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Composting of Sanandaj Digested sewage sludge with sawdust: changes in heavy metals, PCBs, and selected organic compounds

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ABSTRACT

The co-composting of anaerobically digested sewage sludge from the Sanandaj wastewater treatment plant with wood sawdust (at a 2:3 volumetric ratio) was evaluated over a two-month period using an outdoor windrow composting method. Total heavy metal concentrations (arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc) were measured before and after composting via Atomic Absorption Spectroscopy (AAS). Organic micro-pollutants including PCBs, benzo[a]pyrene, organochlorine pesticides, and semi-volatile compounds were analyzed using GC-ECD, GC-FID, and GC-MS. Post-composting data revealed significant reductions in zinc (83%), copper (81%), lead (79%), and arsenic (62%); conversely, chromium levels increased by 64.1%, while nickel concentrations remained unchanged. These trends are attributed to the loss of organic matter mass combined with physical dilution by the bulking agent. All heavy metal concentrations complied with the guidelines set by the Department of Environment of Iran and the U.S. EPA standards (Part 503), while PCBs, pesticides, and other pollutants remained below detection limits. Due to methodological limitations, especifically the lack of replicate windrows, continuous thermophilic monitoring, and comprehensive Quality Assurance/Quality Control (QA/QC) documentation, these findings should be interpreted as apparent concentration shifts rather than absolute mass removals. Nevertheless, they provide foundational insights for the management of sewage sludge in Sanandaj.

Highlights

- Co-composting with sawdust cut dry-basis Zn, Cu, Pb, and As by 62–83% in 60 days.
- Chromium rose 64.1% and nickel 3.7%, reflecting organic-matter mass loss.
- PCBs, organochlorine pesticides, and benzo[a]pyrene stayed below detection limits.
- Final compost met Iranian DOE and US EPA Part 503 Exceptional Quality limits.
- No dry-mass balance was tracked, so shifts are concentrations, not mass removals.

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1. Introduction

Sewage sludge management is a persistent operational challenge for municipal wastewater treatment plants. While digested sludge is widely applied to agricultural land due to its high nitrogen, phosphorus, and organic matter content (Silva & Santos, 2023; Johnson & Smith, 2023), its agronomic utilization carries substantial environmental and toxicological risks (Zhao et al., 2024). The accumulation of heavy metals, particularly arsenic, cadmium, chromium, copper, lead, mercury, and zinc, presents persistent ecological and soil health hazards (Zhang et al., 2022; Wang et al., 2022; Hušek et al., 2026). Furthermore, municipal sludge serves as a sink for persistent organic pollutants (POPs) and emerging contaminants, including PCBs and organochlorine pesticides, which resist conventional wastewater treatment stages and concentrate in the settled solids (Cui et al., 2024; Wang et al., 2024; Wu et al., 2025). Direct land application of unconditioned sludge thus triggers severe phytotoxicity, long-term soil degradation, and potential groundwater contamination. Co-composting provides an effective, ecologically sound pathway for biological stabilization before

land application. Blending dewatered sludge with carbon-rich lignocellulosic bulking agents, such as wood chips or agricultural residues, improves structural porosity, optimizes the carbon-to-nitrogen (C/N) ratio, and sustains the thermophilic conditions driven by specialized microbial communities (Yang et al., 2023; Sellami & Medhioub, 2022; Ivickytė & Povilaitis, 2026). This intensive bio-oxidative process accelerates the degradation of organic matter and promotes the dissipation of toxic micropollutants (Meena et al., 2023; Qiao et al., 2024). However, conservative inorganic contaminants follow distinctly different dynamics. Heavy metals do not degrade; rather, their total concentrations reflect two competing phenomena: physical dilution from the added bulking matrix versus apparent concentration driven by organic matter mineralization and carbon loss (Liu & Song, 2023; Chen et al., 2023). In addition, thermophilic humification alters metal speciation, facilitating passivation and reducing bioavailable fractions in the mature matrix (Awasthi et al., 2022; Li et al., 2022). Comprehensive monitoring of sludge composition before and after the composting cycle is therefore essential to evaluate both total loads and chemical stability.

The Sanandaj wastewater treatment plant in western Iran operates via a conventional activated sludge process followed by anaerobic digestion. Despite steady sludge production, baseline data regarding trace element redistribution and organic micropollutant persistence during outdoor windrow composting remain scarce. Establishing rigorous regulatory compliance is critical to determining the safety of this material for soil amendment. This study evaluates the concentration profiles of ten heavy metals (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, Zn) and target organic micropollutants, specifically PCB congeners, organochlorine pesticides, benzo[a]pyrene, and semi-volatile organic compounds—during a 60-day outdoor co-composting trial utilizing wood chips at a 2:3 volumetric ratio. Final concentrations are evaluated against the regulatory standards established by the Iranian Department of Environment (Iranian Department of Environment, 2013, 2015) and the “Exceptional Quality” criteria defined under the U.S. EPA Part 503 biosolids rule (US EPA, 1993, 1994).

2. Materials and Methods

2.1 Composting Process and Operational Setup

The experimental study was conducted at the municipal wastewater treatment plant in Sanandaj, western Iran. Dewatered anaerobically digested sludge was mixed with locally sourced wood sawdust at a volumetric ratio of 2:3 (sludge to sawdust) to adjust the moisture content and achieve an appropriate carbon-to-nitrogen (C/N) ratio. This mixture was arranged into trapezoidal piles on an impermeable concrete base as part of a pilot-scale setup. Aerobic conditions were maintained by manually turning the material two to three times per week over a 60-day operational period. This turning frequency ensured sufficient oxygen supply while limiting excessive heat loss during the thermophilic phase. Representative samples were collected at two distinct stages: the raw dewatered digested sludge prior to the addition of sawdust (Day 0), and the final co-compost following the 60-day maturation period. For the final compost, a composite sample was prepared by combining subsamples taken from various depths (the core and outer layers) throughout the pile, thereby minimizing spatial heterogeneity.

2.2 Analytical Determinations and Quality Limitations

All chemical analyses were conducted in accordance with standard dry-weight protocols (USEPA, 2002). As the certificates issued by the laboratory reported numerical concentrations and upper-bound values without specifying the Method Detection Limit (MDL) or the Limit of Quantitation (LOQ), values marked with a ">" symbol are presented here as laboratory reporting thresholds. Specific analytical conditions (such as acid digestion matrices, calibration verification, standard reference materials, and the relative standard deviations of replicates) were not documented in the test certificates and are therefore considered limitations of this study.

2.2.1 Heavy Metals

Representative composite samples of raw sludge and final compost were analyzed for heavy metal content (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, and Zn) using Atomic Absorption Spectroscopy (AAS). All analyses were conducted by an accredited laboratory following standard analytical protocols

2.2.2 Organic Micropollutants and Polychlorinated Biphenyls (PCBs)

PCB congeners and six organochlorine pesticides (lindane, heptachlor, chlordane, aldrin, dieldrin, and 4,4′-DDT) were measured by GC-ECD according to standard procedures by an accredited laboratory. Benzo[a]pyrene was determined by GC-FID, and five priority organics (hexachlorobutadiene, hexachlorobenzene, N-nitrosodimethylamine, trichloroethylene, and toxaphene) were analyzed by GC-MS. Testing was performed on two composite samples collected before and after composting

3.1 Results and Discussion

3.1 Trace Metal Concentrations

Table 1 outlines the elemental composition of the digested sludge before mixing and in the cured compost after 60 days. Marked reductions occurred for most metals on a dry-weight basis. Zinc and copper concentrations dropped sharply, decreasing by 83.1% (875 to 148 mg/kg) and 80.8% (211 to 40.5 mg/kg), respectively. Lead and arsenic followed a similar downward path, declining by 79.7% (from 34.4 to 7.0 mg/kg) and 62.2% (from 4.13 to 1.56 mg/kg). Cadmium (initially 1.0 mg/kg) and mercury (0.6 mg/kg) both dropped below their laboratory detection cutoffs (< 0.5 mg/kg for Cd; < 0.1 mg/kg for Hg). Molybdenum similarly fell from 20 mg/kg to under the reporting limit of 20 mg/kg, while selenium concentrations remained constant at 0.5 mg/kg.

In contrast to these reductions, total chromium increased from 56.9 mg/kg in raw sludge to 93.4 mg/kg in the finished compost, representing an apparent 64.1% rise. Nickel levels changed very little, moving from 21.8 to 22.6 mg/kg (+3.7%).

3.2 Concentration Changes and Mass Balance Considerations

Non-volatile heavy metals do not escape through gaseous emission or significant leaching in semi-arid, covered windrow piles. Therefore, the measured shifts reflect the balance between physical dilution by the bulking agent and the

concentrating effect of organic matter loss (Amir et al., 2005; Wang et al., 2016).

The pronounced declines in Zn, Cu, Pb, and As, alongside Cd and Hg falling below detection thresholds, are primarily driven by the addition of wood sawdust at a 2:3 volumetric ratio. Introducing a large volume of low-metal organic material expanded the dry mass of the mixture, effectively diluting baseline sludge concentrations (Alvarenga et al., 2016; Gao et al., 2020).

Conversely, organic matter breakdown concentrates conserved mineral fractions. As microbes consume biodegradable carbon and release CO2 and water vapor, the windrow loses total dry weight (Li et al., 2012), raising the proportion of non-degradable elements per kilogram of dry solid. This mechanism explains the slight rise in Ni and part of the Cr increase. However, the steeper increase in chromium (+64.1%) suggests additional factors, such as trace background metals in the sawdust (particularly if scraps of treated wood were present in the locally acquired batches), hand-turning variability, and localized sampling differences. Because mass loss over the 60-day cycle was not tracked gravimetrically, these values must be treated as dry-basis concentration changes rather than absolute mass changes (Huang et al., 2016).

Table 1 Heavy metal concentration results before and after the composting process (mg/kg)

Element	Before Composting (mg/kg)	After Composting (mg/kg)	Observed Change
Arsenic (As)	4.13	1.56	62% Decrease
Cadmium (Cd)	1	< 0.5	Decrease to < 0.5
Chromium (Cr)	56.9	93.4	Increase 64.1%
Copper (Cu)	211	40.5	81% Decrease
Lead (Pb)	34.4	7	79% Decrease
Mercury (Hg)	0.6	< 0.1	Below Detection Limit
Molybdenum (Mo)	20	< 20	Below Detection Limit
Nickel (Ni)	21.8	22.6	3.7% Slight Increase
Selenium(Se)	< 0.5	< 0.5	No Detectable change
Zinc(Zn)	875	148	Decrease 83%

3.3 Organic Micropollutants and Regulatory Evaluation

Laboratory screening showed low levels of organic micropollutants in the treated material. Total PCBs remained below the 0.2 µg/kg detection threshold in the final compost. Similarly, all six organochlorine pesticides (lindane, heptachlor, chlordane, aldrin, dieldrin, and 4,4′-DDT) were below 0.03 µg/kg, and benzo[a]pyrene was under 0.04 mg/kg. The five monitored semi-volatile compounds (hexachlorobutadiene, hexachlorobenzene, N-nitrosodimethylamine, trichloroethylene, and toxaphene) all registered below 0.5 mg/kg.

These results confirm that industrial chlorinated discharges do not heavily impact the municipal influent at the Sanandaj WWTP. Aerobic thermophilic composting promotes the breakdown of susceptible organics alongside adsorption onto stable humic matter (Cui et al., 2019). Dilution with sawdust further helped maintain these trace contaminants well beneath laboratory limits. Consequently, the final compost complies with Iranian Department of Environment standards (Iranian DOE, 2015), US EPA Part 503 Exceptional Quality criteria (USEPA, 1993), and baseline European sludge thresholds (European Commission, 2001) for heavy metals and organic compounds, demonstrating its chemical suitability for soil improvement and agricultural reuse (Table 2).

Table 2 Comparison of heavy metal concentrations in final compost with environmental and agricultural guidelines (US EPA, 1993; Iranian DOE Compost Standards)

Trace Element	Finished Compost(mg/kg)	Iranian DOE Compost Standards (mg/kg)	US EPA Part 503 (EQ Limits) (mg/kg)	Compliance Status
Arsenic (As)	1.56	< 20	41	Compliant
Cadmium (Cd)	< 0.5	< 3	39	Compliant
Chromium (Cr)	93.4	< 150	1200	Compliant
Copper (Cu)	40.5	< 300	1500	Compliant
Lead (Pb)	7.0	< 150	300	Compliant
Mercury (Hg)	< 0.1	< 1.5	17	Compliant
Nickel (Ni)	22.6	< 50	420	Compliant
Selenium (Se)	< 0.5	< 2	100	Compliant
Zinc (Zn)	148	< 500	2800	Compliant

4. Conclusion

Co-composting dewatered digested sewage sludge with wood sawdust at a 2:3 volumetric ratio produced finished compost compliant with national and international environmental standards for agricultural application. This operational trial demonstrates that the marked decreases in dry-weight concentrations of Zn (83.1%), Cu (80.8%), Pb (79.7%), and As (62.2%) were predominantly driven by physical dilution from the sawdust amendment rather than elemental degradation or loss. Conversely, the apparent increase in Cr (64.1%) and the slight rise in Ni (3.7%) reflect concentration effects caused by organic matter decomposition and windrow dry-mass loss, potentially combined with trace impurities from the bulking agent. Target persistent organic pollutants, including organochlorine pesticides and PCBs, remained consistently below laboratory reporting thresholds. Because routine process parameters and windrow mass balances were

not quantified during this plant-scale monitoring, future studies should establish comprehensive dry-mass balances to strictly decouple physical dilution from biological and chemical transformation mechanisms

Statements and Declarations

Ethical considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the author.

Data availability

Data will be made available on request.

Conflicts of interest

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

Author contribution

All authors contributed to the study conception, data interpretation, and manuscript drafting and review. All authors read and approved the final manuscript.

AI Use Declaration

During the preparation of this manuscript, the authors used AI tools for designing the Graphical Abstract. All content has been carefully reviewed and revised by the authors, who take full responsibility for the final version of the manuscript.

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