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ASSESSMENT OF UFMSW AS A SOIL AMENDMENT: EFFECTS ON PLANT DEVELOPMENT

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Municipal solid waste management faces challenges in handling the undersized fine fraction, which is typically landfilled due to its heterogeneous composition. Unlike source-separated organic waste, undersized fraction of municipal solid waste (UFMSW) from mixed household waste streams contains both organic and inorganic material, limiting its suitability for conventional composting. Increasing restrictions on landfilling demand alternative valorization routes. Owing to its high organic content, the incorporation of UFMSW into soil or planting media is promising, yet its complex composition necessitates the evaluation of its effects on plant growth and contaminant uptake. This study assessed soil properties, plant performance and heavy metal accumulation using UFMSW-treated (20–100% w/w) potting soil. UFMSW was pre-stabilized over 4 weeks beforehand and consisted of particle sizes <4.5 mm in diameter. Garden cress (*Lepidium sativum*) was used for germination tests and marigold (*Tagetes erecta*) for growth as well as uptake studies. Higher UFMSW contents (B60–B100) caused sharp increases in COD, BOD, conductivity and TDS, indicating high organic loads and salinity stress. *L. sativum* germination declined as the concentration increased, showing complete inhibition at ≥B60. In contrast, *T. erecta* at B20 exhibited enhanced growth in terms of its leaves, branches, reproductive structures and the diameter of its stem without notable metal accumulation. No plants survived when treated with B40–B100 due to severe dehydration. These findings highlight that while high UFMSW levels are phytotoxic, low-level amendments (20%) can enhance growth without increasing metal uptake, supporting targeted waste valorization strategies.

Keywords: UFMSW, *Tagetes erecta*, waste valorization, plant test, climatic chamber

1. Introduction

Municipal solid waste (MSW) management faces the significant global challenge of effectively handling the undersized fine fraction, which is often disposed of in landfills [1]. Despite its widespread use, landfilling remains the least preferred waste management option due to severe environmental implications, including groundwater, river and lake contamination from leachate [2]; air pollution from gaseous emissions mostly consisting of methane and carbon dioxide [3]; as well as broader ecological impacts [1], health hazards [4] in addition to fire and explosion risks [5]. Consequently, increasing regulatory pressure is being applied by, for example, the EU Landfill Directive [6] to reduce the reliance on landfilling and explore alternative valorization pathways for these complex waste streams.

Undersized fraction of municipal solid waste (UFMSW) is derived from mixed household waste streams subjected to the Mechanical-Biological Treatment (MBT) technology [7] and is defined as the particle fraction less than 80 mm in diameter. Other studies indicate that these fractions constitute a massive proportion (50-70%) [8] of municipal solid waste (MSW), depending on different factors such as consumption habits and socio-economic background [9]-[11].

Unlike source-segregated organic waste, its heterogeneous composition, including organic and inorganic components such as paper, plastic, wood chips as well as sanitary products [12] generally renders it unsuitable for conventional composting [13]. After preliminary stabilisation, this material is commonly used for landfill coverings or is directly landfilled.

In the literature, studies often focus on composts from source-segregated organic materials, examining their varied effects on plant growth and soil properties, which can range from enhancing the yield [14], soil nutrient content [15]-[16] and water-holding capacity [17] to impeding growth due to salinity or heavy metal stress [18]. Besides, the aerobic route for organic fractions can be subjected to anaerobic digestion and recover energy from the process [19]. Some studies have investigated pulverized refuse fines, a material somewhat analogous to UFMSW [20], and provided general insights into the characteristics of fine MSW [21]-[23]. However, detailed investigations specifically focusing on the physical and chemical properties of stabilized UFMSW below 4.5 mm or 5.0 mm derived from mixed

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municipal solid waste streams in the context of its use as an agricultural soil treatment remain limited. This study aims to fill this critical gap by directly addressing the application of stabilized UFMSW obtained from mixed waste streams, rather than focusing predominantly on fully composted, source-segregated or broadly defined MSW-derived materials. Through a unique and integrated methodology, this research provides novel insights into the agricultural viability and potential phytotoxicity of stabilized UFMSW, thereby bridging the current gap between waste valorization and environmental safety.

2. Experimental

2.1. UFMSW sample collection and preparation

The undersized fraction of municipal solid waste with particle sizes of less than 60 mm in diameter was obtained from the Kökény Waste Management Centre operated by Dél-Kom Nonprofit Kft. This facility manages approximately 150,000 tons of waste annually from 319 settlements, employing selective waste separation, Mechanical-Biological Treatment of MSW, garden waste composting and landfilling. The UFMSW is generated during the MBT process, where incoming MSW is shredded to <350 mm while PVC and ferromagnetic metals are removed before being trommel-screened to separate the fraction <60 mm. After collecting the sample, this sample less than 60 mm was stabilized for up to four weeks under natural temperature conditions, mixed on a weekly basis and protected from the rain in a container. Having been stabilized, the sample was sieved through a 4.5 mm hand sieve.

The experimental planting media were formulated by thoroughly mixing pretreated UFMSW with commercial potting soil (Garri, OBI GmbH, Veszprém, Hungary) using a paddle mixer drill attachment. Five mixtures with UFMSW concentrations of 20, 40, 60, 80 and 100% (w/w) were prepared.

2.2. Germination Assay

Seed germination assays were conducted using Garden Cress (*Lepidium sativum)* (Rédei Kertimag Zrt., Réde, Hungary) in germination pots containing the prepared UFMSW-potting soil mixtures. 0.2 g of seeds, ~100 pieces in total, were uniformly distributed on the surface of each soil mixture in a 50x50 mm pot. The seeds were incubated in a climatic chamber at 20-22 °C with a 16/8-hour light/dark cycle and 70% relative humidity for 7 days.

2.3. Plant Growth Experiment

The plant growth experiment involving Marigold (*Tagetes erecta*) (Rédei Kertimag Zrt., Réde, Hungary) was conducted in two distinct phases. Initially, *Tagetes erecta* seeds were sown in a general, non-polluted potting soil (Garri, OBI GmbH, Veszprém, Hungary), then allowed to germinate and grow for a period of four weeks. Following this germination period, the most vigorous and uniformly developed seedlings were selected and transplanted into the experimental planting media. The control plants were also transplanted into a fresh control soil.

The plants were maintained in a controlled climatic chamber at 20-22 °C with a relative humidity of 70% and a 16/8-hour light/dark cycle. The plants were watered twice a week with 100 ml of tap water per pot by adjusting the water quantity as required. The growing period lasted approximately 12 weeks until the control group bloomed.

2.4. Analytical methods

2.4.1. Physicochemical characterization of the soil samples

The physicochemical properties of the growing media were determined using standardized methods. The pH was measured according to ISO 10390:2021 (Soil quality — Determination of pH). The electrical conductivity was determined using ISO 11265:1994 (Soil quality — Determination of the specific electrical conductivity). The dry matter and water content were measured on a mass basis by a gravimetric method following ISO 11465:1993 (Soil quality — Determination of dry matter and water content on a mass basis — Gravimetric method). Total dissolved solids were quantified using EPA Method 160.1 (Total Dissolved Solids). Biochemical Oxygen Demand for 5 days (BOD_5) was determined according to EN 1899-2:2000 (Water quality — Determination of biochemical oxygen demand after n days — Part 2: Method for undiluted samples). The Chemical Oxygen Demand was determined using EPA 410.4:1993.

2.4.2. Metal accumulation test

Sample preparation

The soil samples were oven-dried at 105 °C to a constant weight. The plant samples (flowers, leaves, stems and roots) from 12-week-old plants were separated, cut and subsequently dried at 105 °C before being gently grinded. For metal determination, the dried plant samples were incinerated at 550 °C for 2.5 hours to produce ash, which was then cooled to room temperature.

Digestion and measurements

All the samples were digested using an Anton Paar 600 W Multiwave 3000 device. Digestion took place in 6 mL of aqua regia (4.5 mL HCl + 1.5 mL HNO_3, VWR Chemicals, analytical grade) in sealed HF100 vessels heated to 175 °C for 30 minutes followed by a 30-minute contact time. Having been cooled, the digested samples were diluted to 25 mL. The metal content was then determined using a PerkinElmer's ICP-OES instrument.

Table 1: Physicochemical parameters (pH, conductivity, TDS, COD, BOD, AT4) of the leachates from soil treated with different proportions of UFMSW (B20–B100) compared to the control

Parameter	pH	Conductivity (µS/cm)	TDS (mg/L)
Control	7.07	344	912
B20	7.85	1119	2690
B40	7.86	1367	2833
B60	7.74	1720	3342
B80	8.17	1720	3865
B100	7.79	23,500	4420

Parameter	COD (mg/L)	BOD (mg/L)	AT4 (mg O_2/g DM)
Control	187	187	2.06
B20	275	42.2	11.99
B40	365	67.5	23.96
B60	1126	160	27.79
B80	2467	428	28.85
B100	2770	473	41.36

3. Results and discussion

3.1. Physicochemical tests on the soil

The soil quality parameters exhibited pronounced changes (*Table 1*) as the UFMSW content increased. pH values shifted from neutral in the Control (7.07) to slightly alkaline in all the samples treated with UFMSW (7.74–8.17). Research by Soobhany confirmed that during the composting of organic constituents of MSW, pH values were observed to increase to 7.4–7.5, which is slightly more acidic than in our findings [24]. VanderGheynst et al. investigated different green waste composts with a similar alkaline pH from 7.9 to 8.6, depending on the input materials [25].

The conductivity and total dissolved solids (TDS) increased progressively as the amount of UFMSW added increased, reaching an extremely high electrical conductivity (EC) in B100 (23,500 µS/cm), indicative of substantial ionic loading. In line with the study by VanderGheynst et al. on green waste [25] as well as the literature review by Agnew and Leonard on compost [26], our EC results of UFMSW-treated soil fall within the same order of magnitude. High electrical conductivity values, indicative of highly soluble salts, are known to be detrimental to plants, particularly during their sensitive early growth stages when metabolic processes and the nutrient balance are disrupted [27]. Organic matter-related parameters also rose sharply: the COD and BOD values were highest in B80–B100 (COD: 2467–2770 mg/L; BOD: 428–473 mg/L), reflecting elevated concentrations of biodegradable organic compounds. The BOD and COD results of

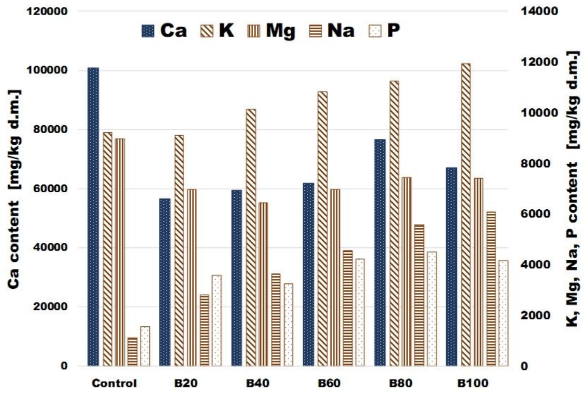

Figure 1: Macronutrient content in UFMSW-treated soil

UFMSW-treated soils are comparable to the COD and BOD values reported for compost leachates in the study by Christensen and Nielsen [28]. The AT4 index, representing the biological degradation potential, increased from 2.06 mg O_2/g dry matter (DM) in the Control to 41.36 mg O_2/g DM in B100, pointing to more intense microbial activity and biological instability.

Overall, higher UFMSW proportions in the soil substantially increased salinity, organic load and biodegradability.

3.2. Soil macronutrient test

The chemical characterization of compost generally depends on its agronomic value and pollutant content (e.g. heavy metals) [29]. The analysis of major nutrient concentrations in the UFMSW-treated soil revealed distinct patterns, reflecting the significant contribution of the waste material (*Figure 1*). Potassium (K) levels consistently increased as the UFMSW content rose, ranging from approximately 9100 mg/kg in B20 to 12,554 mg/kg in B100. These K concentrations are slightly higher than those reported for municipal solid waste composts, which can vary, for example, from 1851 to 6615 mg/kg according to Dimambro et al. [30]. However, it should be noted that the concentration of K in the initial potting soil was also higher (9211 mg/kg DM). Similarly, the phosphorus (P) content exhibited a considerable increase from 1575 mg/kg in the Control to 4819 mg/kg in B100. Reported P concentrations in MSW composts ranged from 23 to 247 mg/kg and 680 to 1820 mg/kg according to Dimambro et al. [30] and Soumaré et al. [29], respectively, indicating that UFMSW is a rich source of this macronutrient with our observed values being at the higher end or exceeding these ranges. Calcium was already present in substantial quantities in the Control soil, moreover, its concentration rose across all treatments, ranging from approximately 56,678 to 74,435 mg/kg in UFMSW-treated samples. This is consistent with the fact that mineral nutrients, including calcium, are generally present in MSW composts but mainly in smaller quantities [29],[31]. Magnesium concentrations ranged from 6117 to 8809 mg/kg in the

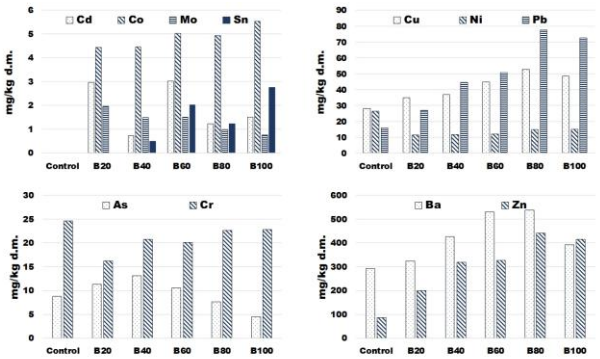

Figure 2: Heavy metal content in UFMSW-treated soils

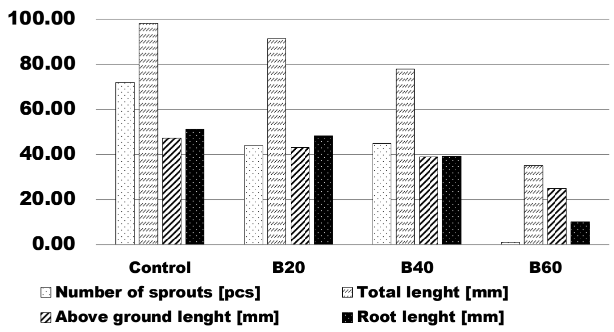

Figure 3: The effect of undersized fine municipal solid waste on the germination and early seedling development of *Lepidium sativum*

UFMSW-treated samples, which supports the presence of magnesium as a key mineral nutrient in compost derived from municipal solid waste [29]. Critically, sodium levels exhibited a sharp increase as samples were treated with more UFMSW, rising from 1127 mg/kg in the Control to 6527 mg/kg in B100. This marked elevation in Na aligns with observations that mixed waste composts can contain higher levels of total salts, predominantly due to high concentrations of various elements, including Na. This also correlates with previously observed increases in electrical conductivity, highlighting the potential for heightened salinity, a key consideration regarding the agricultural application and environmental impact of UFMSW [29],[30]. In the literature, studies consistently report that elevated concentrations of soluble salts in composts or amended soils can critically limit plant growth, interfering with water uptake by roots as well as leading to physiological dehydration and reduced nutrient absorption [32],[33].

Collectively, these findings demonstrate that UFMSW serves as a valuable source of essential plant macronutrients while simultaneously emphasizing the necessity of managing potential salinity concerns associated with its high sodium content.

3.3. Soil essential and heavy metal test

The analysis of the heavy metal content reveals distinct differences between the control soil and the UFMSW-treated media, generally indicating an increase in various metal concentrations with the incorporation of the waste material (*Figure 2*). Specifically, essential metals like copper and zinc, alongside lead and barium, consistently show elevated levels in all UFMSW-treated samples compared to the control with concentrations generally rising as the proportion of UFMSW increases. For instance, the concentration of Pb soars from 15.86 mg/kg in the Control to a high of 77.61 mg/kg in B80, while Zn rises from 86.32 to 442.63 mg/kg in B80, highlighting UFMSW as a significant source of these elements. Other metals such as cadmium, cobalt and tin, which were absent in the control, were found in the UFMSW-treated soils, however, their levels did not always correlate directly with the increasing UFMSW content. Conversely, chromium and nickel generally showed lower concentrations in the UFMSW-treated samples compared to the control before slightly increasing as the UFMSW content rose. The concentrations of these elements are approximately equal to or below the values as stated in previous studies by Koledzi et al. [34] as well as Sharifi and Renella [35]. Arsenic and molybdenum exhibited more complex trends, initially increasing at lower UFMSW concentrations but then decreasing at higher levels with that of arsenic even falling below the control values in B80 and B100. This differential accumulation pattern underscores the heterogeneous nature of UFMSW derived from mixed household waste streams and its varied impact on metal profiles in soil, necessitating the careful consideration of application rates to manage potential environmental risks associated with elevated heavy metal concentrations.

3.4. Germination experiments

A clear negative trend was observed in both germination rate and early seedling development with increasing UFMSW content (*Figures 3* and *4A*). The number of sprouts decreased sharply from 72 in the Control to only 1 in B60, indicating a strong inhibitory effect of high UFMSW content on germination. The moderate reduction observed in B20 and B40 (44 and 45 sprouts, respectively) still suggests some level of phytotoxic stress or suboptimal conditions compared to in the control. In terms of seedling growth, the total length of the plants was highest in the Control (98.3 mm) and decreased progressively as the UFMSW content increased. Using B60, seedling growth was severely stunted (35.0 mm in total), suggesting that this level of UFMSW is not suitable for seedling development. When analyzing separately the shoot and root growth, similar trends were found. While the growth of parts above ground decreased from 47.2 mm in the Control to 25.0 mm in B60, root development was even more drastically inhibited with a drop from 51.2 mm in the Control to just 10.0 mm in B60.

The significant negative trend observed in both germination rate and seedling development with increasing UFMSW content is likely attributable to multiple interacting factors. The strong inhibitory effect on germination and severely stunted seedling growth, particularly of roots, is strongly consistent with the

Figure 4: Seed germination inhibition at high UFMSW contents (A) and the healthy development of *Tagetes erecta* using 20% UFMSW (B)

effects of immature composts, which often contain phytotoxic compounds [36] as proven by the high COD, BOD and AT4 values. This suggests that UFMSW may still contain substantial amounts of readily degradable organic matter or specific toxic metabolites that inhibit plant development as well as hinder seed germination and root elongation [37].

3.5. Plant test in a climatic chamber

3.5.1. Morphological analyses

B20 significantly enhanced both the vegetative and reproductive growth of *Tagetes erecta* compared to in the Control shown in *Figure 4B* and *5*. Plants cultivated in soil treated with 20% UFMSW yielded approximately 73% more leaves (mean of 67 vs. 39 for the Control) as well as 33% more stems and branches (mean of 4 vs. 3 for the Control). Furthermore, the mean number of reproductive organs doubled in B20 (4 vs. 2 for the Control), indicating a pronounced stimulation of the flowering potential. The mean stem diameter was also greater for plants in B20 (5.5 vs. 4.7 mm), suggesting enhanced structural development. These collective results indicate that the moderate incorporation of UFMSW facilitated increased biomass allocation to vegetative structures and augmented the reproductive output without inducing visible morphological damage, a response consistent with a nutrient-enrichment effect.

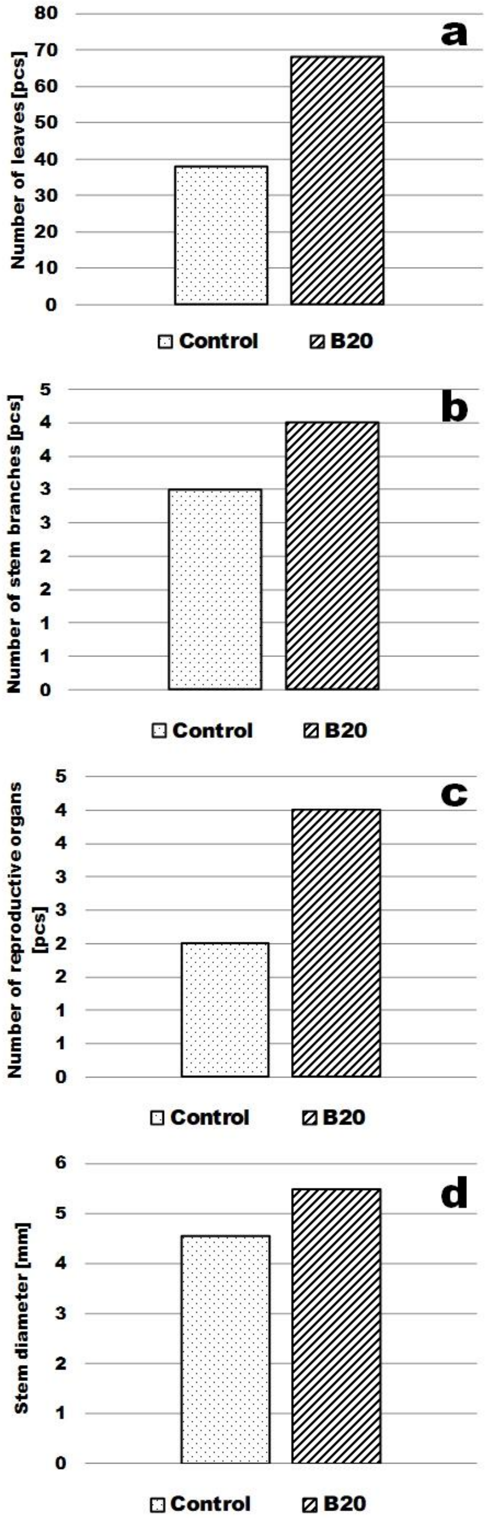

Figure 5: Morphological parameters of *Tagetes erecta* grown in the control soil (Control) and soil containing 20% UFMSW (B20): (a) number of leaves, (b) number of stems and branches, (c) number of reproductive organs and (d) stem diameter

Table 2: Metal concentrations (mg/kg of ash) in different organs of *Tagetes erecta* grown in the control (C) and soil containing 20% UFMSW (B20): leaves (L), stems (S), flowers (F) and roots (R)

	C-L	B20-L	C-S	B20-S
As	1.94	0.72	2.05	1.11
Ba	4.98	9.66	2.05	5.55
Cd	0.28	0.48	0.00	0.00
Co	0.00	0.24	0.00	0.00
Cr	1.11	0.97	1.02	1.11
Cu	26.27	39.12	5.64	10.35
Mo	5.53	8.45	7.68	7.02
Ni	4.15	9.90	11.27	9.98
Pb	1.38	1.21	1.54	1.85

	C-F	B20-F	C-R	B20-R
As	4.67	1.03	21.63	31.02
Ba	0.00	0.00	63.30	87.62
Cd	0.00	0.00	0.80	0.78
Co	0.00	0.00	2.40	3.10
Cr	1.17	1.03	9.62	10.08
Cu	28.01	20.64	101.76	81.42
Mo	1.17	2.06	24.04	32.57
Ni	7.00	23.74	26.44	20.16
Pb	2.33	2.06	10.42	19.39

3.5.2. Metal accumulation

The distribution of different metals in *Tagetes erecta* was strongly organ-specific with roots acting as the primary sink across all treatments (*Table 2*). The treatment with 20% UFMSW (B20) markedly enhanced the accumulation of As, Ba, Co, Mo and Pb in the roots with As and Pb increasing by ~43% and ~86%, respectively, relative to the Control. Levels of Pb accumulation aligned with previous research conducted by Madanan et al. [38]. In the leaves of B20-treated plants, an increase in Cu (+49%) and Ni (+139%) was observed, while As and Pb concentrations decreased. In the stems, the concentrations of Ba, Cu, and Pb moderately increased while those of As, Mo and Ni declined. In contrast, flowers generally exhibited reduced metal concentrations in B20, except for pronounced increases in Ni and Mo. The allocation of nickel to flowers had previously been observed in the same test plant [39]. Overall, B20 shifted the metal accumulation profile toward the greater root sequestration of toxic elements and enhanced foliar enrichment of micronutrients such as Cu and Ni, indicating altered plant translocation and partitioning patterns.

4. Conclusions

Collectively, this study identified the complex role of UFMSW as a soil amendment, contingent on its application rate. While high concentrations of UFMSW (B40-B100) exhibited severe phytotoxicity, leading to significantly reduced germination rates and stunted seedling development in *Lepidium sativum* as well as complete plant mortality in *Tagetes erecta*, moderate concentrations (B20) yielded substantial benefits. The observed phytotoxicity at elevated UFMSW levels is attributable to a combination of factors, including the presence of immature organic matter and toxic compounds, as evidenced by the high COD, BOD and AT4 values as well as critically pronounced osmotic stress due to elevated sodium concentrations in addition to the associated high electrical conductivity and total dissolved solids. Conversely, B20 significantly enhanced both the vegetative and reproductive growth of *Tagetes erecta*, underscoring the nutrient-enrichment potential of UFMSW at optimized application rates. Furthermore, while metal accumulation within *Tagetes erecta* was organ-specific, with roots primarily acting as a sink, B20 did not lead to its increase in edible or transferable parts that would compromise plant safety. This indicates that a carefully controlled incorporation rate can mitigate concerns regarding contaminant uptake, supporting its potential as a safe and effective amendment.

In conclusion, despite the inherent phytotoxic risks associated with high UFMSW concentrations, this research highlights that targeted low-level amendments can substantially improve plant growth and yield, effectively transforming a challenging waste stream into a valuable resource. These findings are crucial for the development of sustainable waste valorization strategies, bridging the current gap between effective waste management and environmentally sound agricultural practices.

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