Identification of industrial sewage sludge based on heavy metal profiles: a case study of printing and dyeing industry

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Abstract

The illegal disposal of industrial sewage sludge has caused serious environmental pollution. To develop identification technology of industrial sewage sludge based on the characteristic fingerprints is a promising method that is helpful to clarify the responsibility of illegal enterprises. In this study, heavy metal profiles of sewage sludge from industries (including printing and dyeing industry and other industries) and municipal sewage treatment plant located in eastern China were determined, and their performance of classification was evaluated by principal component analysis (PCA) and linear discrimination analysis (LDA). Results showed that heavy metal composition can be an effective tool for distinguishing sewage sludge between printing and dyeing industry and other industries, with an accuracy rate of 82.9%. Meanwhile, heavy metal speciation may be a promising method for identification of printing and dyeing sludge from municipal sewage sludge, the accuracy rate of which reached 100%. Moreover, antimony (Sb) and zinc (Zn) are two indicators, which can be used to identify sewage sludge between printing and dyeing sub-industries, and the accuracy rate was 90%. We concluded that heavy metal profiles may be a precise and promising tool for identification of printing and dyeing sludge. This study developed a potential method for tracing the source of industrial sewage sludge and establishing the identification database of industrial sewage sludge and provided technical support for the government to supervise the illegal dumping and disposal of industrial sewage sludge.

Keywords Traceability technology • Source identification • Illegal disposal • Heavy metal composition • Heavy metal speciation • Characteristic fingerprints • Database

Introduction

With the development of urbanization and industrialization, water consumption and wastewater production are increasing annually in China. As a result, more and more sewage treatment facilities have been built to meet the increasing demand for wastewater treatment. According to statistics (GOMEP 2016), a total of 3809 wastewater treatment plants (WWTPs) have been established in China in 2016, which has doubled in the past decade (Xu et al. 2019; Zhou et al. 2019). Similarly, the sewage treatment capacity (i.e., the wastewater treatment rate) of WWTPs has rapidly increased from 25.6 (70.2%) to 46.5 billion m³/a (94.5%) (MOHURD 2017; Zhou et al. 2019). With the increase of sewage treatment capacity, the total sewage sludge production increased significantly. China’s sewage sludge production (80% moisture content) increased from 30 million tonnes in 2012 to 34 million tonnes in 2015, and it is expected to exceed 60 million tonnes in 2020, with an annual growth rate of 15% (Chen et al. 2019; Feng et al. 2015). The accumulation of sewage sludge will pose growing environmental problems and secondary pollution if treated improperly (Shao et al. 2015), due to sewage sludge can cause toxicity and genotoxicity in plants and animals (da Silva et al. 2021; de Siqueira et al. 2021; Zuo et al. 2021).

The environmental impact of industrial sewage sludge is significantly greater than that of municipal sewage sludge because of its high content of toxic and harmful pollutants, such
as heavy metals, organic contaminants, and pharmaceuticals (Liu et al. 2021). Moreover, the yield of industrial sewage sludge is obviously greater than that of municipal sewage sludge. Generally, treatment of 10,000 tonnes of domestic wastewater produces 5-8 tonnes of sewage sludge with 80% water content, while for industrial wastewater, it produces 10-30 tonnes of sewage sludge. However, in China, the combined treatment of municipal wastewater and industrial wastewater brings obstacles to the disposal of sewage sludge (Feng et al. 2015), resulting in its inability to be applied to land as fertilizer or soil conditioner (Geng et al. 2021). As high as 35% of industrial wastewater enters WWTPs in China, while only 20% of sewage sludge is treated and disposed safely (Feng et al. 2015). The Chinese government is actively addressing the issue of sewage sludge treatment and disposal and has proposed that the non-hazardous treatment and disposal efficiency of sewage sludge is expected to be 90% by 2020 (NDRC, MOHURD 2017). To achieve this goal, China is actively deploying and building sewage treatment facilities to meet the requirement of the separate treatment of municipal wastewater and industrial wastewater. However, implementation of this proposal will remain a challenge. Many industrial enterprises in China are scattered and not integrated into industrial parks for unified management. Meanwhile, most industrial parks are not equipped with independent wastewater treatment facilities. Furthermore, different from developed countries, China’s investment in sewage sludge treatment and disposal (29.4 billion CNY/year) is much lower than that in wastewater treatment (193.8 billion CNY/year) (NDRC, MOHURD 2017). Low capital investment and marketization operation make enterprises bear most of the pressure of sewage sludge treatment and disposal. Enterprises involved in wastewater discharge are required to set up wastewater treatment facilities or concentrate their wastewater into the wastewater treatment facilities in industrial park for centralized treatment. The sewage sludge produced by the sewage treatment facilities should be safely treated and disposed by enterprises with relevant qualifications, the cost of which is relatively high (~400 yuan per tonnes). To save these costs, some enterprises may dump or bury sewage sludge privately. However, it is difficult for regulators to identify the companies responsible for these violations. One of the feasible methods is to develop an effective and promising identification technology based on the characteristic fingerprints of sewage sludge that can be used to trace the enterprises discharging sewage sludge. The key is to select indicators that can represent different industries. Compared with organic pollutants and pathogens, heavy metals are ubiquitous in industrial sewage sludge, and they cannot be degraded under natural conditions (Dai et al. 2019; Marchenko et al. 2018; Xu et al. 2017). Common treatment methods, e.g., composting and aerobic/anaerobic digestion, cannot remove heavy metals from sewage sludge (Chipasa 2003; Paulsrud and Nedland 1997). Likewise, the sludge disposal measures of land application, incineration, and landfill can effectively degrade organic pollutants; however, these methods cannot remove heavy metals, leading to their accumulation in the sewage sludge (Cai et al. 2007; Williams 2005). Moreover, the concentration and composition of heavy metals in sewage sludge discharged by industrial enterprises are quite different due to different production processes and raw and auxiliary materials. Therefore, heavy metals possess the properties of characteristic fingerprints in industrial sewage sludge, and we predict heavy metal profiles can be used to identify sewage sludge between different industries, which may be a potential method for tracing the source of illegally discharged industrial sewage sludge.

China has the largest textile production and manufacturing market, ranking first in terms of exports of textiles and clothing, with an annual export value of $109.9 billion of textiles and $158.4 billion of clothing (Sheng 2018). As an important part of textile manufacturing, printing and dyeing industry is a traditional pillar of light industry in China. Printing and dyeing wastewater generally has high concentration of contaminants and a complex chemical composition (including heavy metals, organic pollutants, and dyes), and it is difficult to be removed by conventional water treatment technologies (Liang et al. 2013). The major treatment technologies of printing and dyeing wastewater contain physicochemical treatment (such as coagulation or flocculation) and biodegradation, both of which produce a large amount of sewage sludge (Gotvajn and Zagorc-Koncan 2004). Studies indicated that 1000 tonnes of printing and dyeing wastewater can produce 10 tonnes of printing and dyeing sludge (80% moisture content) (Zhang et al. 2018). According to China Statistical Yearbook on Environment 2016 (NBS 2016), China produced 20.2 million tonnes of printing and dyeing sludge from 2.02 billion tonnes of printing and dyeing wastewater in 2015 (Ran et al. 2019). The production of a large amount of printing and dyeing sludge is easy to cause environmental risk because of the weak legal consciousness of enterprises and the high cost of sludge treatment (most printing and dyeing enterprises are small- and medium-sized enterprises). Therefore, the development of traceability technology of sewage sludge is conducive to the emergency response and accountability for environmental risks caused by illegal disposal of printing and dyeing sludge.

In this study, the heavy metal profiles of industrial and municipal sewage sludge were analyzed to evaluate the application of this technique in identification of printing and dyeing sludge. The aim of the present study was to establish a new and potential method for tracing the source of industrial sewage sludge and provide technical support for the government to supervise the illegal disposal of sewage sludge.
Materials and methods

Sample collection

A total of 41 sewage sludge samples were collected from eastern China (Fig. 1), including 23 sewage sludge samples from printing and dyeing industry (PD); 14 sewage sludge samples from other industries, containing metalworking industry (MW), chemical industry (CH), papermaking industry (PM), rubber and plastic industry (RP), and electron industry (EL); and 4 sewage sludge samples from municipal sewage treatment plant (MS) (Table S1, “S” indicates the Supporting Information here and thereafter). The collected sewage sludge samples were wrapped in silver paper and frozen in the refrigerator at −20°C. The frozen samples were placed on the stainless steel disk of the freeze-dryer and freeze-dried at −50°C for 48 h. The freeze-dried samples with large particles of impurities (such as stone particles) removed were pulverized by using a glass mortar and pestle, passed through a 60-mesh/inch (250 μm) nylon sieve, and then stored in glass bottles under −20°C conditions.

Sample preparation

Total extraction

In the present study, the total concentration of heavy metals was extracted by mixed acid digestion method (Yan et al. 2018). Briefly, 0.2 g of sewage sludge sample was added into the teflon digestion tube, and then 12 mL of HCl-HNO₃ (3:1, v/v) was added. The contents were heated at 130°C and evaporated to near dryness. 5 mL of HF was added to the digestion tube and heated at 130°C for half an hour, and then 8 mL of HClO₄ was added, and the temperature was adjusted to 200°C until the sample was clarified. 4 mL of HNO₃ (1:1, v/v) was added to the digestion tube and heated at 130°C until the remaining 1-2 mL of the sample was obtained. After cooling, the sample was diluted to 10 mL with 2% HNO₃ and passed through a 0.22-μm syringe filter. The filtered sample was transferred to a clean centrifuge tube and stored in a 4°C refrigerator.

Sequential extraction

In this study, the three-step sequential extraction method proposed by the European Communities Bureau of Reference (BCR) (Rauret et al. 1999) was performed to extract the speciation of heavy metals, the operation process of which was detailed in the previous studies (Chen et al. 2008; Wang et al. 2005). Heavy metals were divided into four fractions, namely acid-soluble/exchangeable fraction (F1), reducible fraction (F2), oxidizable fraction (F3), and residual fraction (F4). In addition, we improved the extraction method of F4 and applied the mixed acid digestion method (“Total extraction” section) to extract F4.

Sample analysis

The concentrations of copper (Cu), manganese (Mn), nickel (Ni), and zinc (Zn) were determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES, Agilent), the wavelengths of which were 327.395 nm, 257.610 nm, 231.604 nm, and 213.857 nm, respectively. The concentrations of barium (Ba), chromium (Cr), cobalt (Co), plumbum (Pb), antimony (Sb), and vanadium (V) were determined using inductively coupled plasma mass spectrometry (ICP-
The carrier gas was Ar (99.999% purity). The partial pressure was maintained at 0.6-0.7 Mpa. The regression coefficient ($R^2$) of the constructed standard curve was greater than 0.999.

**Quality assurance and quality control (QA/QC)**

The QA/QC procedures were performed by analysis of blanks (including method blanks and procedure blanks), replicates, and standard reference materials (SRM2781, American National Standards Institute; GBW07404 and GBW07430, National Research Center of Certified Reference Materials of China). Two blank samples and one standard sample (3 replicates for each standard sample) were determined in each batch (20 samples). 20% of the total samples were performed on parallel experiments (2 samples for every 10 samples). During the experiment, the recovery rates of the standard samples ranged from 70 to 110%, showing a good agreement with the certified values. Meanwhile, the standard deviations between the duplicated samples were within 10%. In the present study, three times of the standard deviation of the blank values was used as limit of detection (LOD), and ten times of that was used as limit of quantitative (LOQ).

**Statistical analysis**

SPSS 19.0 (SPSS Inc., USA) was applied to data analysis. One-way analysis of variance (ANOVA) was used to test the significance of differences between sewage sludge from different industries based on the contents of heavy metals and the relative percentages of heavy metals, and the significance was set as $p < 0.05$. A post hoc test was carried out using the least significant difference (LSD) or Tamhane’s T2 to assess significance. Pearson correlation test was performed to analyze the possible relationships among different heavy metals. Principal component analysis (PCA) was employed on the percentages of heavy metal contents and heavy metal forms to reveal the variability of sewage sludge among industries. Linear discriminant analysis (LDA) was used to evaluate whether the different groups could be mathematically distinguished according to heavy metal contents and heavy metal forms for the prediction of industrial source. Due to the limited number of samples, self-verification was used to assess the accuracy of the obtained models.

**Results and discussion**

**Heavy metal concentration**

The heavy metal concentration of printing and dyeing sludge was 3060 ± 1770 mg kg$^{-1}$, which was similar to municipal sewage sludge (3450 ± 1770 mg kg$^{-1}$), but less than sewage sludge from other industries (12,000 ± 19,500 mg kg$^{-1}$) ($p > 0.05$; Fig. 2). Specifically, the heavy metal concentrations of sewage sludge from PD (chemical fiber), PD (cotton), and PD (wool, silk, and others) were 2820 ± 1390 mg kg$^{-1}$, 2930 ± 1590 mg kg$^{-1}$, and 4400 ± 3440 mg kg$^{-1}$, respectively. The most abundant heavy metal in printing and dyeing sludge was Zn (50.8-5160 mg kg$^{-1}$), followed by Mn (72.2-2200 mg kg$^{-1}$), Sb (3.65-2560 mg kg$^{-1}$), Cr (25.0-1310 mg kg$^{-1}$), Cu (5.38-2310 mg kg$^{-1}$), and Ba (28.3-504 mg kg$^{-1}$). V, Ni, Pb, and Co were relatively scarce, the contents of which were 6.88-241 mg kg$^{-1}$, 8.32-203 mg kg$^{-1}$, 5.23-200 mg kg$^{-1}$, and 3.85-136 mg kg$^{-1}$ (Table S2). This was consistent with the results obtained by Liang et al. (2013), which indicated that the heavy metal contents of printing and dyeing sludge varied greatly. There was a significant difference in Sb between PD and other industries ($p < 0.01$) and MS ($p < 0.05$). However, for other heavy metals, no significant difference was found between these groups. Consequently, Sb could be used as a characteristic heavy metal in printing and dyeing sludge (Li et al. 2018).

A significant correlation between heavy metals may imply that these elements have a same source or a similar process of transformation and migration (Suresh et al. 2011). The results showed that Co had significant positive correlations with Mn ($r = 0.737; p < 0.01$) and Cr ($r = 0.507; p < 0.05$). Likewise, there was a significant positive correlation between Ba and Cu ($r = 0.683; p < 0.01$) (Table S3). Cr and Co are the main components of metal complex reactive dyes, and MnO$_2$ is an oxidizing agent in neutral dyes (mainly composed of metal complex dyes), resulting in Cr, Co, and Mn having a same source of neutral dyes (Rongqi 2000). Copper salt is used in fixing agent and finishing agent as an important auxiliary agent, and Ba is an important component of auxiliary agent.

![Fig. 2 Box plot of heavy metal contents in industrial and municipal sewage sludge (mg kg$^{-1}$). PD and MS represent printing and dyeing industry and municipal sewage treatment plant, respectively](image)
used in the textile process, leading to Cu and Ba having a same source of auxiliary agent (Ying et al. 2011). However, there were differences in the correlation of heavy metals in printing and dyeing sub-industries (Tables S4, S5, S6). Pb had significant positive correlations with V (r = 0.831; p < 0.01) and Cu (r = 0.610; p < 0.05), and Sb had a significant positive correlation with Ni (r = 0.674; p < 0.05) in PD (chemical fiber). Zn had a significant positive correlation with Ni (r = 0.999; p < 0.05) in PD (wool, silk, and others). For PD (cotton), there was no significant positive correlation between heavy metals. The results indicated that the sources of heavy metals in sewage sludge varied greatly in printing and dyeing industry due to the different materials used.

The percentage of heavy metals in sewage sludge may be more indicative of the characteristics of heavy metals. Table S7 listed the percentage of heavy metal contents in sewage sludge from PD, other industries, and MS. The proportions of Zn, Mn, Sb, and Cr in printing and dyeing sludge were relatively large, accounting for 29.4 ± 19.0%, 22.4 ± 14.6%, 18.6 ± 19.3%, and 11.5 ± 10.1%, respectively. However, the proportions of other heavy metals were less than 10%. The proportions of most heavy metals in printing and dyeing sub-industries were similar, but some heavy metals such as Cr, Pb, and Zn were different, indicating that the raw materials used in printing and dyeing industry may cause a great influence on the heavy metal compositions in sewage sludge. The percentage of Sb in printing and dyeing industry was significantly different from that of other industries and MS (p < 0.01), which was consistent with the results of heavy metal speciation (such as Sb, Ba, and V) was the characteristic fingerprints in printing and dyeing sludge and the speciation of Zn can specify sewage sludge between printing and dyeing sub-industries.

**Heavy metal speciation**

The toxicity and mobility of heavy metals depend on their total concentration and chemical speciation. The chemical composition of heavy metals can significantly affect their bioavailability and environmental risk. Among them, F1 and F2 have direct eco-toxicity and bioavailability, F3 has potential eco-toxicity and bioavailability, and F4 is stable and has no eco-toxicity and bioavailability (Hu et al. 2011). Therefore, the chemical speciation of heavy metals is one of the characteristic fingerprints of sewage sludge. Tables S8, S9, S10, and S11 showed the contents of heavy metal forms in sewage sludge from PD, other industries, and MS. The sum of four fractions was similar to the total concentration of heavy metals in original samples, which is consistent with the results of Islam et al. (2017) and Yuan et al. (2011), demonstrating that heavy metals were mainly composed of these four forms. There was no significant difference in most of heavy metal speciation between PD, other industries, and MS, except for three forms of Sb (acid soluble, oxidizable, and residual), reducible Ba, and reducible V (p < 0.05) (Fig. S2). Moreover, there was a significant difference in reducible Zn between printing and dyeing sub-industries (p < 0.05). The results clarified that heavy metal speciation (such as Sb, Ba, and V) was the characteristic fingerprints in printing and dyeing sludge.

**Identification of printing and dyeing sludge**

**PCA of heavy metal composition and speciation**

Significant differences were found in heavy metal composition and heavy metal speciation among different industries, especially in the percentages of these two indicators, indicating that the percentage of heavy metals in sewage sludge can be more effective to trace its source. PCA is arguably the most widely used statistical tool for data analysis for source identification of heavy metals (Wang et al. 2019; Zhao et al. 2020; Zhou et al. 2020). In this study, PCA of heavy metal contents and heavy metal forms was analyzed to identify sewage sludge between PD, other industries, and MS. Figure 4 showed the PCA of heavy metal contents in sewage sludge from PD, other industries, and MS. Five significant factors were obtained, accounting for 79.2% of the total variance (Table S12). Factor 1 explained 19.5% of variance, and it was highly loaded by Mn and Co, which was consistent with the results of Pearson’s correlation analysis (“Heavy metal
Factor 2 explained 17.6% of variance, and the highest contributors were Ba and Pb. Factor 3 yielded 16.4% of explainable results, with Sb and V loading heavily. Factor 4 explained 14.3% of variance, which was dominated by Cu and Zn. Factor 5 (11.4%) was loaded by Cr. The results illustrated that sewage sludge collected from PD and other industries may be distinguished effectively according to the results of PCA, indicating that heavy metal contents, combined with PCA, can be used for identification of sewage sludge between different industries. However, these results could not effectively discriminate printing and dyeing sludge from municipal sewage sludge. In addition, sewage sludge between printing and dyeing sub-industries also could not be distinguished. Therefore, further analysis was needed to

*concentration* section). Factor 2 explained 17.6% of variance, and the highest contributors were Ba and Pb. Factor 3 yielded 16.4% of explainable results, with Sb and V loading heavily. Factor 4 explained 14.3% of variance, which was dominated by Cu and Zn. Factor 5 (11.4%) was loaded by Cr. The results illustrated that sewage sludge collected from PD and other industries may be distinguished effectively according to the results of PCA, indicating that heavy metal contents, combined with PCA, can be used for identification of sewage sludge between different industries. However, these results could not effectively discriminate printing and dyeing sludge from municipal sewage sludge. In addition, sewage sludge between printing and dyeing sub-industries also could not be distinguished. Therefore, further analysis was needed to
distinguish sewage sludge between PD and MS, as well as between printing and dyeing sub-industries.

Figure 5 showed the PCA of heavy metal forms in sewage sludge from PD, other industries, and MS. Five significant factors were obtained, accounting for 60.2% of the total variance, among which factors 1, 2, 3, 4, and 5 accounted for 17.9%, 14.4%, 10.6%, 10.0%, and 7.3%, respectively (Table S13). Factor 1 was highly loaded by V (acid soluble),
Cu (reducible), and Co (reducible). Factor 2 was highly contributed by Ni (acid soluble) and Co (acid soluble and residual). Factor 3 was dominated by Cr (oxidizable and residual) and Cu (oxidizable). Factor 4 was heavily loaded by Ba (reducible) and Mn (residual). Factor 5 was predominated by Pb (oxidizable and residual) and Ba (oxidizable). The results showed that sewage sludge can be effectively distinguished between PD and other industries, as well as between PD and MS. We inferred that heavy metal forms, combined with PCA, can be a potential method for identification of industrial sewage sludge from municipal sewage sludge. However, sewage sludge between printing and dyeing sub-industries could not be discriminated according to the results of heavy metal forms. Thus, it is necessary to develop another effective method for identification of sewage sludge between printing and dyeing sub-industries.

To evaluate the effect of the obtained models on authentication of sewage sludge between PD, other industries, and MS, the classification matrices of heavy metal contents and heavy metal forms for source prediction were performed by LDA. The method of heavy metal contents was able to correctly classify 82.9% of the sewage sludge samples (Table S14; Fig. S3), and the accuracy rate of heavy metal forms for identification of industrial sewage sludge was 100% (Table S14; Fig. S4). These results demonstrated the potential of heavy metal contents and heavy metal forms for sewage sludge identification database establishment and revealed these two methods could be precise and effective techniques for identification of industrial sewage sludge. However, with regard to identification of sewage sludge between printing and dyeing sub-industry, a new technology should be developed to meet the needs of in-depth identification within printing and dyeing industry.

Analysis of characteristic heavy metals

Heavy metals in industrial sewage sludge mainly come from wastewater discharge during industrial production, and their composition can reflect the characteristics of heavy metal discharge in specific industries. The dominant heavy metals emitted by a specific industry can be regarded as features distinguishing from other industries, which could be used as the characteristic heavy metals. In the present study, the concentration of Sb in printing and dyeing sludge (3.65-2560 mg kg\(^{-1}\)) was significantly higher than that in other industries (0.07-33.7 mg kg\(^{-1}\)), indicating that Sb could be used as a characteristic heavy metal in printing and dyeing industry. Moreover, the content of Sb in sewage sludge from printing and dyeing sub-industries was also different. Briefly, the content of Sb in sewage sludge from PD (chemical fiber) (97.6-1390 mg kg\(^{-1}\)) was higher than that from PD (cotton) (3.65-2560 mg kg\(^{-1}\)) and PD (wool, silk, and others) (69.0-444 mg kg\(^{-1}\)) (\(p < 0.05\)). The main reason may be that the production process of polyester fiber used a large number of additives containing antimony compounds, such as antimony ethylene glycol oxide, antimony acetate, and diantimony trioxide. We speculated that Sb can be used as a characteristic heavy metal to distinguish sewage sludge between printing and dyeing sub-industries. In addition, Zn (reducible) can differentiate sewage sludge between printing and dyeing sub-industries, which inferred that Zn can be applied as a characteristic heavy metal. Therefore, Sb and Zn were used to distinguish sewage sludge between printing and dyeing sub-industries (Fig. 6). The results illustrated that sewage sludge from PD (chemical fiber), PD (cotton), and PD (wool, silk, and others) could be effectively discriminated by the concentrations of Sb and Zn, even though the data of PD (wool, silk, and others) were relatively small (only 3 samples), resulting in an insignificant identification effect. Based on the above results, we predicted that the accuracy rate of identifying sewage sludge between PD (chemical fiber) and PD (cotton) by using the characteristic heavy metals (Sb and Zn) may reach 90%, as a result of two samples belonging to PD (cotton) which were identified as PD (chemical fiber) (Fig. 6). It was concluded that the application of characteristic heavy metals could be an effective method for identification of sewage sludge between printing and dyeing sub-industries.

Conclusion

The results indicated that heavy metal compositions and heavy metal forms, combined with PCA, can be effective methods for identification of printing and dyeing sludge, the accuracy rates of which were 82.9% and 100%, respectively. In addition, Sb and Zn may be two indicators to identity sewage sludge between printing and dyeing sub-industries, with an accuracy rate of 90%. It was concluded that heavy metal profiles may be a precise and promising tool for identification
of printing and dyeing sludge. The relevant conclusion of this study develops a potential and effective method for tracing the source of industrial sewage sludge and establishing the identification database of industrial sewage sludge and provides technical support for the government to supervise the illegal disposal of industrial sewage sludge. In the future studies, the number of samples will be further increased to improve the database for accurate identification of printing and dyeing sludge. Moreover, the scope of research can be extended from printing and dyeing industry to other industries to meet the requirements of government regulation.

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Author contribution  XZ designed the research scheme and analyzed the experimental data and was a major contributor in writing the manuscript. SC was responsible for experiment operation and data acquisition. FA, LJ, and NZ participated in the software application and data processing. XM modified this article.

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Data availability  The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate  Not applicable.

Consent for publication  Not applicable.

Competing interests  The authors declare no competing interests.

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