$ 0.21	
TOC (% dm)	1.37 $\pm$ 0.04	3.42 $\pm$ 0.07	2.22 $\pm$ 0.03	8.9 $\pm$ 0.04	6.51 $\pm$ 0.03	10.36 $\pm$ 0.75	11.25 $\pm$ 0.07	
TN (% dm)	0.17 $\pm$ 0.04	1.16 $\pm$ 0.05	1.08 $\pm$ 0.16	1.36 $\pm$ 0.06	1.27 $\pm$ 0.04	1.4 $\pm$ 0.02	1.42 $\pm$ 0.04	
TP (% dm)	0.18 $\pm$ 0.02	0.32 $\pm$ 0.01	0.43 $\pm$ 0.04	0.57 $\pm$ 0.01	0.73 $\pm$ 0.02	0.85 $\pm$ 0.03	0.8	
TK (% dm)	1.14 $\pm$ 0.57	1.12 $\pm$ 0.01	1.21 $\pm$ 0.01	1.34 $\pm$ 0.03	1.35 $\pm$ 0.02	1.55 $\pm$ 0.02	1.54 $\pm$ 0.03	
Trace metals (mgkg ⁻¹ DM)								
Cu	146.4 $\pm$ 6.39	94.1 $\pm$ 3.57	125.6 $\pm$ 4.59	162.1 $\pm$ 3.4	152.2 $\pm$ 2.3	375.6 $\pm$ 4.01	386.4 $\pm$ 2.74	135-270 ^a
Cr	35.3 $\pm$ 6.88	43.7 $\pm$ 2.71	52.1 $\pm$ 2.42	85.6 $\pm$ 2.14	83.5 $\pm$ 3.56	98.9 $\pm$ 4.51	116.7 $\pm$ 3.60	NA
Cd	0.86 $\pm$ 0.01	2.97 $\pm$ 0.73	2.74 $\pm$ 0.44	4.11 $\pm$ 0.62	4.67 $\pm$ 0.56	5.56 $\pm$ 1.41	6.5 $\pm$ 0.34	3-6 ^a
Pb	57 $\pm$ 3.60	74.5 $\pm$ 4.88	87.6 $\pm$ 3.63	88.3 $\pm$ 2.76	105.1 $\pm$ 4.61	121.4 $\pm$ 9.21	115.6 $\pm$ 2.27	250-500 ^a
Ni	71 $\pm$ 2.54	76.3 $\pm$ 1.67	81.2 $\pm$ 2	103.2 $\pm$ 2	83.8 $\pm$ 2.11	86.5 $\pm$ 3.12	86.4 $\pm$ 3.52	75-150 ^a

Values are the mean of three replicates, ^aAwashthi [61].

application at the 25 % rate can be considered safer for agricultural practices.

It's been found that metal concentration was relatively higher in roots than in edible parts might be due to more exposure of roots to soil. Metal concentration in the edible fraction of crops grown with higher MSWC doses was identified and found to exceed the WHO permissible levels. Based on our study findings, it can be deduced that soil amendments containing 25 % or less than 50 % MSWC have effectively improved various soil physiochemical parameters, such as health, crop production, SFW, SDW, RFW, RDW, RWC, and RL. The growth of spinach was observed to be stimulated with increased PH, LN, etc., at higher MSWC dosages (T4-B and T4-O). Similarly, other morphological parameters and yield were significantly impacted at higher concentrations of MSWC in a consistent manner. Spinach exhibited maximum yield at higher MSWC concentrations (>75 %), possibly due to its nature as a hyperaccumulator plant. Nevertheless, it is not feasible to recommend the amendment with the lowest toxicity for crops. To ensure safe and optimal crop cultivation, it is imperative to conduct additional toxicity studies, including field-based investigations and comprehensive toxicological assessments. These studies will focus on TMs and Persistent Organic Pollutants (POPs) to identify the most suitable soil amendment using MSWC within the recommended HRI limits (<1). This thorough approach is crucial for the well-being of the environment and the success of agricultural endeavors.

The field experiments conducted over two years in Turkey where MSWC was applied at varying rates (0 to 200 t ha⁻¹) discovered that even though trace metal contents in the compost were within legal limits, higher application rates significantly increased soil concentrations of metals such as Cu, Zn, Ni, Cr, Cd, and Pb. It was found that overuse of MSWC, particularly at rates greater than 10 t ha⁻¹ in soils with a pH of ≥ 7 , may result in long-term trace metal risks [67]. In the present study, the soil was mainly contaminated with Cu, Cr and Cd after the MSWC application, with Cu concentration exceeding the SPL in T3-B and T3-O. Cu concentration exceeded by 39 % and 43 % in T3-B and T3-O, respectively, as compared to SPL. Similarly, Cr concentrations were observed to increase with the increasing dose of MSWC. Maximum Cr concentration was found in T3-O and T3-B (116.7 and 98.9 mgkg⁻¹ DM) and increased by 230 % and 180 % as evaluated to the control (35.3 mgkg⁻¹ DM). Cd concentrations in soil post-amendment with 75 % exceeded the SPL. 25 % and 50 % application of MSWC increased the Cd concentrations in soil but were within the SPL. Maximum Cd concentration was detected in T3-O (6.5 mgkg⁻¹ DM), which exceeded the SPL by 8.3 %. Contrarily, Pb and Ni concentrations were found to follow the increasing trend, but within the SPL, indicating no contamination. Maximum Pb (115.6 mgkg⁻¹ DM) and Ni (86.4 mgkg⁻¹ DM) concentrations were observed in T3-O as compared to T0. In relation to the control, Pb and Ni values rose by 103 % and 22 %, respectively. It is possible to draw the conclusion that OCS has more metal than BCS based

on the data.

However, a nine-year field experiment showed that MSW application increased microbial biomass C by up to 46 %, while Cow dung manure (MA) increased it by 29 %. Oxidoreductase enzyme activities (dehydrogenase and catalase) were significantly higher in MSW and MA treatments, indicating enhanced microbial metabolism. However, phosphatase and urease activities decreased, likely due to TMs in MSW, while β -glucosidase and protease-BAA increased, especially in MA-treated soils [68]. Another long-term of seven-year application of MSWC, along with sewage sludge (SS) and farmyard manure, significantly increased soil organic carbon (SOC), reduced bulk density (BD), and improved soil consistency limits, enhancing tillage and traffic conditions. Higher manure application rates (up to 100 Mg ha⁻¹) led to the most favorable soil properties, with SS showing the greatest improvement. The study found strong linear relationships between SOC and soil plasticity indices, highlighting the role of organic amendments in improving soil workability in arid regions [69]. Though there is limited long term study on use of MSWC and its impact on soil and the environment, however, it is always imperative to curtail the risk by segregating the waste before composting, especially segregation at the source.

Pollution status of the soil after the amendments

The PI and PLI are commonly utilized in the evaluation of soil contamination caused by TMs [70,71]. The regular PI value of the treatments in comparison to non-amended soil is mentioned in Table 3. The PI values for Cu, Cr, Pb, Cd, and Ni in the treatments varied from 2.59 to 6.83, 0.30 to 1.02, 4.35 to 8.82, 2.46 to 18.57, and 2.56 to 3.11, respectively. With an increasing MSWC ratio, the average values of the metals (PI) were observed to increase, surpassing 1. This suggests a heightened level of soil contamination [71]. Additionally, Fig. 3 illustrates the PLI values and classification of the studied soils following the application of multiple dosages.

The PLI of the unamended or control soil was 1.85, suggesting that the soil was either unpolluted or had a moderate pollution load (Fig. 3). Conversely, after amendment with an increasing MSWC ratio, the PLI ranged from 2.43 to 5.13. A 25 % MSWC amendment indicated a moderate pollution load, while 50 % showed a moderate to high pollution load. Moreover, the amendment with 75 % was found to have a high pollution load (BCS) and a very high pollution load (OCS). The PLI of the amended soils was 31 % to 177 % higher than the control.

In the measurement of the precise stage of soil input from manmade sources, the EF is frequently employed [46]. Table 3 provides a summary of the computed EF values of TMs in different MSWC amendments. The unamended soil had average EF values of 0.23, 0.01, 1.74, 0.00, and 2.56 for Cr, Cu, Cd, Pb, and Ni, respectively. Post-amendments with MSWCs, Ni, Cd, Cr, and Cu EF in the soil indicated no enhancement, with values ranging from 0.23 to 0.40, 0.01 to 0.02, 0.00, and 0.51 to 0.61, respectively (Fig. 4). Conversely, in the case of Pb, the EF ranged from 1.74 to 2.23, signifying a moderate enrichment of the soil.

Based on the findings, specific locations in India may not be universally applicable due to variations in waste management practices, soil types, and climate conditions across different regions. For instance, regions with more advanced waste segregation and composting technologies may have lower contamination levels in the compost, reducing

the risks associated with TM accumulation [72]. Similarly, soil types with better buffering capacities or organic matter content may exhibit different responses to MSWC application [73]. The climate of a region can also influence the degradation rate of compost, which may affect the bioavailability of contaminants. Therefore, to determine the broader applicability of these results, further research in diverse geographical regions with varying waste management practices and soil conditions is required which would help establish more generalized guidelines for the safe use of MSWC in agriculture.

Correlation matrix

The dimension of similarities and the interdependence of the investigated elements are both known and evaluated using Pearson's correlation matrix (Table 4). As listed in the correlation matrix, all the metals (Cu, Cr, Pb, Cd) are found to be considerably concurrent ($p < 0.01$) by the concentration of MSWC applied, except Ni. Ni was observed to be significantly correlated ($p < 0.05$) with MSWC concentration. On the other hand, metals were detected and correlated with each other. Cu was significantly ($p < 0.01$) correlated with Cr, Cd, and Pb in the treatments. MSWCs were not shown to have a negative impact on metal concentration. The information showed that there was no meaningful relationship between the metals and Ni at $p < 0.01$ and $p < 0.05$ levels.

Crop analysis

Morphological response of crops to the treatments

It is well known that compost can improve plant health by changing the soil's composition and the microbial action, thereby improving mineral absorption [75]. The PH, LN, LW and LL are apparent indicators of plant development. The results from both treatment groups with MSWCs indicated a dose-dependent enhancement in the physical attributes of the plants in relation to the unamended treatment group (T0) (Fig. 5).

All the morphological parameters in spinach were found to be improved with the increase rate of MSWC when correlated with the unamended treatment group (T0). High MSWC treatments helped the maximum PH considerably ($p < 0.05$), increasing by 61.6 % and 64.6 % in T4-B (35.2 cm) and T4-O (35.9 cm), respectively, compared to unamended soil, i.e. T0 (21.8 cm). Maximum LL was observed in T4-B (15.8 cm) and T4-O (16.5 cm) and increased by 31.5 % and 37.1 %. The LW was increased considerably ($p < 0.05$) with an increased dosage of MSWC by 60.2 % in T4-B (8.36 cm) and by 62.1 % in T4-O (8.5 cm) as judged against T0 (5.2 cm). In addition to this, at the highest applied rate, the greatest number of leaves was discovered. LN was 33.7 % and 32.4 % more in T4-B and T4-O in relation to unamended soil, i.e. T0. The trend followed by each parameter was T0 < T1 < T2 < T3 < T4, indicating that spinach growth is favored by MSWC application. The morphology of plants has allegedly been enhanced in similar cases. It has been revealed that morphological traits of the pistachio (*Pistacia vera* L.) seedlings improved, with an increased number of leaves and leaf surface area, when the soil was treated with MSWC [76]. With this, it was found that adding MSWC significantly increased spinach yield and improved its physical characteristics [27].

Table 3
Pollution indices (EF, enrichment factor; PI, pollution index) of trace metals in different treatments.

TMs	T0		T1-B		T1-O		T2-B		T2-O		T3-B		T3-O	
	PI	EF	PI	EF	PI	EF	PI	EF	PI	EF	PI	EF	PI	EF
Cu	2.59	0.23	1.66	0.14	2.22	0.18	2.86	0.22	2.69	0.20	6.64	0.43	6.83	0.40
Cr	0.30	0.01	0.38	0.01	0.45	0.01	0.75	0.02	0.73	0.02	0.86	0.02	1.02	0.02
Pb	4.35	1.74	5.68	2.10	6.68	2.39	6.74	2.21	8.02	2.54	9.26	2.59	8.82	2.23
Cd	2.46	0.00	8.48	0.001	7.82	0.001	11.74	0.001	13.34	0.001	15.88	0.001	18.57	0.00
Ni	2.56	0.51	2.75	0.50	2.93	0.52	3.72	0.61	3.02	0.47	3.12	0.43	3.11	0.39

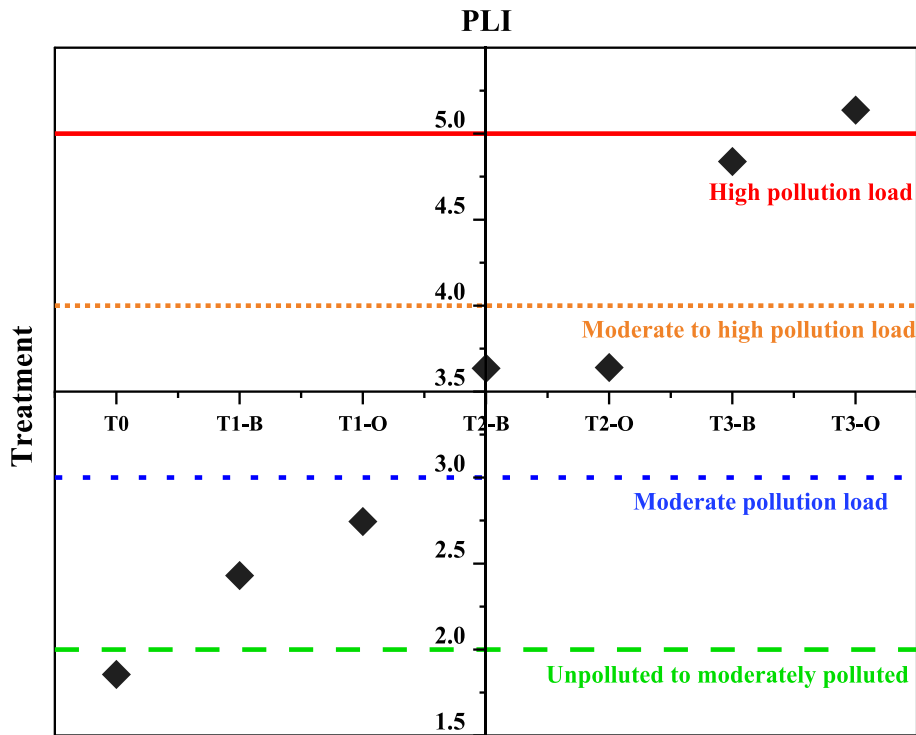


Fig. 3. Classification and distribution of pollution load index under different treatments.

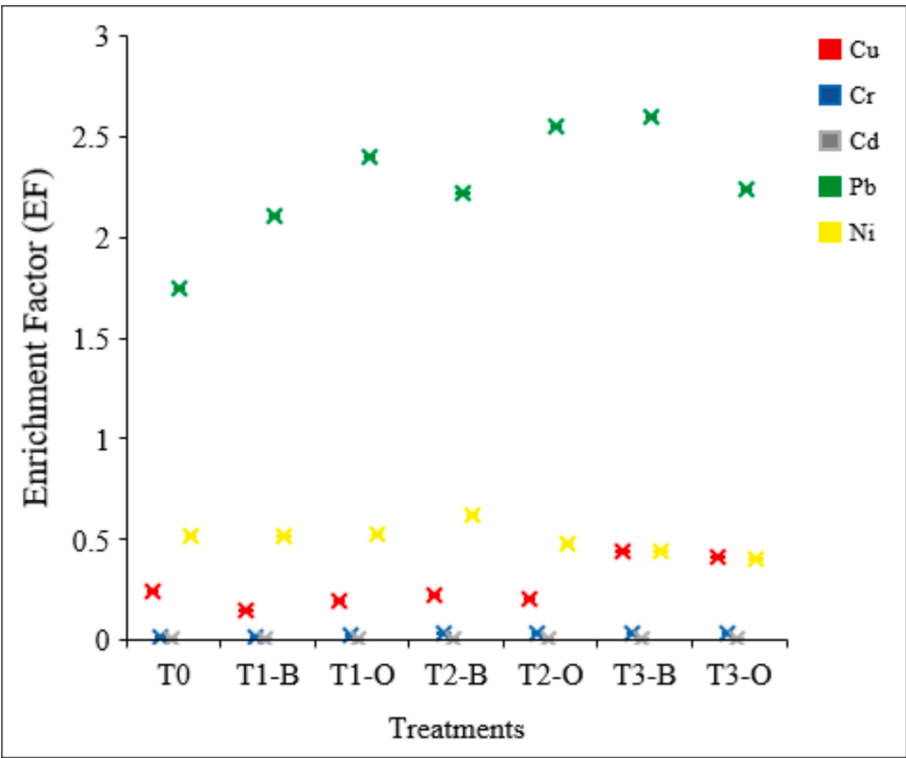


Fig. 4. Box plot displaying the distributions of the different trace metals and respective EF in different treatments.

Yield of crop

There was a significant positive correlation between the amount of MSWC applied and the yield of spinach, with highest yield observed at 100 % MSWC application in T4-B and T4-O, resulting in a 40.2 % and 42 % increase in yield compared to the control (40.1 g) (Fig. 6).

Fresh weight and dry weight

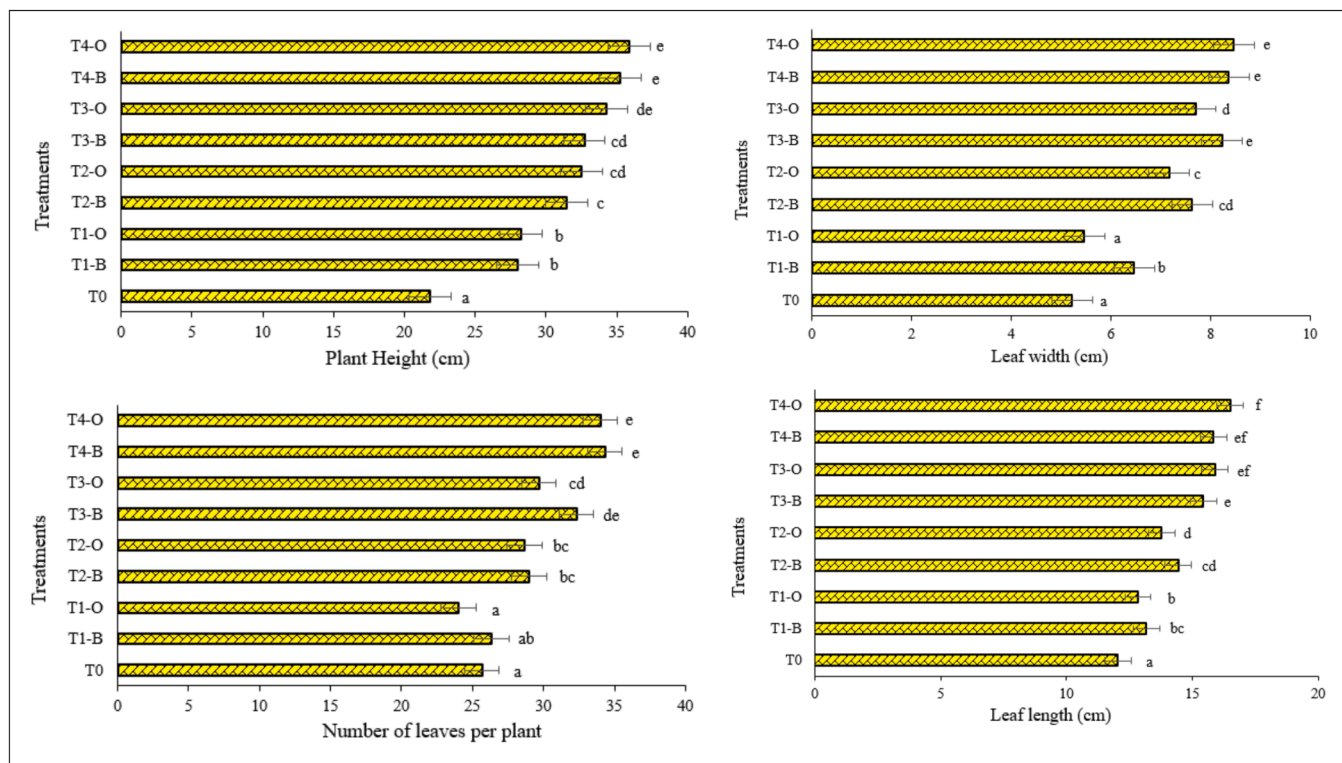
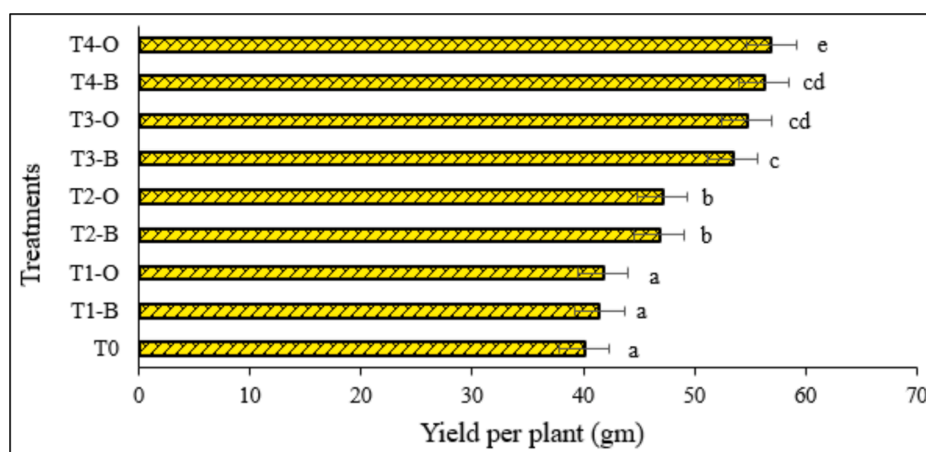
Through the application of MSWC, a remarkable improvement together in the SFW and SDW of spinach was observed, with the highest values notably achieved in T4. Specifically, the maximum fresh weight increased by 22.6 % and 28.3 % in T4-B (33.6 g) and T4-O (35.1 g), considerably, compared to the T0, i.e. control (27.4 g). Similarly, dry

Table 4

Pearson's correlations matrix for the MSWC concentration and trace metals [74].

	MSWC concentration	Cu	Cr	Pb	Cd	Ni
MSWC concentration	1					
Cu	0.815**	1				
Cr	0.961**	0.823**	1			
Pb	0.934**	0.769**	0.886**	1		
Cd	0.934**	0.740**	0.910**	0.861**	1	
Ni	0.531*	0.217	0.549*	0.374	0.420	1

**Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

**Fig. 5.** Morphological parameters encompass (a) plant height, (b) leaf count, (c) leaf width, and leaf length of spinach at the harvesting stage when subjected to various concentrations of MSWC. Significant differences between means are denoted by distinct letters at a significance level of $p < 0.05$. Each bar represents the mean value derived from three replicates, with error bars indicating the standard deviation.**Fig. 6.** Yield of spinach at the harvesting stage when subjected to various concentrations of MSWC. Significant differences between means are denoted by distinct letters at a significance level of $p < 0.05$. Each bar represents the mean value derived from three replicates, with error bars indicating the standard deviation.

weight was enhanced by 50 % and 33.6 % in T4-B (14.1 g) and T3-O (12.6 g) to the unamended soil, i.e., T0 (9.4 g). Notably, there was no decrease in fresh weight and dry weight when spinach was grown in MSWC-amended soils (Fig. 7).

The levels of applied MSWC had a positive influence on both RFW and RDW, with increased dosages of MSWC resulting in higher RFW and RDW. The highest RFW and RDW were observed within T4-B and T4-O. Specifically, RFW increased by 51 % and 44.8 % in T4-B (7.7 g) and T4-O (7.4 g) compared to T0 (5.1 g). Similarly, RDW increased by 98 % and 102 % in T4-B and T4-O when matched up to T0 (Fig. 7).

Root length

Spinach exhibited substantial ($p < 0.05$) enhancements in RL in a manner dependent on the dose. It rose as the application of MSWC increased. The maximum increase in RL was observed in T4-B (9.1 cm) and T4-O (9.2 cm) by 58 % plus 59.1 %, respectively, in relation to the unamended soil, i.e., T0 (5.8 cm). In each treatment, there was a remarkable enhancement in RL compared to the control group, showcasing a substantial impact of the interventions (Fig. 8).

Relative water content (%)

Composting greatly improves the mineral content and soil structure, both of which are favorable to plant growth. This process also enables the soil to retain moisture for longer periods, as compost can hold two to six times the volume of water, preventing wastage. Moreover, composting promotes soil porosity and facilitates improved air circulation in soils. Spinach RWC significantly increased as a result of the use of MSWC, with the highest observed RWC in T4-B (83.5 %) and T4-O (82.19 %), representing a substantial increase compared to the control, T0 (67.9 %) (Fig. 8).

Crops grown in the treatments and their available TM content

The utilization of organic amendments has shown promising results

in enhancing the productivity and quality of crops. However, the potential escalation of the absorption of detrimental metals by spinach grown in soil treated with organic fertilizers presents a significant concern [77]. The outcomes of the research indicated that crops grown in soils supplemented with MSWC exhibited higher concentrations of metals, as illustrated in Fig. 9. Notably, the absorption of TMs was observed to be elevated in the roots of plants compared to their shoot. In all treatments, the roots consistently demonstrated elevated levels of TMs when compared to the Spinach leaves. In T1-B and T1-O, i.e. 25 % MSWC treatment, the concentrations of Cu in the crops' edible portions were still below the SPL, suggesting that there was minimal Cu buildup at this rate; nevertheless, as the dosages were raised, the concentrations of Cu rose.

For spinach, both the edible portions and roots exceeded the SPL for Cr, with the concentration escalating as the MSWC concentration increased. In treatment T4-O, the roots of spinach exhibited the highest levels of Cr at 100.2 mgkg^{-1} , whereas the leaves showed values of 80.6 mgkg^{-1} . However, Cu accumulation remained within threshold limits up to a 75 % MSWC rate in edible parts. Conversely, Cu concentration surpassed the SPL in roots even at a 50 % MSWC rate. The maximum Cu concentration was observed in T4-B and T4-O, reaching 68.2 mgkg^{-1} in roots and 52.1 mgkg^{-1} in leaves in T4-O. On the other hand, Ni accumulation in leaves and roots increased with the applied rate and exceeded the SPL at a 100 % MSWC dosage, with the highest Ni accumulation found in T4-O leaves (68.2 mgkg^{-1}).

The amendment of MSWC increased the levels of Pb in spinach. This increase was dependent on the amount of MSWC used and was higher than the recommended levels (SPL) in both the roots and the edible parts, even when a lower amount of MSWC (25 %) was used. Pb levels remained within acceptable limits only in plants grown in control soil. Even at a low MSWC dose (25 %), spinach leaves accumulated 21.3 mgkg^{-1} and 25.6 mgkg^{-1} in T1-B and T1-O, respectively. Similarly, Cd accumulation in spinach was more pronounced even at low MSWC levels (25 %), increasing with higher MSWC application rates. Cd levels

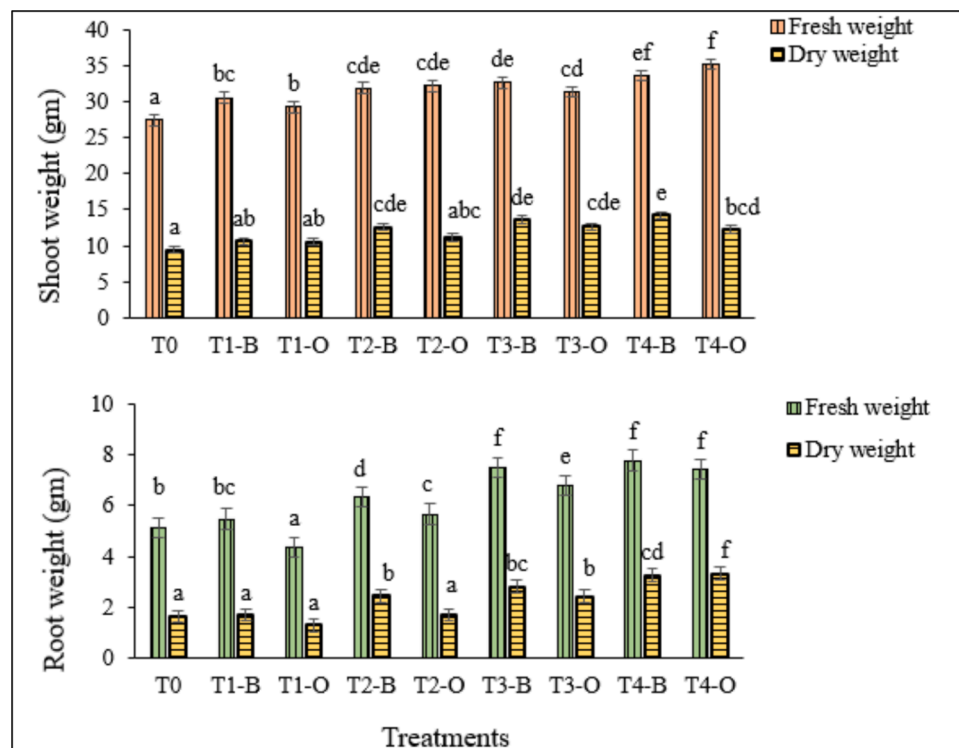


Fig. 7. Modifications in the fresh weight and dry weight of spinach shoots and roots were found during the harvesting stage when subjected to varying concentrations of MSWC. Means with distinct letters are statistically significant at a significance level of $p < 0.05$. The mean of three replicates is represented by each bar, while the error bars reflect the standard deviation.

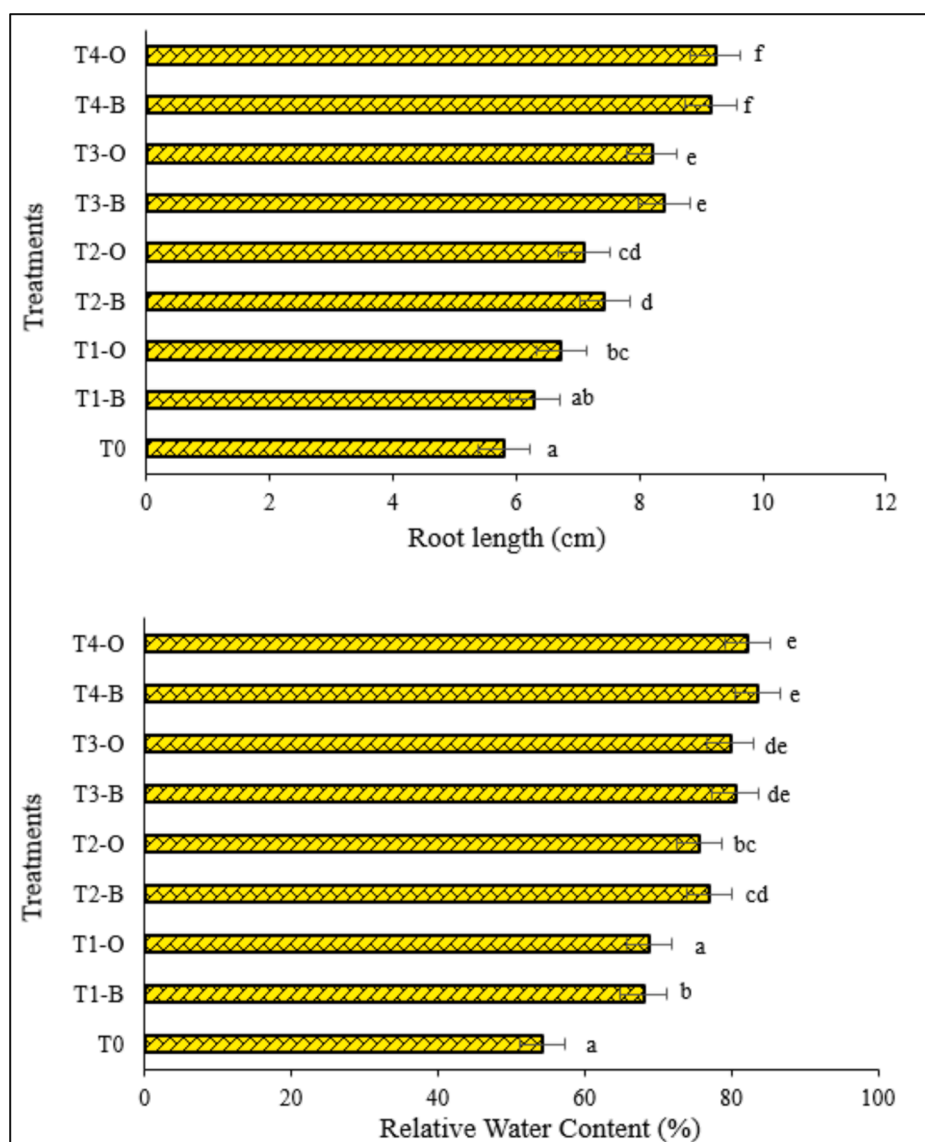


Fig. 8. Root length and Relative Water Content (RWC) of crops were measured at the harvesting stage after exposure to various amounts of Municipal Solid Waste Compost (MSWC). Means with distinct letters are statistically significant at a significance level of $p < 0.05$. Each bar corresponds to the average value of three repeated measurements, while the error bars indicate the standard deviation.

remained within acceptable limits only in plants grown in control soil, with spinach leaves accumulating 0.513 mgkg^{-1} and 0.612 mgkg^{-1} in 25 % MSWC (T1-B and T1-O), respectively.

Furthermore, multiple investigations on the application of MSWC have demonstrated an enhanced absorption of metals by crops. In a recent comprehensive study, it was demonstrated that the Potato (*Solanum tuberosum* L.) tubers have increased TM levels when treated with MSWC as a soil conditioner. The author disclosed that the amounts of Pb, Cr, and Ni in tubers exhibited a progressive rise using the addition of MSWC, reaching values of up to $3\text{--}6 \text{ mgkg}^{-1}$, $15\text{--}20 \text{ mgkg}^{-1}$, and $12\text{--}20 \text{ mgkg}^{-1}$, respectively [78]. In contrast, the levels of TMs in Faba bean grains fell considerably as MSWC was provided [79]. Our study concludes that there is a correlation between greater MSWC dosages and increased metal concentration in soil.

Typically, plants grown in pots exhibit higher metal accumulation compared to those cultivated in fields. This difference can be attributed to the confined environment of pots, including limitations in soil volume and space, leading to greater exposure of plant roots to soil amendments. This elevated exposure is believed to be a vital factor to the higher level of metals found in crops. In a previous study, it was found that willows cultivated in pots showed higher levels of Pb accumulation compared to crops cultivated in fields [80]. Although crops with increased TM status have less visible phytotoxicity consequences like Pb and Cd, these metals may still pose potential dangers in the food chain as they can be easily absorbed by people upon consumption.

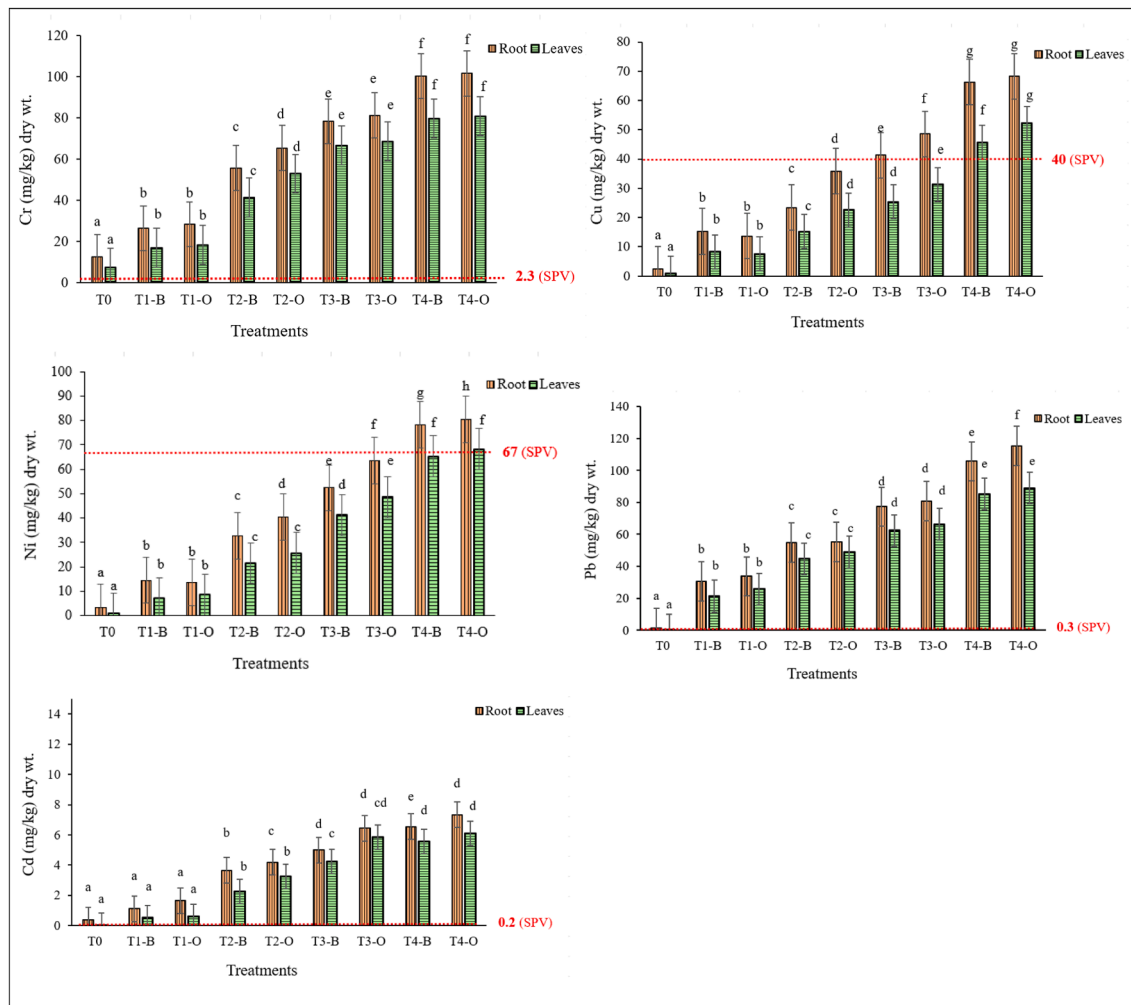


Fig. 9. The metal concentrations in the roots and leaves of spinach at various MSWC concentrations (mg kg^{-1} dry weight).

Hazards to human health linked to the ingestion of HMs-Contaminated crops

The ingestion of TM-contaminated crops poses severe health risks as these toxic elements tend to bioaccumulate in human tissues over time. Chronic exposure to trace metals such as Pb, Cd, and As through food consumption can lead to neurological disorders, kidney damage, and even carcinogenic effects. These metals interfere with essential biological processes by replacing vital nutrients in enzymes and proteins, disrupting metabolism and causing organ dysfunction. HRI, an extensively researched metric that carefully considers the BCF and the DMI, unequivocally indicates the transfer of metals to the consumable parts of crops.

Bioaccumulation potential of TMs

The Bioconcentration Factors (BCFs) of Cr and Cu consistently remained below 1 in each treatment, indicating a minimal accumulation of these metals by the crops. However, for Pb, Ni, and Cd, the BCF values exceeded 1 at higher MSWC levels (i.e., 75 %). Application rates of MSWC were found to correlate with an increase in the accumulation of these three metals in the crops, exceeding 50 %. Fig. 10 shows the BCF

values for both roots and leaves. The BCFs below 1 for edible sections suggest that the buildup of Cr, Cu, and Ni in these parts is not substantial. Understanding the ecological and environmental consequences of the accumulation of Cr, Cu, Ni, Pb, and Cd relies on a comprehensive assessment of their presence and mobility. The levels of Cd and Pb within spinach exhibited a compelling correlation with elevated levels of MSWC.

Daily metal intake

Consuming the analyzed crops produced at > 25 % MSWC has been shown to significantly lower human DMI and may pose a risk to adult and pediatric health (Fig. 11). Children are particularly more exposed to TMs when they consume vegetables grown at a rate of more than 25 % MSWC due to their higher DMI. Due to their lower body weight (16.2 kg) than adults (70 kg), children have greater DMI levels [81]. The research highlights that crops may pose health concerns even when their DMI levels fall within the threshold. The threshold values (0.046) were found to be exceeded by the DMI for Cd above 25 % MSWC, while Pb's DMI rose beyond the permissible limit, and Cu's DMI was consistently below the limits for crops in all treatments.

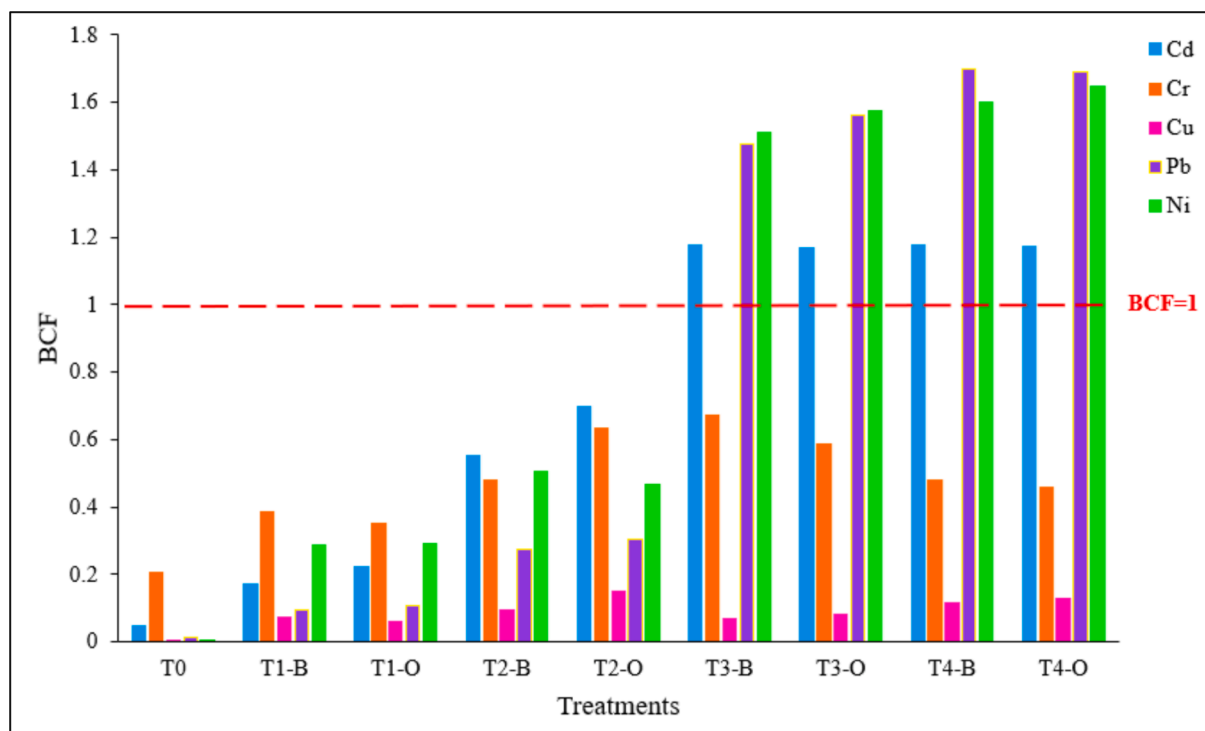


Fig. 10. BCF of associated metals in spinach leaves under different MSWC concentrations.

Health risk Index (HRI)

HRI analysis indicates that a concerning health threat will be experienced by the local population if the HRI is greater than or equal to 1. The HRI values of crops cultivated in the control and treatment groups were compared in Fig. 12. Both children's and adults' HRI levels in the control groups were below the safe limits. However, Pb, Cu, Cd, and Ni HRI values were still superior to 1 even when administered at a 25 % MSWC dosage. It is crucial to determine the suitable MSWC ratio (<25 %) that does not pose any health risks for usage in modifications.

A similar study on Kernels grown on plots altered with 4 t ha⁻¹ of MSWC had increased HRI values, which may put children at non-carcinogenic risk [82].

Conclusions

The present study suggests that lower concentrations of MSWCs can enhance soil parameters and crop growth, while higher concentrations may lead to increased metal concentrations in edible parts of crops, potentially exceeding permissible levels set by the World Health Organization (WHO).

The purpose of the current study was to assess the value of compost made from MSW, its potential impact on soil contamination, as well as to show how different treatment rates affect crop and soil factors. The Clean Index (CI), Fertilizing Index (FI) of MSWCs, and the Pollution Load Index (PLI), Pollution Index (PI), and Enrichment Factor (EF) of soil

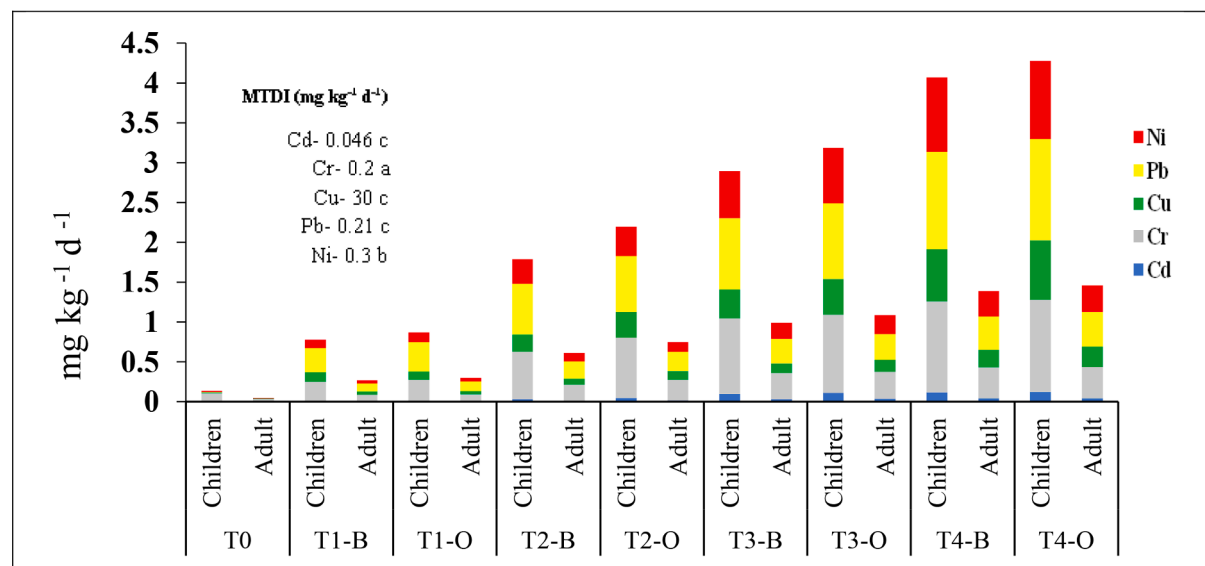


Fig. 11. Predicted daily intake of trace metals in humans of different ages via consumption of spinach ($\text{mg kg}^{-1} \text{ d}^{-1}$) under different amendments.^aRDA, 1989; ^bWHO, 1996; ^cJECFA, 2003; MTDI—maximum tolerable daily intake.

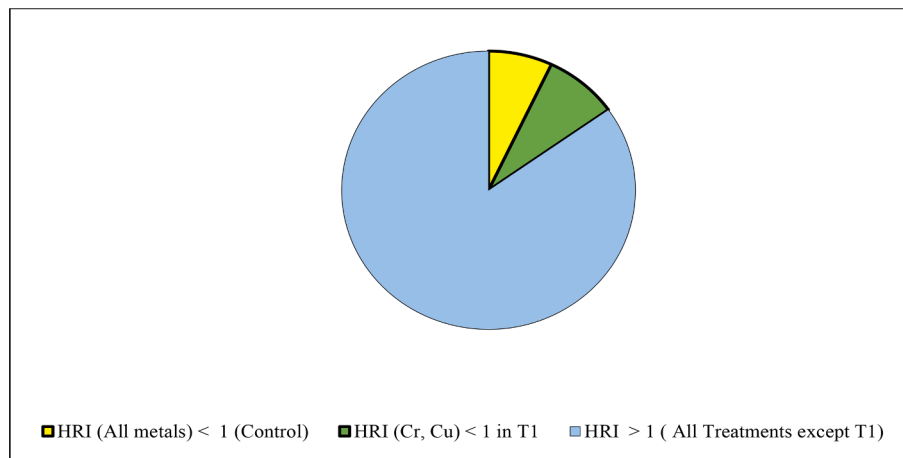


Fig. 12. HRI values linked with studied metals for the spinach crops grown in MSWC amendments.

amended with MSWCs were assessed to gain deeper insights into the quality of compost and the level of TM contamination caused by its use.

This classification system also helps determine the necessary treatment amount before using the compost for different applications. The FI values of MSWCs studied in the current study were within the permissible standards, whereas the lower CI value indicates MSWCs polluted with TMs. The MSWCs produced at Delhi's Waste-to-Energy (WtE) plants had FI values that complied with quality control norms, but their CI values were far lower—possibly because the compost included too many TMs. TMs, primarily from electrical waste, can infiltrate the compost when non-segregated waste is composted in compost plants, leading to elevated concentrations of TMs in the resulting compost. Cr, Cu, Pb, Cd, and Ni in MSWCs were found to exceed acceptable limits set by regulations. Additionally, the Okhla Compost Sample exhibited higher contamination levels compared to the Bawana Compost Sample.

CRediT authorship contribution statement

Pallavi Bhardwaj: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Abhishek Chauhan:** Resources. **Anuj Ranjan:** Writing – review & editing, Supervision, Software. **Vishnu D. Rajput:** Supervision. **Usha Mina:** Supervision. **Naveen Chandra Joshi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Laurent Dufossé:** Writing – review & editing, Validation, Supervision, Methodology. **Ashutosh Tripathi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cacint.2025.100207>.

Data availability

Data will be made available on request.

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Further reading

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