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Characterization of Soil-like Materials from Inactive Zone of Piyungan Waste Disposal Facility, Indonesia: Implications for Compost and Organic Fertilizer Use

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ABSTRAK

Sampah padat perkotaan (MSW) yang dibuang di tempat pembuangan akhir (TPA) mengandung proporsi sampah organik yang signifikan, yang terurai menjadi material seperti tanah dan berpotensi digunakan kembali. Penambangan TPA merupakan strategi yang dapat dilakukan untuk memulihkan material ini dari timbunan sampah lama. Integrasi material ini ke dalam praktik pengelolaan sampah sirkular dapat mengurangi volume TPA dan memulihkan sumber daya yang berharga. Namun, mengingat sifat heterogen sampah yang dibuang di TPA dari waktu ke waktu, muncul kekhawatiran tentang kualitas dan keamanan material seperti tanah, terutama ketika dimaksudkan untuk digunakan sebagai kompos atau pupuk organik. Dalam studi ini, material seperti tanah dikumpulkan dari dua kelompok usia penghuni TPA, yaitu timbunan muda (16–20 tahun) dan timbunan tua (21–25 tahun). Sampel dikarakterisasi berdasarkan sifat kimia, karakteristik fisik, dan kandungan logam berat. Hasilnya kemudian dibandingkan dengan Standar Nasional Indonesia (SNI) 19-7030-2004 untuk kompos rumah tangga organik dan SNI 7763:2024 untuk pupuk organik padat. Hasil penelitian menunjukkan bahwa total kandungan NPK pada material yang lebih tua (0,80 ± 0,35%) memenuhi ambang batas NPK untuk kompos organik domestik (≥ 0,70%), sedangkan material yang lebih muda (0,40 ± 0,17%) tidak memenuhi. Kedua kelompok usia tersebut tidak memenuhi persyaratan NPK untuk pupuk organik padat (≥ 2). Selain itu, konsentrasi kadmium (Cd) pada material yang lebih muda (39,81 ± 11,32 mg/kg) maupun yang lebih tua (33,47 ± 12,60 mg/kg) jauh melampaui ambang batas regulasi (≤ 3 mg/kg untuk kompos; ≤ 2 mg/kg untuk pupuk). Konsentrasi timbal (Pb) memenuhi standar pada kedua kelompok timbunan (11.32 ± 7.92 mg/kg dan 21.43 ± 11.38 mg/kg). Penambangan TPA Piyungan berpotensi menyediakan bahan baku kompos, tetapi pemilahan bahan pengotor, pengayaan nutrisi, dan remediasi kadmium sangat diperlukan sebelum diaplikasikan pada tanah.

Kata kunci: Bahan terkompos, penambangan sampah, kematangan sampah, kompos organic domestic, pupuk organic padat

ABSTRACT

Municipal solid waste (MSW) disposed of in landfills contains a significant proportion of organic fraction that decomposes into soil-like materials that can be potentially recovered and reused. Landfill mining is an emerging strategy to recover these materials from older waste deposits. Integration of these materials into circular waste practices can therefore reduce landfill volume and recover valuable resources. However, given the heterogeneous nature of waste deposited in landfills over time, concerns arise about the quality and safety of the soil-like material, particularly when intended for use as compost or organic fertilizer. In this study, soil-like material samples (*n=4*) were collected from two landfill age groups, i.e., younger piles (16–20 years) and older piles (21–25 years). Samples were characterized for chemical properties, physical characteristics, and heavy metal content. The results were then compared with the Indonesian National Standards (SNI) 19-7030-2004 for organic domestic compost and SNI 7763:2024 for solid organic fertilizer. Findings revealed that total NPK content in older material (0.80 ± 0.35%) met the NPK threshold for organic domestic compost (≥ 0.70%), whereas younger material (0.40 ± 0.17%) failed. Both age groups failed the NPK requirement for solid organic fertilizer (≥ 2). Furthermore, cadmium (Cd) concentrations in both younger (39.81 ± 11.32 mg/kg) and older (33.47 ± 12.60 mg/kg) materials severely exceeded regulatory thresholds (≤ 3 mg/kg for compost; ≤ 2 mg/kg for fertilizer). Lead (Pb) concentrations (11.32 ± 7.92 mg/kg and 21.43 ± 11.38 mg/kg) complied with statutory standards across both groups. These findings indicate that while mined soil-like materials possess resource potential, post-recovery treatments, including inert screening, nutrient enrichment, and heavy metal remediation, are essential prior to land application.

Keywords: Soil-like material, landfill mining, compost quality, organic domestic compost, solid organic fertilizer

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1. INTRODUCTION

The increasing volume of municipal solid waste (MSW), which consists of a significant amount of organic matter such as food scraps, yard waste, and agricultural residues, presents a growing environmental and management challenge in urban areas worldwide. Rapid urbanization, population growth, and changing consumption patterns contribute to this rising waste generation, often exceeding the capacity of existing waste management systems. In many developing countries, a large share of this organic waste is still disposed of in landfills or open dumpsites without adequate treatment or segregation. The uncontrolled decomposition of organic waste in such settings often results in the emission of greenhouse gases, particularly methane, a gas with a global warming potential many times greater than carbon dioxide (Erses et al., 2008; Ishii & Furuichi, 2013). Additionally, the production of leachate poses significant threats to surrounding soil and groundwater quality, especially when landfills lack proper lining or leachate management systems (Gómez et al., 2019; Alam et al., 2020; Naveen et al., 2018). Despite these risks, organic waste holds immense potential as a resource when managed correctly. With appropriate screening, separation, and treatment processes, decomposed organic waste, particularly that in the form of soil-like material, can be converted into nutrient-rich compost or solid organic fertilizer (Rong et al., 2017; Sall et al., 2019; Zhou et al., 2015). This not only helps reduce the volume of waste destined for disposal but also supports environmentally sustainable agricultural practices by improving soil health and reducing reliance on synthetic fertilizers.

Piyungan landfill served as the central municipal waste disposal site for Yogyakarta, Indonesia, for over two decades. Designed as a controlled landfill, it became increasingly overburdened due to the rising volume of waste generated by the city and surrounding regions. Despite several temporary closures and public demands for better waste solutions, the site continued to receive waste until it was permanently closed in May 2024. This closure followed concerns over landfill overcapacity, environmental pollution, and the lack of alternative waste processing infrastructure. The city faces post-closure challenges of managing legacy waste, during which landfill mining has emerged as a promising strategy to recover recyclable, reusable, or biodegradable materials. In this facility, the potential of mined waste material for refuse-derived fuel (RDF) has been identified (Parimita et al., 2018). However, the baseline chemical properties, biological stability indicators (organic carbon, C/N ratio, respiration), and toxicological safety of the soil-like materials recovered from Piyungan remain understudied. Specifically, it is unknown whether natural stabilization across different landfill burial ages (e.g., 15–20 years vs. 21–25 years) enables these materials to comply with Indonesian statutory standards for organic amendments.

The utilization of landfill materials for solid organic fertilizer focuses on compostable materials that have undergone partial or full decomposition, identified by the formation of soil-like material. Such material, especially in older sections of the landfill, is likely to have stabilized over time and may exhibit characteristics suitable for further processing into compost or organic fertilizer. Integrating this approach into landfill management could bring multiple benefits, such as reducing the burden on existing landfill volume, reclaiming land for future uses, and contributing to nutrient recovery for agricultural applications (Chandana et al., 2021; Jain et al., 2023). These practices are increasingly recognized as integral to circular economy principles and sustainable waste management frameworks.

Despite the potential benefits, the reuse of landfill-derived organic material poses considerable challenges, particularly regarding quality and safety. Over time, landfills become complex matrices of various waste types, including household, industrial, plastic, and hazardous waste, which may co-decompose with the organic fraction. As a result, recovered materials from landfills often carry contaminants such as heavy metals (e.g., cadmium, lead, copper, arsenic, etc.), persistent organic pollutants, pathogenic organisms, and microplastics (L. Liang et al., 2025; Y. Liang et al., 2023; Liu et al., 2019). If such contaminants are not adequately identified and mitigated, their introduction into agricultural systems can have serious ecological and public health implications. Therefore, the quality of compost produced from these sources must be assessed carefully, using standardized protocols and regulatory benchmarks, before it can be deemed safe for agricultural or landscaping applications. Ensuring compliance with these standards is vital to safeguard soil health, food safety, and consumer confidence.

Given this context, the present study aims to characterize the quality of soil-like materials taken from the inactive zone of the Piyungan Landfill in Yogyakarta. The primary objective is to determine whether these materials can meet the compost quality standards outlined by the Indonesian government, specifically the Indonesian National Standard Quality for organic domestic compost and solid organic fertilizer (Standar Nasional Indonesia, SNI 19-7030-2004 and SNI 7763:2024, respectively). We hypothesize that soil-like materials from the older landfill age, where organic matter has undergone prolonged anaerobic or aerobic decomposition, are higher in quality, particularly in terms of macronutrient content, compared to more recent deposits. If validated, this hypothesis could support the development of sustainable landfill mining practices in Yogyakarta and similar urban centers, promoting resource recovery, reducing environmental risks, and enabling the beneficial reuse of previously discarded organic waste.

2. METHODS

2.1. Sampling Location

The study site is located at the Piyungan Integrated Waste Processing Facility (IWPF), Bantul Regency, Special Region of Yogyakarta (7°52'03.7310" S and 110°25'44.0459" E). Zone I received unsegregated municipal waste between 1999 and 2009. The site was divided into two blocks based on historical operational landfilling logs provided by the facility management, i.e., Block I (younger age group) that was deposited between 2004 and 2009 (15–20 years of burial age at sampling) and Block II (older age group) that was deposited between 1999 and 2003 (21–25 years of burial age at sampling).

The samples used in this study were soil-like materials collected from the landfill mining process in the inactive zone (Zone I) of the facility. Various types of waste were disposed of in this area, and the composition at the sampling site is illustrated in Table 1 and Figure 1. The soil-like landfill materials were collected from four sampling points in Blocks I (16–20-year-old landfill) and II (21–25-year-old landfill) of Zone I. At each sampling point, the samples were collected from five subsampling points and composited. The samples were brought to the laboratory for further analysis.

Table 1. Waste Composition in the 16–20 and 21–25 Year-Old-Landfill (National Waste Management Information System, 2022)

Composition	16–20-yo-landfill (%)	21–25-yo-landfill (%)
Market & household waste	44.13	42.87
Woods	13.17	14.51
Paper	11.78	12.92
Plastics	19.66	18.91
Metal & electronics	3.45	3.37
Fiber	2.86	2.87
Rubber & leather	2.08	2.42
Glass	2.56	2.48

2.2. Chemical Properties Measurement

Chemical properties measured in this study include pH and the concentration of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), in the soil-like material. The total N was measured by the Kjeldahl method, while P and K were measured by the digestion method.

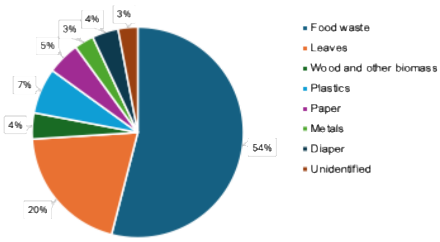

Figure 1. Garbage Composition in the Sampling Site (Pemerintah Daerah DIY, 2023)

For the N measurement, 0.5 g of ground sample was placed in a Kjeldahl flask and mixed with 10 mL sulfuric acid–salicylic acid solution. After 24 hours, 4 g $Na_2S_2O_2{\cdot}5H_2O$ was added, and the mixture was heated gradually to 300 °C for 2–3 h. After cooling, 10 mL of 40% NaOH was added, and the distillate was collected in 20 mL of 1% boric acid containing three drops of Conway indicator. Distillation was stopped at 100 mL, and the distillate was titrated with 0.05 N H_2SO_4 to the endpoint (green to pink). The final titrant volume was recorded.

For the P and K, 0.5g of samples were digested using a strong acid mixture of HNO_3-$HClO_4$ (4:1 v/v) at 180°C. Total P (P_2O_5) and total K (K_2O) were measured using Atomic Absorption Spectrophotometer (AAS). Total NPK was calculated as the total N, P_2O_5, and K_2O.

2.3. Physical Properties Measurement

Physical properties measured in this study are the percentage of particles with a size of 2–4.75 mm and the water content of the soil-like material. Particles of different sizes were separated using the sieving method and weighed. The water content was measured by the gravimetric method.

2.4. Heavy Metal Contaminant Measurement

Due to the diversity of waste thrown in the facility, there is a possibility of heavy metal contamination in the composted materials. Thus, heavy metal content, including lead (Pb) and cadmium (Cd), was measured. Pb and Cd content of the composted material were measured by the acid digestion method. Briefly, 1g of sieved sample was digested with 10mL of concentrated trace-metal grade HNO_3 and $HClO_4$ (4:1 v/v) on a hot plate at 150–200°C until a clear solution was obtained. The digestate was filtered through Whatman No. 42 filter paper and diluted to 50 mL with 0.1 M trace-grade HNO_3. Concentrations of Pb and Cd were quantified using AAS. Quality assurance and quality control measures included procedural reagent blanks, duplicate sample analyses, and standard matrix spikes. Calibration curves exhibited high linearity ($R^2 > 0.998$). Method Detection Limits (MDL) were 0.05 mg/kg for Pb and 0.01mg/kg for Cd. Mean spike recoveries ranged between 94.2% and 102.5%.

2.5. Statistical Analysis

All measured parameters of the soil-like material in the two age groups were compared to the Indonesian National Quality Standard (Standar Nasional Indonesia, SNI) 19-7030-2004 and SNI 7763:2024 to see the potential use as compost and solid organic fertilizer, respectively (Table 2). Data were evaluated for normality using the Shapiro-Wilk test ($p > 0.05$). Differences between the two age groups (15–20 years vs. 21–25 years) across paired spatial composite sampling locations (n = 4, df = 3) were analyzed using paired two-sample t-tests with a significance threshold set at $\alpha = 0.05$ in R statistics software.

Table 2. Standard Quality for Organic Compost and Solid Organic Fertilizer Based on Indonesian National Quality Standard (Standar Nasional Indonesia, SNI) 19-7030-2004 and 7763:2024

Parameter	Compost Quality Standard*	Solid Organic Fertilizer Quality Standard**	Unit
pH level	6.8–7,49	4–9	-
NPK	≥ 0.7	≥ 2	%
Particle with size of 2–4.75 mm	-	≥ 60	%
Water content	≤ 50	8–25	%
Lead (Pb)	≤ 150	≤ 50	mg/kg
Cadmium (Cd)	≤ 3	≤ 2	mg/kg

**SNI 19-7030-2004, quality standard for organic domestic compost, **SNI 7763:2024, quality standard for solid organic fertilizer*

Table 3. Comparison Between Composted Material Characteristics and the Quality Standard (*n* = 4)

Parameter	16–20 years old			21–25 years old		
	Main Values	Compost	Organic Fertilizer	Mian Values	Compost	Organic Fertilizer
pH level	7.41 ± 0.28	Yes	Yes	7.98 ± 0.20*	No	Yes
NPK (%)	0.40 ± 0.001	No	No	0.80 ± 0.003*	Yes	No
Particle with size of 2–4.75 mm (%)	62.38 ± 0.12	-	Yes	79.04 ± 0.20	-	Yes
Water content (%)	29.75 ± 0.05	Yes	No	31.10 ± 0.07	Yes	No
Lead (Pb, mg/kg)	11.32 ± 6.86	Yes	Yes	21.43 ± 9.85	Yes	Yes
Cadmium (Cd, mg/kg)	39.81 ± 9.80	No	No	33.46 ± 10.91	No	No

Note: 'Yes' and 'No' indicate that compost quality meets and does not meet the quality standard, respectively. The asterisk symbol (*) indicates a significant difference at P<0.05.

3. RESULTS AND DISCUSSION

The characteristics of soil-like materials in the waste processing facility in Piyungan varied depending on the landfill age. The chemical and physical properties, as well as the heavy metal content, of the sample were measured to evaluate whether it meets Indonesian regulatory standards for organic compost and solid organic fertilizer quality (Table 3). Overall, the quality of the soil-like material did not meet either the compost or the solid organic fertilizer standards.

3.1. Chemical Properties of Compost

The younger samples (7.41 ± 0.28) met the pH standard for both organic domestic compost and solid organic fertilizer, while the older samples (7.98 ± 0.20) only met the pH standard for solid organic fertilizer (Table 3). None of the soil-like materials met the macronutrient (N, P, and K) content standard for solid organic fertilizer, and only the material collected from the older landfill (0.80 ± 0.003 %) met the standard for organic domestic compost. Both chemical properties (i.e., pH level and macronutrient content) were significantly higher in the samples collected from the older landfill (Figure 2a & b).

Organic matter decomposes by microorganisms over time and gradually releases nutrients, including macronutrients (N, P, and K) into solid and liquid materials (Ma et al., 2022; Tognetti et al., 2008; Yaashikaa et al., 2022). During the decomposition process, the organic matter becomes more stabilized, and the nutrient content increases due to the mineralization of organic compounds. This is evident in the older landfill samples, where higher NPK levels were recorded, indicating a longer period of microbial activity and nutrient accumulation. However, total NPK values measured in this study reflect elemental presence rather than immediate plant-available ionic pools (NH_4^+, NO_3^-, extractable P, and exchangeable K), underscoring the need for supplementary nutrient fortification.

3.2. Physical Properties of Compost

The physical properties of soil-like materials were not different between the younger (62.38 ± 0.12 %) and older (79.04 ± 0.20 %) landfills (Table 3, Figure 2c & d). The number of particles with a size of 2–4.75 mm met the standard of solid organic fertilizer, indicating acceptable textural properties of the materials. However, the water content (29.75 ± 0.05 & and 31.10 ± 0.07 % for younger and older materials, respectively) only met the acceptable standard for organic domestic compost, and not the solid organic fertilizer (Table 3).

The decomposition process generally alters waste appearance, as indicated by the change in physical properties of the waste (Mokhtari et al., 2019). However, the similarity in physical properties across landfill ages in this study suggests limited physical transformation, possibly due to the presence of non-degradable or slow-degrading materials such as plastics, glass, and synthetic fibers. These impurities reduce the overall homogeneity and processability of compostable fractions and may contribute to mechanical inefficiencies in downstream composting processes.

3.3. Heavy Metal Loading

The presence of heavy metals in soil-like materials raises concerns regarding environmental and agricultural safety. Lead (Pb) and cadmium (Cd) were detected in all the samples. The amount of Pb met the organic domestic compost and solid organic fertilizer quality standard (i.e., 11.32 ± 6.86 mg/kg in younger materials and 21.43 ± 9.85 mg/kg in older materials). On the other hand, the amount of Cd exceeded the regulatory limit, with 39.81 ± 9.80 mg/kg and 33.46 ± 10.91 mg/kg Cd detected in younger and older materials, respectively (Table 3). Furthermore, landfill age did not influence the amount of both heavy metals in the compostable materials (Figure 3), indicating that these contaminants persist in the landfill regardless of decomposition duration.

Heavy metal contamination caused global concern, and its persistence in the composted materials can be attributed to inadequate waste segregation and insufficient preprocessing before landfill deposition. Lead and cadmium are among the contaminants of concern (Hölzle et al., 2022; Somani et al., 2020), although the lead content detected in this study met national regulatory criteria. These materials are not biodegradable and may become more concentrated in the remaining compostable fraction as organic matter decomposes and mass is reduced. Consequently, impurities not only reduce the physical quality of compost but also limit its chemical safety and agronomic applicability. Therefore, while longer landfill age generally contributes to improved nutrient content through continued organic matter breakdown, the presence of impurities and contaminants remains a limiting factor in meeting compost quality standards. Further treatment and contamination control at the waste segregation stage are essential to enhance the final compost quality and safety.

In this study, only Pb and Cd were evaluated as primary heavy metals and contaminant indicators. Unsegregated municipal waste may harbor additional toxic trace elements (As, Hg, Cr, Ni, Zn), microplastics, persistent organic pollutants (POPs), and pathogenic microorganisms such as *E. coli* and *Salmonella spp*. Comprehensive ecotoxicological and microbiological screening is required before processing for field application. Furthermore, landfill age in this study was only grouped into two age groups (15–20 and 21–25 years). Future studies may consider continuous age profiling across additional cells, which would provide finer insights into degradation kinetics.

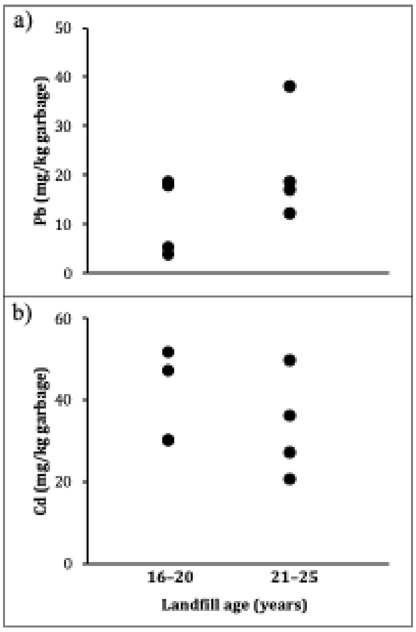

Figure 3. Concentration of a) Lead (Pb) and b) Cadmium (Cd) Content of the composted Landfill Material. No Significant Differences were Found Between the Two Landfill Materials (*P* > 0.05, *n* = 4).

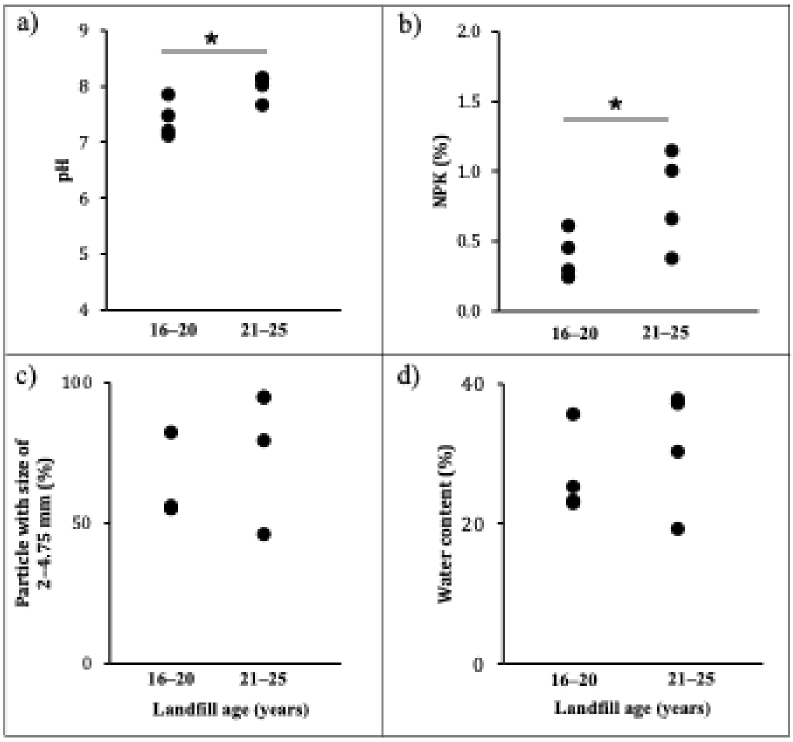

Figure 2. a) pH, b) Total Nitrogen, Phosphate, and Potassium (NPK) Content, c) Particle Size of 2–4.75 mm, and d) Water Content of the Composted Landfill Material. The Asterisk Symbol (*) Indicates a Significant Difference at *P* < 0.05. *n* = 4

4. CONCLUSION

Characterization of soil-like materials from the inactive zone of Piyungan Landfill demonstrated age-dependent chemical stabilization alongside persistent physical and toxicological limitations. Landfill aging resulted in significantly higher pH and total NPK. Older material met the NPK requirements for organic domestic compost, whereas younger material failed. However, both age groups failed the NPK requirement and moisture threshold for commercial solid organic fertilizer. Furthermore, cadmium concentrations exceeded the required standard for domestic compost and solid organic fertilizer. Thus, materials from both are not recommended to be utilized as solid organic fertilizer directly. Further monitoring and specific treatments may be needed to improve the composting process and optimize final product quality for agricultural applications.

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AUTHOR CONTRIBUTION

All authors contributed to the conception of the study. UKAR conducted field sampling and laboratory analysis. AC conducted data analysis, visualization, and prepared the initial manuscript. LP supervised the study and reviewed the manuscript.

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