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IDENTIFICATION AND ANALYSIS OF HAZARDOUS CHARACTERISTICS OF BIOCHEMICAL SLUDGE FROM A WASTEWATER TREATMENT PLANT IN HEBEI PROVINCE

With increasingly stringent environmental regulations, the management and disposal of sludge generated by wastewater treatment plants (WWTPs) have become an urgent problem. Using a WWTP in Hebei Province as an example, this paper examined the identification of hazardous characteristics in sludge. The analysis combined traceability analysis of upstream industrial production processes with plant-specific operating conditions. The primary screening tests for the biochemical sludge included corrosivity, ignitability, leaching toxicity, reactivity, toxic substance content, and acute toxicity. During testing, the risk characteristics of sludge were preliminarily identified using different physical and chemical indices. Subsequently, hazardous sludge characteristics were further identified. Results showed that the pH ranged from 8.22 to 8.28, which is within the non-corrosive range. Furthermore, key leaching indicators were far below the regulatory limits, with total zinc at 0.145 mg/dm³ and inorganic fluoride at 1.20 mg/dm³. Based on these results, the sludge was identified as non-corrosive, non-acutely toxic, non-leaching-toxic, non-flammable, and non-reactive. In addition, total concentrations of toxic constituents were below applicable limits. Therefore, the sludge should be managed as general (non-hazardous) solid waste. To support long-term management, routine sludge testing, stronger oversight of sludge disposal, and further improvement of sludge-related environmental standards are recommended.

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1. INTRODUCTION

With the acceleration of industrialization and urbanization, the volume of wastewater discharged has been increasing steadily [1]. The treatment of sewage sludge has become an important environmental issue. Sludge has both pollutant and resource attributes [2]. If not properly treated and disposed of, it can lead to severe waste resource and environmental pollution, which in turn may pose risks to human health. As urbanization continues, the management and disposal of sludge from wastewater treatment plants (WWTPs) has become a pressing issue [3]. In this study, a WWTP in Hebei Province was selected as a case study to identify the hazardous characteristics of biochemical sludge generated in the biological treatment section and to propose corresponding management recommendations.

The WWTP had a designed capacity of 60,000 m³/day, including municipal sewage and industrial wastewater. The treatment process started with preliminary filtration through the coarse and fine screens, followed by grit removal in the aerated grit chamber. The multi-stage A²/O biological tank then provided efficient biological degradation to remove suspended solids, organic matter, nitrogen, phosphorus, and other pollutants [4]. As a key unit in biochemical treatment, the multi-stage A²/O tank alternates anaerobic, anoxic, and aerobic conditions to promote pollutant transformation and removal, particularly for nitrogen and phosphorus [5]. The effluent met Class B of the *Discharge Standard of Water Pollutants for Municipal Wastewater Treatment Plant (DB11/890-2012)* in Beijing. Subsequently, the secondary sedimentation tank separated the mixed liquid after biological treatment [6, 7]. The sludge evaluated in this study was generated from the biological treatment section (multi-stage A²/O tank and secondary sedimentation tank). The excess activated sludge was pumped to the sludge handling system by a sludge pump, and the dewatered sludge cake was produced after thickening and dewatering.

Regarding the identification and treatment of sludges from the biological treatment unit, their waste classification was unclear. According to the “National Catalogue of Hazardous Wastes” (2021 edition), a thorough hazardous waste identification is required [8]. This process supports regulatory compliance and risk control. Therefore, this study applied China’s hazardous waste identification standards and relevant technical guidance (GB 5085 series) to identify hazardous characteristics of the biochemical sludge generated from the biological treatment section. The assessment focused on typical hazardous characteristics, including corrosivity, ignitability, reactivity, leaching toxicity, acute toxicity, and total concentrations of toxic constituents. In addition, based on source-traceability information and a targeted indicator set, the study developed an engineering-oriented identification workflow and proposed practical recommendations for compliant classification, routine monitoring, and management. The results may serve as a reference for similar municipal-industrial co-treatment WWTPs where sludge classification is uncertain.

raw and auxiliary materials were used for automotive seat frame materials. Therefore, heavy metals and petroleum solvents may be introduced during hot-water cleaning.

Table 1

Statistics of enterprise discharges introduced into the WWTP

Code	Main raw and auxiliary materials	Discharged wastewater	Characteristic pollutant
A	xylitol, wheat flour, grease	non-polluted industrial wastewater, domestic sewage	COD, NH ₃ -N
B	potato, wheat flour, grease	non-polluted industrial wastewater, domestic sewage	COD, NH ₃ -N
C	cattle and sheep	non-polluted industrial wastewater + domestic sewage	COD, NH ₃ -N
D	live sheep, live cattle	non-polluted industrial wastewater	COD, NH ₃ -N, total phosphorus, total nitrogen, pH, BOD ₅ , <i>E. coli</i>
E	raw milk, auxiliary materials, white granulated sugar, and food additives	industrial wastewater + domestic sewage	COD, NH ₃ -N
F	fresh pepper	domestic sewage + non-polluted industrial wastewater	pH, COD, chroma, animal and vegetable oil, SS, BOD ₅
G	CPS powder, diatomite, sodium hydroxide, hydrochloric acid, formic acid, ethyl alcohol, methylbenzene, active carbon, phosphoric acid, acetone, trichloromethane, anhydrous	industrial wastewater + domestic sewage	pH, NH ₃ -N, COD, suspended matter, five-day biochemistry, oxygen demand
H	mica, sodium hydroxide, hydrochloric acid, titanium dioxide, ferric chloride	industrial wastewater	pH, COD, NH ₃ -N
L	aluminum	industrial wastewater + domestic sewage	pH, COD, NH ₃ -N
M	steel	industrial wastewater + domestic sewage	COD, NH ₃ -N, suspended matter, BOD ₅ , petroleum
N	viscose, polyester	industrial wastewater + domestic sewage	COD, NH ₃ -N
O	waterborne cathode electrophoretic coating, abluent	industrial wastewater + domestic sewage	pH, COD, NH ₃ -N
P	lotion, powder, water	domestic sewage	COD, NH ₃ -N
Q	coal, oxygen, nitrogen	domestic sewage	COD, pH, NH ₃ -N, BOD ₅
R	germanium, hydrochloric acid, nitric acid	domestic sewage	NH ₃ -N, COD

COD – chemical oxygen demand, BOD₅ – 5-day biochemical oxygen demand, SS – suspended solids, CPS powder – a powdered raw/auxiliary material used by the enterprise G, retained according to the enterprise-provided material list.

Wastewater from Enterprise P did not involve leachate-toxic substances. For Project Q, pre-reforming water was used in natural gas reforming reactions and was not discharged. Wastewater from Enterprise R was mainly domestic sewage. The domestic wastewater was treated in a septic tank before being discharged into the municipal sewage network. It did not involve leachate-toxic substances.

Sludge sampling and preservation. To ensure accurate characterization of sludge composition and reliable identification of relevant pollutants, representative sampling was essential. In this study, two sludge samples (sludge-1 and sludge-2) were collected from the secondary sedimentation tank of the WWTP. This unit was selected because it is the main accumulation point for excess activated sludge after biological treatment and therefore reflects the integrated contributions of the influent sources.

Sampling was performed in strict compliance with the *Technical Specifications on Identification for Hazardous Waste (HJ 298-2019)* [11]. Given the relatively homogeneous sludge after mechanical mixing and settling, grab sampling was adopted. Two sampling points were established at the sludge discharge outlet, and samples were collected at a depth of 0.5–1.0 m below the liquid surface using a vertical sludge sampler to improve representativeness. Each sample, weighing approximately 5 kg, was immediately sealed in polyethylene containers, labeled, and transported to the laboratory under refrigeration at 4 °C for preservation prior to analysis.

Determination of screening test items. Screening items for biochemical sludge were determined based on the national hazardous waste identification standards and technical guidance (GB 5085 series), together with WWTP process information and influent source-traceability analysis. The selected items covered corrosivity, ignitability, leaching toxicity, reactivity, toxic substance content, and acute toxicity. For each hazardous characteristic, the decision approach was defined as either measurement of key target pollutants or standard-based screening criteria, and the corresponding thresholds in the relevant GB 5085 standards were applied.

Indicator selection was conducted in accordance with GB 5085.7-2007 [12]. Based on a review of raw and auxiliary materials and process flows of upstream enterprises, potential pollutants were identified. Accordingly, representative indicators were selected for analysis, including heavy metals (e.g., Cu, Zn, and Cr) and selected organic compounds (e.g., benzene series and PAHs), consistent with the source-traceability findings and the expected contaminant profile of the influent.

Corrosivity was screened by measuring the pH of sludge slurry and comparing it with the corrosivity criteria specified in the relevant national identification standard ($\text{pH} \geq 12.5$ or $\text{pH} \leq 2.0$). When the measured pH clearly did not meet the corrosivity criterion, no further corrosivity confirmatory testing was performed.

Ignitability was evaluated following the screening criteria and procedures specified in GB 5085.4-2007 [13]. Sludge samples were assessed under the prescribed test conditions

using a standard ignition source, and the results were compared with the standard thresholds to determine whether ignitability was present.

Before chemical analysis, sludge samples were freeze-dried, ground, and sieved through a 100-mesh screen to ensure homogeneity. For heavy metal analysis, aliquots (0.2 g) were microwave-digested using an HNO_3 – HF – H_2O_2 mixture (6:2:1, v/v). For organic pollutants, samples were dehydrated with anhydrous sodium sulfate, ultrasonically extracted with dichloromethane/acetone (1:1, v/v), and purified with silica-gel columns. Heavy metals were quantified by ICP-MS, and selected organic pollutants were analyzed by GC-MS.

Leaching tests were conducted to evaluate potential release of toxic constituents from sludge. The leaching procedure followed HJ/T 299-2007 [14], using a liquid-to-solid ratio of 10: 1 and 18 h of agitation, and the hazardous characteristic was judged against the threshold values specified in GB 5085.3-2007 [9]. Concentrations of selected inorganic and organic indicators in the leachate were measured using ICP-MS for metals and GC-MS for organic compounds.

Differences among samples (e.g., Zn in Table 3) were attributed to two factors. First, industrial influent varied over time due to production cycles and intermittent loadings from multiple enterprises. Second, the sludge matrix was heterogeneous, and metals may occur as precipitates or adsorbed phases that are not uniformly distributed in grab samples.

Reactivity was evaluated according to GB 5085.5-2007 using the standard screening criteria [15]. The sludge was assessed for evidence of abnormal reactions (e.g., heat generation, gas evolution, or abrupt pH change) under the specified test conditions. If none of the criteria were triggered, the sludge was classified as non-reactive without additional confirmatory testing. Total concentrations of toxic constituents were evaluated with reference to GB 5085.6-2007 [10]. Heavy metals were quantified by ICP-MS, and selected organic toxic substances were analyzed by GC-MS as needed, with results compared against the applicable criteria.

Acute toxicity was evaluated following GB 5085.2-2007 [17]. Acute toxicity tests were performed using appropriate test organisms (such as *Daphnia magna* or *Danio rerio* embryos). The test organisms were exposed to different concentrations of sludge extracts, and endpoints such as mortality, immobilization, or abnormal development were observed and recorded to assess the acute toxicity of the sludge. When the screening result did not indicate acute toxicity, no animal-based bioassay or aquatic organism exposure test was conducted.

Risk characteristics identification and analysis method. During testing, measured physicochemical parameters were compared with the relevant standards and decision thresholds. Based on these comparisons, the sludge was preliminarily screened for potential hazardous characteristics. For example, if the concentration of a heavy metal in the leachate exceeded the applicable limit, the sludge was flagged as potentially exhibiting leaching toxicity. Following the initial screening, confirmatory analyses were performed as needed,

including replicate measurements, method cross-checks, or additional tests under specified conditions. The results were then used for an overall assessment of the sludge's hazardous characteristics.

3. RESULTS AND DISCUSSION

3.1. TESTING AND ANALYSIS OF PRELIMINARY SCREENING SAMPLE

After sampling and preservation, the sludge samples were analyzed for their major and potential hazardous components. Compositional analysis (including GC-MS) [18] indicated that the sludge mainly comprised water and major inorganic or organic constituents, including aluminosilicate, inorganic iron salts, cellulose, and polyacrylamide; the results of composition determination of the two sludge samples are shown in Fig. 2. Water accounted for 86.5 wt % of the sludge. This high moisture content is typical for activated sludge and has important implications for handling, transport, and subsequent treatment or disposal.

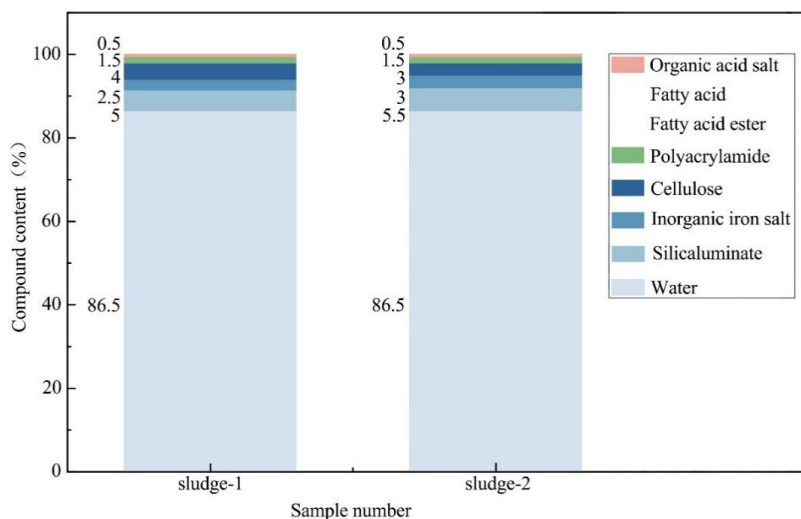


Fig. 2. Composition of preliminary screening samples

Based on the average values of the two samples, aluminosilicates accounted for 5.25 wt % of the sludge. Aluminosilicates are common inorganic constituents in soil and sediment. They may enter WWTP through surface runoff from surrounding areas or industrial wastewater inputs. Inorganic iron salts constituted 2.75 wt % of the sludge and may originate from industrial inputs, pipe corrosion, or iron-based coagulants used in treatment. Iron salts can affect redox conditions and may participate in chemical transformations within the sludge matrix. Cellulose comprised 3.5 wt % of the sludge and likely

derived from biodegradable organic matter in wastewater, including plant debris and microbial biomass. Although generally biodegradable, cellulose contributes to the organic fraction of sludge. Polyacrylamide accounted for 1.5 wt % and is commonly used as a flocculant in wastewater treatment. Its presence in sludge reflects its role in solid-liquid separation. However, potential persistence and transformation of products may warrant attention in environmental management.

3.2. PRELIMINARY SCREENING OF HAZARDOUS PROPERTIES OF SLUDGE

Preliminary screening for sludge corrosivity. According to the wastewater quality requirements for the influent and effluent of the WWTP, pH is generally controlled between 6 and 9 to ensure stable operation of the activated sludge system, and effluent pH is typically maintained within the same range [19]. The measured pH values of the sludge samples were 8.28 and 8.22 (Table 2), indicating a slightly alkaline condition. According to the corrosivity identification criterion ($\text{pH} \geq 12.5$ or $\text{pH} \leq 2.0$) specified in the relevant national standard, the sludge did not meet the corrosivity threshold and was therefore classified as non-corrosive in the screening step. Although the pH values were slightly alkaline, they may influence the solubility of certain constituents in the sludge. For example, the mobility and leaching potential of some heavy metals can change with pH during sludge handling and disposal.

Table 2

pH of preliminary screening for sludge

Test item	Standard limit	Sludge-1	Sludge-2
pH	$\text{pH} \geq 12.5$ or $\text{pH} \leq 2.0$	8.28	8.22

Notably, the slightly alkaline condition ($\text{pH} > 8.0$) can favor the immobilization of many cationic heavy metals. Under alkaline conditions, metals such as Cu, Zn, Pb and Ni tend to precipitate as hydroxides or carbonates, which reduces their dissolved fractions and thus their potential for leaching. This interpretation is consistent with the low leaching concentrations observed in the subsequent leaching tests.

Based on the pH-based screening result, no further confirmatory corrosivity testing was required in this study. This conclusion follows the standard pH thresholds for corrosivity. Nevertheless, other factors (e.g., aggressive chemicals) could affect material corrosion behavior and should be considered where relevant.

Preliminary screening for sludge ignitability. A comprehensive analysis of the sludge revealed that its main components were water, aluminosilicate, inorganic iron salt, cellulose, and polyacrylamide. As the dominant component, water acts as a diluent and heat sinks in the sludge matrix. Due to high heat capacity, it can absorb a significant amount

of heat, thereby reducing the likelihood of rapid temperature rises that could potentially lead to combustion. Cellulose is a polysaccharide and is generally considered a relatively stable organic compound under normal temperature and pressure conditions. Although it is an organic material, its molecular structure and the energy required to break its chemical bonds make it non-spontaneously combustible under standard environmental conditions.

Aluminosilicate, an inorganic compound, is well known for its thermal stability. It has a high melting point and does not readily participate in exothermic reactions that could cause ignition or combustion. Polyacrylamide, a synthetic polymer, also demonstrates stability under normal temperature and pressure. Its chemical structure is relatively inert, and it does not decompose or release flammable gases easily under ambient conditions. This overall composition of the sludge indicates a low inherent risk of ignitability.

To accurately classify the sludge in terms of its ignitability, a detailed comparison was made with the *Identification standards for hazardous wastes-identification for Ignitability (GB 5085.4-2007)* [13]. Under standard temperature and pressure conditions (25°C, 101.3 kPa), which are representative of typical environmental settings, the sludge showed no signs of spontaneous combustion. Spontaneous combustion occurs when a material undergoes an exothermic reaction with oxygen in the air without an external ignition source, leading to self-ignition. The absence of such behavior in the sludge indicates that its components do not react with oxygen in a way that would cause a self-sustaining ignition event.

The sludge did not ignite due to friction. Friction can generate heat, and in the case of some material, this heat can be sufficient to reach their ignition temperature. However, the sludge, with its specific composition of water, cellulose, silicate, and polyacrylamide, was able to dissipate the heat generated by friction effectively, preventing ignition. Even when an external ignition source was applied, the sludge did not sustain violent combustion. Once ignited, materials that are classified as flammable will continue to burn vigorously, consuming oxygen and releasing large amounts of heat. In contrast, the sludge was extinguished quickly, indicating that it lacks the necessary combustible properties to support a continuous and intense combustion process.

Based on the above-mentioned analysis of sludge components and their behavior in relation to the ignitability standards, it was concluded that the sludge should be excluded from being classified as flammable. This classification is crucial as it has significant implications for sludge management, including storage, transportation, and disposal. Non-flammable sludge can be handled using standard procedures and equipment, reducing the need for special safety measures that would be required for flammable materials.

Preliminary screening for leaching toxicity of sludge. To accurately evaluate the leaching toxicity of the sludge, a set of detection parameters was proposed based on the relevant leachate indicators in the *Identification standards for hazardous wastes-identification for leaching toxicity (GB 5085.3-2007)* [9]. The initial step in assessing the leaching toxicity of the sludge was to conduct a comprehensive analysis of potential pollutants from the source. By tracing back the industrial processes and wastewater sources contributing to

the sludge, a broad spectrum of substances was identified as potential contaminants in the leachate. The testing results of the preliminary screening sample, as presented in Table 3, further supported these findings. Heavy metals emerged as a significant concern.

Table 3

Leaching toxicity of preliminary screening samples

Test item	Limit (GB 5085.3-2007) [g/dm ³]	Sample number/Test result	
		Sludge-1 [mg/dm ³]	Sludge-2 [mg/dm ³]
Total beryllium	0.02	ND	ND
Total chromium	15	0.0066	0.0048
Total nickel	5	0.0233	0.0150
Total copper	100	0.0066	0.0080
Total zinc	100	0.145	0.0415
Total arsenic	5	0.0289	0.0155
Total selenium	1	ND	ND
Total silver	5	ND	ND
Total cadmium	1	ND	ND
Total barium	100	0.0659	0.0522
Total lead	5	ND	ND
Total mercury	0.1	0.0035	0.0021
Alkyl mercury	ND	ND	ND
Hexavalent chromium	5	ND	ND
Inorganic fluoride (excluding calcium fluoride)	100	1.20	1.05
Cyanides expressed as CN ⁻	5	1.56	1.39
Benzo[a]pyrene	0.0003	ND	ND
Benzene	1	ND	ND
Toluene	1	ND	ND
Ethylbenzene	4	ND	ND
Xylene	4	ND	ND
Trichloromethane	3	ND	ND

ND (not detected) means that the measured concentration was below the method detection limit of 10 ng/dm³ (i.e., 1.0×10^{-5} mg/dm³).

Metals such as copper, zinc, lead, chromium, mercury, beryllium, barium, nickel, silver, arsenic, and selenium are often introduced into the wastewater treatment system through industrial discharges from sectors like mining, electroplating, and manufacturing. These metals can accumulate in the sludge and have the potential to leach out into the environment, posing risks to human health and ecosystems due to their toxicity, persistence, and bioaccumulative properties.

In addition to heavy metals, inorganic fluoride (excluding calcium fluoride) and cyanides (expressed as CN^-) were also identified as potential leachate toxins. Inorganic fluoride can originate from industrial processes involving the use of fluorine-containing compounds, such as in the production of aluminum or glass. Cyanides are commonly found in wastewater from industries like metal processing and electroplating, where they are used in metal-cleaning and surface treatment operations.

Organic pollutants like toluene, ethylbenzene, xylene, trichloromethane, and benzo[a]pyrene were also identified as potential leachate components. Toluene, ethylbenzene, and xylene are volatile organic compounds (VOCs) often associated with industrial solvents, gasoline, and chemical manufacturing. Trichloromethane, also known as chloroform, can be formed during disinfection processes in wastewater treatment or from industrial discharges. Benzo[a]pyrene, a polycyclic aromatic hydrocarbon (PAH), is a well-known carcinogen that can enter the wastewater system through sources such as incomplete combustion of organic matter in industrial facilities or vehicle emissions that eventually reach the sewer system. Overall, all measured leachate indicators, including CN^- and inorganic fluoride, were below the corresponding GB 5085.3-2007 limits [9].

Preliminary screening for sludge reactivity. Based on the process of sewage treatment and sludge generation, the sludge was not classified as an oxidizing waste or organic peroxide, and it did not exhibit explosive properties as outlined in the *Identification standards for hazardous wastes-identification for reactivity (GB 5085.5-2007)* [15]. The sludge and its generation process contain water, so it did not have water-reactive properties. Based on the preliminary screening results of the sludge (see Table 3), trace amounts of cyanides (13.01–43.38 mg/kg) and sulfides (0.28–3.24 mg/kg) were detected. Considering that CN^- and S^{2-} may generate HCN and H_2S under acidic conditions, a conservative worst-case estimation was performed based on the measured concentrations. Under acidic conditions, the maximum potential releases were estimated as 46.850 mg/kg sludge for HCN and 3.44 mg/kg sludge for H_2S . Both values were below the screening thresholds specified in GB 5085.5-007 [15]. Therefore, the sludge did not contain significant amounts of hazardous substances such as sulfides or cyanides. Overall, it was determined that the sludge was not reactive and did not require further reactivity testing.

Preliminary screening of contents of toxic substances. The identification of these potential toxic substances is of paramount importance. Each of these pollutants has unique environmental and health implications. Due to their toxicity, persistence, and bioaccumulative nature, heavy metals can cause severe damage to ecosystems and human health. For example, mercury is known to cause neurological disorders in humans, especially when it accumulates in the food chain through fish consumption. Arsenic exposure is linked to various cancers, skin lesions, and cardiovascular diseases. At high concentrations, fluoride ions can lead to dental and skeletal fluorosis in humans and can also be toxic to aquatic

life. Cyanide ions are highly toxic, capable of inhibiting cellular respiration and causing rapid death in living organisms.

Organic pollutants also pose significant risks. Petroleum solvents can contaminate soil and groundwater, causing soil degradation and water pollution. Formaldehyde is a known human carcinogen, and long-term exposure can lead to respiratory problems and cancer. PAHs, such as benzo[a]pyrene, are potent carcinogens that can cause DNA damage and increase the risk of cancer in humans and animals. By identifying these potential pollutants, we can take proactive measures to manage and mitigate their impact.

Compared with previous studies, the identified potential toxic substances in the sludge both align with and expand upon previous findings. Previous studies have often focused on a subset of these pollutants, typically the more common heavy metals like lead, mercury, and arsenic, and well-known organic pollutants such as benzene and toluene. However, this study broadened the scope by including less-studied heavy metals like beryllium, vanadium, and palladium, as well as a more comprehensive list of PAHs. This expansion is crucial as it provides a more complete picture of the potential contaminants in the sludge. For example, while previous research might have emphasized the risks associated with a few major heavy metals in wastewater-derived materials, the inclusion of additional metals in this study highlights the need for a more holistic approach to pollution control and management.

Preliminary screening of acute toxicity. Environmental pollutants in the air primarily enter the body through inhalation by animals. The identified sludge was a solid material with high moisture content and did not contain a significant amount of volatile toxic substances. Therefore, animals' inhalation through steam, smoke, or dust was not a major exposure pathway; the harmful characteristics of acute inhalation toxicity could be excluded. The sludge did not pose a risk due to its non-adsorptive and weak adsorption characteristics [16]. Therefore, the acute dermal toxicity risk was also excluded. Given that metals, toxic organic substances, and other characteristic pollutants were contained in the sludge, they might migrate to drinking water and food, and be absorbed into the body via the gastrointestinal tract. Therefore, oral ingestion was the most significant exposure pathway, which was importantly evaluated.

3.3. IDENTIFICATION OF HAZARDOUS CHARACTERISTICS OF SLUDGE

According to the Technical Specification for Hazardous Waste Identification" (HJ 298-2019) [11], hazardous characteristics of sludge were identified. Based on the identification of the solid waste property of the material and a comparison with the *National Catalogue of Hazardous Wastes* [8], the sludge was classified as solid waste but not listed in the *National Catalogue of Hazardous Wastes*. Based on the production process, main raw and auxiliary materials, and the analysis of preliminary screening samples, it was found that the sludge did not exhibit corrosivity, ignitability, reactivity, inhalation toxicity,

or dermal acute toxicity. Based on the testing results and data analyses, beryllium, total silver, alkyl mercury, hexavalent chromium, benzo[a]pyrene, benzene, toluene, ethylbenzene, xylene, and chloroform were not detected. However, inorganic fluoride and cyanide (as CN^-) were detected. However, their leachate concentrations were below the corresponding limits specified in GB 5085.3-2007 [9]. Therefore, the sludge did not exhibit leaching-toxicity characteristics.

Table 4

Assessment of the acute oral toxicity of sludge components

Component	Category	Acute oral toxicity LD_{50} [mg/kg]	Maximum content in sludge [wt %]
Beryllium oxide	carcinogenic	2062	0.0000556
Vanadium	toxic	50	0.00147
Titanium	toxic	50	0.0670
Manganese	toxic	9000	0.0297
Cobalt sulfate	carcinogenic	424	0.00147
Nickel subsulfide	carcinogenic	5	0.00211
Barium chloride	toxic	118	0.02234
Lead phosphate	reproductive toxic	50	0.000969
Arsenic triiodide	highly toxic	5	0.00522
Selenium chloride	highly toxic	5	0.000168
Mercury iodide	highly toxic	5	0.0000738
Petroleum solvents	toxic	50	0.0129
Sodium cyanide copper	highly toxic	5	0.000110
Formaldehyde	carcinogenic	800	0.00111
Acetone	toxic	5800	0.00150
Palladium	toxic	50	0.00000185
Organic acid salts	—	5000	0.5
Fatty acids			
Fatty acid esters			
Polyacrylamide	—	190	1.5
Cellulose	—	5000	4.0
Inorganic iron salts	—	5000	3
Silica-alumina salts	—	5000	5.5
Water	—	—	86.5
Estimated minimum oral LD_{50} , mg/kg			7312

The values in the last column represent the maximum estimated mass fractions of the corresponding substances in the sludge. For the major matrix components, including water, polyacrylamide, cellulose, inorganic iron salts, and silica-alumina salts, the values were derived from the compositional analysis shown in Fig. 2. These values were used for the conservative estimation of acute oral toxicity. The estimated minimum oral LD_{50} of the sludge sample was calculated under a conservative scenario based on the contents of the listed substances and their corresponding oral LD_{50} values.

For the leaching toxicity indicators of the collected sludge samples, the test results did not exceed the standard limits set by GB 5085.3-2007 [9]. Therefore, it is concluded that the sludge did not exhibit the characteristics of leaching toxicity. As shown in Table 4, the toxic substance content in the samples was used to estimate the oral acute toxicity of the sludge. Considering the worst-case scenario, the calculated estimation values of oral acute toxicity for the sludge were much higher than the corresponding median lethal dose limit value of 200 mg/kg set by the *Hazardous Waste Identification Standard for Acute Toxicity Screening (GB 5085.2-2007)* [17]. It could be concluded that the sludge did not exhibit acute toxicity as a hazardous characteristic.

The comprehensive identification of the sludge's hazardous characteristics has important implications for compliant management. Classifying the material as general solid waste rather than hazardous waste can simplify handling, transport, and disposal for the WWTP. This classification may translate into lower operational costs and reduced administrative burden, as the facility can avoid requirements associated with hazardous-waste transport and specialized disposal routes (e.g., hazardous-waste incineration) and follow the applicable procedures for general solid waste.

Furthermore, this study provided a practical reference for other municipal-industrial co-treatment WWTPs. It demonstrates that the acceptance of industrial wastewater does not necessarily result in hazardous sludge. Instead, an evidence-based identification framework that integrates source-traceability information with targeted screening and standard-based decision criteria can support scientifically defensible classification and management decisions, helping plants avoid unnecessary over-classification while maintaining environmental and regulatory safeguards.

In terms of disposal, it can be handled using standard solid waste disposal methods, reducing the need for specialized and costly hazardous waste treatment facilities. The lack of corrosivity, ignitability, reactivity, inhalation toxicity, dermal acute toxicity, leaching toxicity, and acute toxicity means that the potential risks to human health and the environment during storage, transportation, and disposal are significantly reduced. For example, in a landfill setting, the non-leaching-toxic nature of the sludge ensures that it is less likely to contaminate groundwater, protecting water resources.

In summary, the sludge from the WWTP did not exhibit hazardous characteristics such as corrosivity, acute toxicity, leaching toxicity, ignitability, reactivity, or excessive content of toxic substances after identification. It was recommended to manage the sludge as generally solid waste.

4. CONCLUSIONS

To ensure the stable operation and treatment effectiveness of WWTP, the following management recommendations have been proposed.

- Industrial contributors should clearly document wastewater sources, treatment processes, treatment capacity, and chemicals used. On-site facilities and equipment should be properly maintained to ensure stable operation and compliant influent quality.
- Other solid wastes generated at the WWTP were outside the scope of this assessment and should not be co-stored or co-disposed with the sludge evaluated in this study.
- A source–sludge linkage protocol is recommended to improve operational control. Firstly, monitoring indicators should be aligned with the characteristic pollutants identified by source-traceability analysis, with emphasis on heavy metals (Zn, Cu, Ni, and Cr) and trace organic solvents (e.g., toluene), rather than relying only on conventional indicators such as COD. Secondly, monthly compliance checks are recommended for higher-risk upstream enterprises (e.g., metal processing) to track variability in pollutant loads. Thirdly, a tiered response mechanism should be established. If influent concentrations of target hazardous substances exceed predefined warning thresholds, sludge-toxicity testing should be increased from routine quarterly monitoring to a higher frequency (e.g., daily, as warranted by risk) to detect potential accumulation from intermittent (“shock”) loadings before disposal.

Overall, this study developed and applied an engineering-oriented workflow that integrates influent source-traceability information with targeted screening and standard-based decision criteria to identify hazardous characteristics of WWTP sludge. Based on the results obtained during the sampling period, and under the current influent composition and operational conditions of the WWTP, the evaluated sludge can be managed as general solid waste rather than hazardous waste. The workflow and findings may provide a reference for similar municipal-industrial co-treatment WWTPs facing uncertain sludge classification.

This study also has limitations, including the sampling period and sample size. Future work should conduct long-term monitoring across seasons and under varying operating conditions to further verify the stability of the sludge’s non-hazardous classification and support consistent environmental safety.

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