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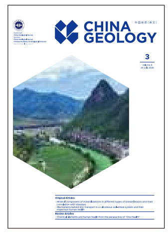

Characteristics and ecological risk assessment of antibiotics and hormones in landfill waters

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A R T I C L E I N F O

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A B S T R A C T

Antibiotics, as emerging pollutants, pose significant risks to aquatic ecosystems and human health by disrupting the endocrine systems of aquatic organisms and affecting ecosystem stability through food chain enrichment. In a study conducted in Hebei Province, China, liquid chromatography-triple quadrupole-linear ion trap mass spectrometry (LC-TQ-LIT-MS) was used to analyze 90 different antibiotics in 31 water samples, including surface water, groundwater, and waste leachate from three urban landfills. This analysis included hormones, broad-spectrum antimicrobials, macrolides, tetracyclines, β-lactams, sulfonamides, and quinolones. The study's results indicated that quinolones, β-lactams, and macrolides were the most frequently detected substances in the landfills. It is noteworthy that the concentrations of these antibiotics varied significantly among different cities, reflecting local production and living characteristics. The results of the tests showed that the concentration of amoxicillin was 1171 ng/L in surface water, 811 ng/L in groundwater, and 1926 ng/L of ciprofloxacin in waste leachate. Furthermore, a consistent pattern was observed between the compounds present in the leachate, groundwater, and surface water at the three sites. Risk assessments revealed that the ecological risk was higher for surface water and lower for groundwater.This study is the first to systematically analyze the pollution status of antibiotics and hormones in the water around the landfill in Hebei Province, which not only fills the blank of groundwater-related research in Hebei Province but also provides key data support and theoretical basis for local groundwater hydrological and environmental detection and pollution prevention.

1. Introduction

Antibiotic and hormone drugs are a category of emerging contaminants (Frieri M et al., 2017), and their frequent detection in the global aquatic environment in recent years has triggered widespread concern among the scientific community and the public (Chen YL et al., 2022). Groundwater is the main source of freshwater globally, with 97% of the Earth's currently available freshwater being groundwater, while the remaining 3% is mainly surface water. It is considered the most important source of water supply in many areas of the world (Zainab SM et al., 2020). A variety of emerging contaminants, such as antibiotics, anti - inflammatory drugs, hormonal drugs, antimicrobials, cosmetics, and detergents are currently and continuously entering the groundwater environment through metabolic excretion by humans and animals (Joakim Larsson DG and Flach CF, 2022; Niu Y et al., 2023), discharge of medical wastes, and disposal of household products (Cheng DL et al., 2020). Although these compounds are usually present in the environment in trace concentrations, their persistence, bioaccumulation, and potential ecotoxicity may pose a long-term threat to aquatic organisms, microbial communities, and even human health (Feng L et al., 2020). It has been shown that some antibiotics and hormones can disrupt the endocrine system of aquatic organisms and even affect the stability of ecosystems through enrichment in the food chain, or even create drug - resistant

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genes or antibiotic resistance (Davies J and Davies D, 2010). The problem is closely linked to the United Nations Sustainable Development Goals (SDGs), in particular, the achievement of clean water and sanitation, climate action, and protection of groundwater (Crystal YO et al., 2024). The widespread nature and complexity of this pollution problem highlight the serious challenges facing the world in terms of environmental protection and sustainable development (Lee KH et al., 2020). Therefore, taking effective control measures to reduce the release of such substances and protect water resources and ecosystems is not only a necessary action to achieve the United Nations Sustainable Development Goals (SDGs) but also a key initiative to safeguard human health and the ecological future of the planet.

Landfills are considered to be the main pathways for antibiotics and hormones to enter the environment, and most studies have focused on the removal efficiency of antibiotics and hormones by wastewater treatment processes for landfill leachate (Zhang R et al., 2022). However, as the final disposal sites of municipal solid waste (Yu X et al., 2020), the characteristics and ecological risks of antibiotics and hormones in leachate have not been sufficiently emphasized (Parvin F and Tareq SM, 2021). Expired medicines, discarded personal care products, and adsorbent wastes containing antibiotics and hormones (e.g., diapers, sanitary napkins, etc.) in landfills may release high concentrations of antibiotics and hormones through leachate during long-term landfilling (Seifrtová M et al., 2009). Due to the complex composition of leachate and the significant influence of site hydrogeological conditions on contaminant migration (Feng L et al., 2020), antibiotics and hormones may enter the neighboring water bodies through subsurface infiltration or surface runoff (Abiriga D et al., 2020), forming a hidden and persistent source of pollution (Abdel-Shafy HI et al., 2024). In recent years, some studies have detected a variety of antibiotic and hormone drugs in landfill leachate and neighboring groundwater, but their spatial distribution pattern, environmental behavior, and multimedia transport mechanisms remain unclear (Abd El-Salam MM and Abu-Zuid GI, 2015).

Antibiotics and hormones have been detected in surface water and groundwater in many places in China and abroad (Yu KN et al, 2023). Ofloxacin (31.9 ng/L) and dehydrated erythromycin (2.2 ng/L) were detected in groundwater and surface water around hospitals in Wuhan City, with the overall antibiotic detection concentrations in groundwater ranging from 13.4 ng/L–38.3 ng/L (Liu K et al., 2024). Sulfadiazine, sulfamethoxazole, and sulfadimethoxine were detected in the water bodies of Pudong New Area, Shanghai, China, at concentrations ranging from 0.07 ng/L–0.41 ng/L with a detection rate of 27.3%–45.5% (Pan CY et al., 2020). Ofloxacin and ciprofloxacin were detected in surface water and groundwater in Wuxi City, Jiangsu Province, China, with a concentration range of 1.38 ng/L–31.5 ng/L (Wu HX et al., 2024). Amoxicillin and cefadroxil were detected in the state of São Paulo, Brazil, at concentrations ranging from 0.31 ng/L to 0.71 ng/L, with a detection rate of 66.7%–100%. In Dhaka, Bangladesh, oxytetracycline, tetracycline, and sulfamethoxazole were detected at concentrations of 0.06 ng/L–0.64 ng/L, and similar detection rates were observed (Salma U et al., 2025). At present, research on surface water and groundwater in Hebei Province mainly focuses on the detection of inorganic substances, while there is relatively little research on the contamination of antibiotics and hormones in water bodies, and there is a lack of basic data related to surface water and groundwater.

Currently, research on antibiotics and hormones in landfill groundwater faces multiple challenges: first, the detection methods for antibiotics and hormones in groundwater are imperfect, with longer pre-processing time and fewer types of detected substances, and poor data comparability between different studies (Gaston L et al., 2019); second, the spatial distribution of antibiotics and hormones in groundwater is more complex due to unclear groundwater movement trajectories. The spatial distribution of antibiotics and hormones is complex due to unclear groundwater flow trajectories and significant regional variability (Samadder SR et al., 2017); third, there is a lack of basic data for testing typical water bodies in multiple landfills, which cannot comprehensively reflect the correlation between groundwater contamination and landfills. Therefore, analyzing the characteristics of antibiotics and hormones in landfill leachate and groundwater (Rouhani A et al., 2022) and constructing an ecological risk evaluation system adapted to the characteristics of the landfill (Zhou P et al., 2022) are of great significance for improving the control strategy of emerging pollutants and guaranteeing the safety of the regional groundwater environment.

At present, liquid chromatography-mass spectrometry (LC-MS) is one of the widely used methods for the determination of antibiotics and hormones, especially suitable for the precise detection of multiple antibiotics and hormones in complex matrix samples (Li CQ et al., 2024; Ying JL et al., 2022). In this study, landfills in three cities with rapid economic and industrial development in Hebei Province were selected, and nearby surface water, groundwater, and waste leachate were collected, and the direct injection method combined with LC-TQ-LIT-MS was employed to characterize antibiotics and hormones in landfill groundwater and to evaluate ecological risks. The method simplifies operational steps, improves analytical efficiency, reduces costs, enhances sensitivity, and achieves a detection limit as low as 1 ng/L. The whole process takes only 20 minutes to complete the pre-processing and overall analysis of more than 90 antibiotics and hormones. The results of the study provide a scientific basis and data support for the development of environmental management policies for landfill groundwater.

2. Overview of the research area

Hebei Province is located in the northern North China Plain, with a flat terrain, low elevation, and a topography that gradually slopes from northwest to southeast. The hydrogeological conditions of the region are complex, and the groundwater and surface water systems play an important role in regional water supply and ecology. Hebei Province has a generally shallow water table and a large number of surface water bodies, which are susceptible to human interference. As an important province in northern China, Hebei Province faces increasingly severe environmental pollution problems. With the acceleration of urbanization and industrialization, the production of domestic waste in Hebei Province has increased rapidly. Waste leachate contains a variety of hazardous substances, which can cause serious pollution to the surrounding soil and groundwater, as well as exacerbate the eutrophication of surface water, affecting ecological functions. As of 2022, there are 126 domestic waste landfills in Hebei Province, so it is necessary to pay great attention to the treatment of landfill leachate and explore the occurrence of organic pollutants in leachate.

Three typical cities in Hebei Province, P, S and X, with rapid economic and industrial development, were selected as the study area. These three cities are characterized by diverse hydrogeological conditions, significant changes in groundwater levels, overexploitation of groundwater, and rapid economic development. Among them, city P has a serious problem of declining groundwater levels and is an important site for studying the impact of human activities on groundwater levels. City S is a city with rapid economic development, active industrial and agricultural activities, and a high demand for water resources. City X, another city with rapid economic development and a groundwater level that fluctuates greatly due to human influence, is a good location to study the impact of human activities on water resources. The collection of surface water and groundwater samples from these three cities can provide basic data for assessing the quality of water resources and the trend of change, which is of great research value.

3. Materials and methods

3.1. Sample collection

Surface water, groundwater, and waste leachate samples were collected from the study area according to relevant standards and Surface water, groundwater, and waste leachate samples were collected from the study area according to relevant standards and specifications, as shown in Fig. 1. Among them, seven surface water and one groundwater sample were collected in city P, five surface water and three groundwater samples were collected in city S, eight surface water and four groundwater samples were collected in city X, and there was one landfill leachate sampling site in each city. Surface water, groundwater, and leachate samples were collected in accordance with the requirements of the relevant standards (GB/T 18772-2017). The collected samples were transferred to 15 mL brown glass bottles, placed in a 4°C refrigerator for transportation, and stored at 4°C protected from light for 7 days before analysis.

3.2. Reagents and equipment

Methanol, acetonitrile, and ammonia were HPLC grade and purchased from Merck (Germany), and hormones, broad-spectrum antimicrobials, macrolides, tetracyclines, β-lactams, sulfonamides, and quinolones mixed standards were purchased from Tianjin Alta Company. High-performance liquid chromatography-triple quadrupole-linear ion trap mass

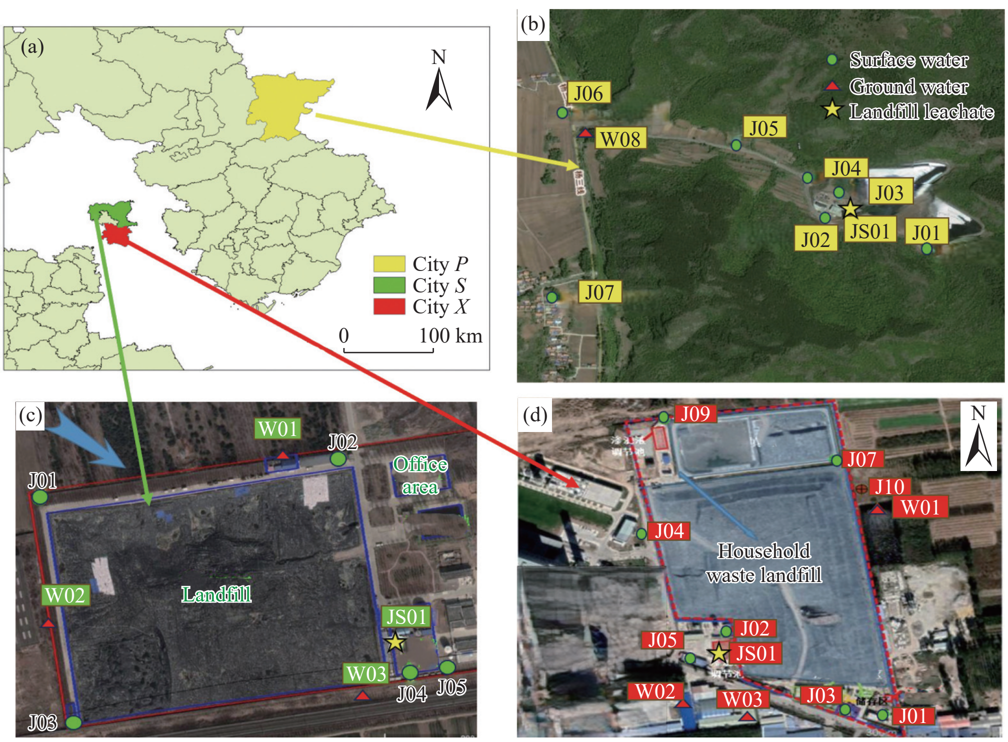

Fig. 1. Map of sampling sites in the three cities.

spectrometer (SCIEX 7500, Sciex, USA), column Kinetex F5 column (100×3.0mm, 2.6μm, Phenomenex, USA), centrifuge (Sigma, Germany).

3.3. Sample preparation

A 100 ml water sample was measured and centrifuged at high speed. Subsequently, 50 mg Na_4EDTA was added to the water sample and vortexed to mix well. After centrifugation at high speed for 5 minutes, 1.0 mL of the treated water sample and 10 μL of the internal standard solution were removed from the sample, mixed well, and analyzed directly by the instrument. Laboratory blanks and spiked samples were inserted into each batch, and the recoveries of target compounds were controlled at 75%–110% with relative standard deviation (RSD) <15%.

Instrument operating conditions: ion source type is electrospray ion source (ESI) and positive ion mode; Detection method: multi-reaction monitoring (MRM); Spray Voltage: 2000 V; Ion source temperature: 500 °C; Curtain gas pressure: 45 psi; Ion Source Gas 1: 60 psi; Ion Source Gas 2: 40 psi; Collision gas pressure: 9 psi.

Mobile phase A was 0.1% (v/v) formic acid aqueous solution; mobile phase B was acetonitrile. The flow rate was 0.4 mL/min; the injection volume was 100 μL, ESI source, and multiple reaction monitoring (MRM) modes. The positive/negative ion mode was synchronized for detection. The recoveries of the method were 93%–112%, and the detection limits were 1 ng/L–5 ng/L. Fig. 2 represents the total ionic current (TIC) plots of 90 antibiotics at a concentration of 50 ng/L.

3.4. Risk assessment

To calculate the risk quotients (RQs) for each substance, the Predicted No Effect Concentration (PNEC) of the substance is first determined. The risk quotient (RQ) is the ratio of the measured environmental concentration (MEC) of the target compound to the Predicted No Effect Concentration (PNEC) of the target compound, and is calculated by the following formula:

$$RQ = \frac{MEC}{PNEC}$$

The risk level is categorized as low, moderate, or high if the RQ value is less than 0.1, between 0.1 and 1.0, or greater than 1.0, respectively. The PNEC value is obtained by dividing the acute toxicity data (LC50 or EC50) by the assessment factor (AF) of 1000. To obtain long-term/chronic NOEC values for nutrient concentrations only, an AF of 1000, 100, 50, or 10 is used. Toxicity data for multiple species used in this document are still collected from the literature and the USEPA ECOTOX database (https://cfpub.epa.gov/ecotox/).

MEC—the detected concentration of the target substance in the actual sample;

PNEC —Predicted No Effect Concentration for the substance, calculated from the LD50 or Maximum Half Effect Concentration (EC50).

4. Results and discussion

4.1. Characteristics of main pollutants

The concentrations of antibiotics and hormonal substances in 31 samples from three cities were obtained by analytical tests and are shown in Table S1 (supplementary material), with concentrations ranging from nd (not detected) to 1926 ng/L. For the analysis of the samples of surface water, groundwater and waste leachate from three cities in Hebei Province, the distribution characteristics of the target compounds showed that quinolone antimicrobial drugs (e.g., ciprofloxacin, norfloxacin), β-lactams (e.g., cefazolin), and macrolides (e.g., azithromycin, lincomycin) showed a significant trend of enrichment in the three types of water, and the detection frequency of all of them was more than 65%. The concentration levels in the waste leachate were significantly higher than those in surface water and groundwater, reflecting the preferential mobility and potential ecological risk contribution of these three types of drugs in the environmental media surrounding the solid waste landfill. These three types of drugs are mainly used as human and veterinary drugs, but due to intestinal absorption problems, only 30% are absorbed. The remaining unmetabolized fraction and metabolites are excreted in feces and urine, some of which go directly to the environment, while the rest go to wastewater treatment plants (Ma JW et al., 2021). Among them, amoxicillin, clindamycin, lincomycin, and virginiamycin were detected in different water bodies with

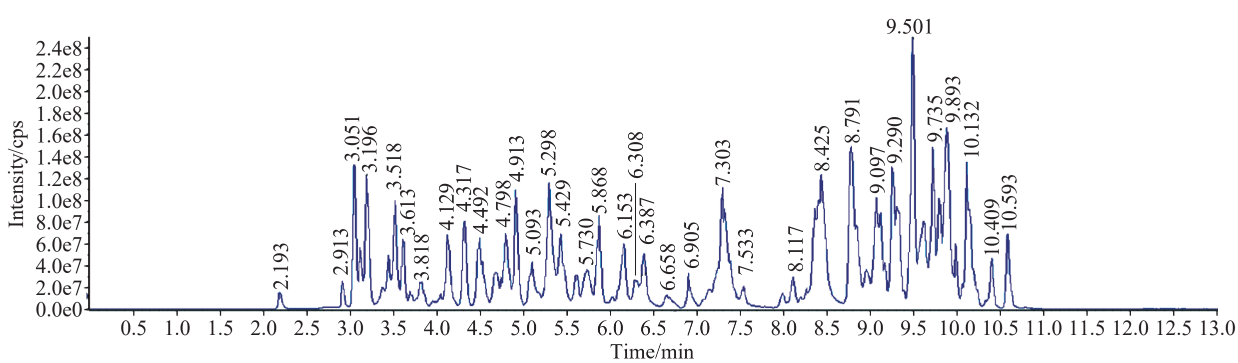

Fig. 2. Total ion current diagram (TIC) of 90 antibiotics at 50 ng/L.

high detection rates and detection concentrations. The groundwater around the landfills in the three cities was contaminated to different degrees, and the types of contaminants were highly consistent with the highly-detected substances in the waste leachate.

4.1.1. Characteristics of pollutants in surface waters of landfills

Comparison of the distribution of antibiotics and hormones in surface water of three cities, as shown in Fig. 3. A variety of target compounds were detected in the surface water of City P, with drug concentration levels ranging from nd–1172 ng/L. The highest concentration of amoxicillin (1172 ng/L) was detected at point J02 in City P's surface water. The remaining points had relatively low concentration levels. The compounds with high detection rates mainly included seven substances, such as amoxicillin, clindamycin, lincomycin, and virginiamycin. Amoxicillin was detected at all points in the surface water with a high detection rate of 100%. Clindamycin was detected at 100% of the points with concentrations ranging from 10.6 ng/L to 28.7 ng/L. Cefadroxil was detected at several sites with concentrations ranging from 1.62 ng/L to 14.8 ng/L. Virginiamycin was detected at concentrations ranging from 3.90 ng/L to 96.2 ng/L with a 100% detection rate. Other substances with a 100% detection rate included megestrol, prednisone, and miconazole. The main substances detected in surface water were hormones, macrolides, and β-lactams.

The overall concentration levels of the target substances in the surface water of City S ranged from nd–605 ng/L. The highest concentration of penicillin (605 ng/L) was detected at site J02 in the surface water. The rest of the points had relatively low concentration levels. Compounds with high detection rates mainly included ciprofloxacin, ofloxacin, penicillin, glyburide, and kynurenine. Ciprofloxacin was detected at several surface water sites with a detection rate of 40% and an average concentration range of nd–215 ng/L. Penicillin had a detection rate of 40% and a concentration range of nd–604 ng/L. Kynurenine had a detection rate of 100% and a concentration range of 150 ng/L to 253 ng/L. The detection rate of hydrocortisone and triclosan was relatively low. Hydrocortisone and triclocarban were detected in 60%–80% of the samples. The main substances detected in surface water were quinolones, β-lactams, and certain hormones.

The overall concentration levels in the surface water of City X ranged from nd-51.6 ng/L. Compared to the other two cities, the overall concentrations of the substances detected in City X were lower, but most of the substances were detected. Among substances with 100% detection were amoxicillin, azithromycin, clarithromycin, erythromycin, lincomycin, dactinomycin, roxithromycin, tilmicosin, tylosin, medroxyprogesterone acetate, kynurenine oxime, norethindrone, trenbolone, medroxyprogesterone, cortisone, hydrocortisone, and triclocarban, with concentration levels ranging from 3.40 to 201 ng/L. Cefadroxil, lincomycin, virginiamycin, 17α-estradiol, prednisone, miconazole, and 4-epioxytetracycline were detected in 50%–87.5% of samples, with concentrations ranging from 1.11 ng/L to 217 ng/L. The main types of substances detected in City X were classified into two major groups: macrolides and hormones.

Compared with the results of this paper, the overall detected concentrations of target substances in the surface water of a city in Vietnam were low. In this city, the average concentrations of several antibiotics were: sulfonamides (118 ng/L) > β-lactams (31.3 ng/L) > quinolones (20.2 ng/L) > macrolides (17.7 ng/L). The highest concentration of sulfonamides in surface water was 807 ng/L (Duong HA et al., 2021). These types of drugs have different characteristics. Sulfonamides are mainly polar molecules with high water solubility, low volatility, and high mobility, which make them easy to transfer and diffuse in the aqueous environment. Whereas β-lactams are easily hydrolyzed under ambient pH and temperature. Quinolones are highly polar, typically amphoteric, and exhibit poor water solubility at pH 6–8. They are strongly adsorbed by solid substrates rich in organic matter and metal oxides (Al, Fe aqueous oxides, etc.) and also show chelating potential for transition metal ions, including

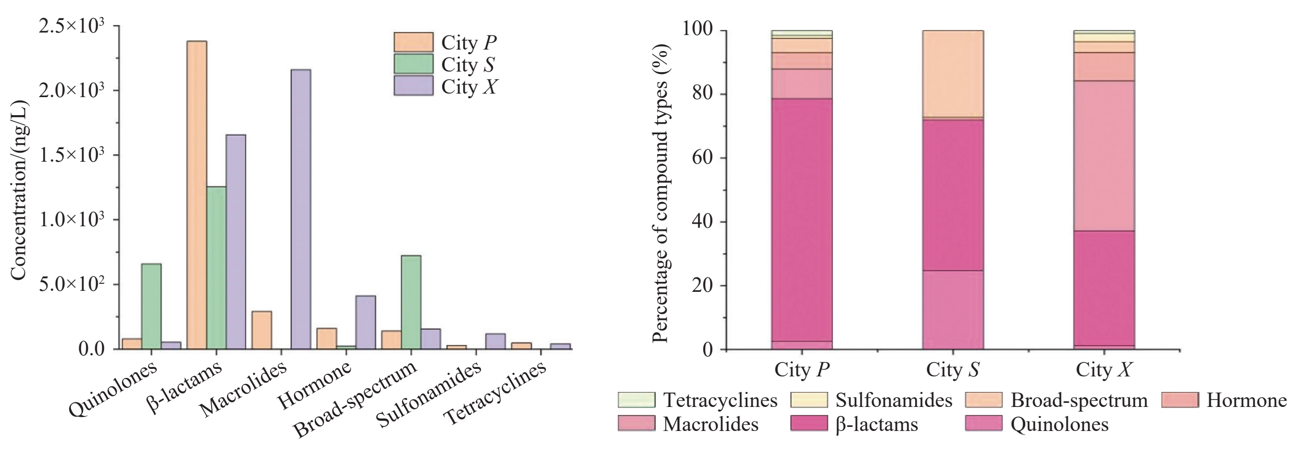

Fig. 3. Comparison of the distribution of antibiotics and hormones in surface water of three cities. a–Map of antibiotic and hormone detection concentrations in surface waters of three cities; b–map of the proportion of antibiotic and hormone detection substances in surface waters of three cities.

copper, lead, zinc, and magnesium. Macrolides are weakly acidic and lipophilic, but poorly water-soluble, and have poor adsorption capacity (Jafari Ozumchelouei E et al., 2020).

4.1.2. Characteristics of pollutants in groundwater of landfills

Comparison of the distribution of antibiotics and hormones in groundwater of three cities, as shown in Fig. 4. Of the more than 90 target compounds, 10 were detected in groundwater in City P. The overall concentration levels ranged from 3.90 ng/L to 81.9 ng/L, with amoxicillin showing the highest concentration (81.9 ng/L), followed by cefazolin (19.2 ng/L), virginiamycin M1 (3.90 ng/L), clindamycin (10.8 ng/L), and medroxyprogesterone acetate (6.03 ng/L). The main compounds with high detection rates were amoxicillin, cefazolin, and virginiamycin, all with 100% detection rates. The results of the analysis of 90 compounds showed that there was a high degree of consistency among the compounds detected in landfill leachate, groundwater, and surface water.

Eighteen target compounds were detected in the groundwater of City S. The overall concentration levels ranged from nd–374 ng/L, with norfloxacin showing the highest concentration (374 ng/L) and a 100% detection rate, followed by kynurenine (257 ng/L) > desmethyl-chlortetracycline (201 ng/L) > glybutyrine (9.03 ng/L) > sulfamethoxypyridazine (2.55 ng/L). The rest of the sites had concentration levels below 30 ng/L. The compounds with high detection rates were mainly clindamycin, norfloxacin, pefloxacin, amoxicillin, penicillin, lincomycin, kynurenine oxime, and triclocarban, with detection rates ranging from 66.7% to 100%. The overall detected concentration of groundwater in City S is low, but there are many types of detected compounds. Although the overall concentration of groundwater was low, the prolonged contamination of groundwater could still pose a threat to the ecological environment.

Thirty target compounds were detected in the groundwater of City X. The overall concentration levels ranged from 1.02 to 224 ng/L, with amoxicillin having the highest concentration level (224 ng/L), followed by virginiamycin (95.4 ng/L), sulfamethoxydiazine (86.8 ng/L), glyburide (63.2 ng/L), and fluconazole (18.0 ng/L). The concentration levels of the remaining sites were below 30 ng/L. The main compounds with high detection rates were: cinoxacin, ofloxacin, lomefloxacin, levofloxacin, cefadroxil, nafcillin, clindamycin, lincomycin, tilmicosin, virginiamycin, medroxyprogesterone, testosterone, prednisone, sulfacetamide, sulfamethoxazole, sulfathiazole, with a detection rate ranging from 50%–100%. Similar to surface water, groundwater in City X had the highest number of detected species among the three cities, but concentrations were generally lower than those in the other two cities. The northern part of City X is a zone of general over-exploitation of shallow groundwater, including shallow groundwater (mainly for irrigation) and deep groundwater (mainly for drinking water and irrigation).

Seventy-eight antibiotics were detected in groundwater in areas associated with the Belgian livestock industry, and the concentrations detected were generally low. Only 7 out of 50 groundwater sites had detected concentrations between nd–300 ng/L, which is in the same order of magnitude as the results of this study (Tuts L et al., 2024).

4.1.3. Characteristics of contaminants in waste leachate

Twelve, fourteen, and fourteen target compounds were detected in the leachate from cities P, S, and X, respectively. The concentration range of the samples from City P was nd-1233 ng/L, and amoxicillin was detected at the highest concentration, followed by 17α-estradiol, cefazolin (23.3 ng/L), clindamycin (28.7 ng/L), and sulfamethoxydiazine (9.12 ng/L). The samples from City S showed a wider concentration gradient (nd-1926 ng/L), and ciprofloxacin was the major contaminant, followed by azithromycin (700 ng/L), lincomycin (419 ng/L), roxithromycin (283 ng/L), and norfloxacin (35.0 ng/L). Samples from City X showed a wider concentration gradient (nd-1131 ng/L), with azithromycin as the main detected contaminant, and concomitant contaminants included glyburide (63.2 ng/L), sulfamethoxypyridazine (86.8 ng/L), and fluconazole (180 ng/L). The results showed that azithromycin, sulfamethoxypyridazine, 17α-estradiol,

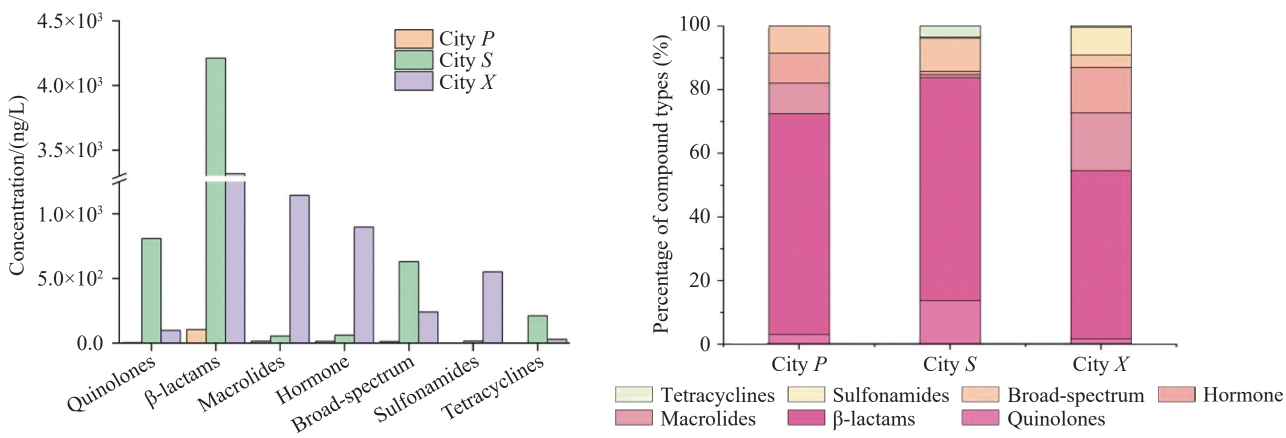

Fig. 4. Comparison of the distribution of antibiotics and hormones in groundwater of three cities. a–Map of antibiotic and hormone detected concentrations in groundwater in three cities; b–map of the proportion of antibiotic and hormone detected substances in groundwater in three cities.

amoxicillin, ciprofloxacin, and lincomycin were detected in the three cities, reflecting the prevalence and chemical stability of these compounds in the leachate environment. In terms of geographical differences, City P had the lowest number of detected substances (12), but the overall concentration levels of the target compounds were significantly higher than those in Cities S and X. Despite the differences in the specific compounds detected in the three cities, the distribution patterns of pollutant compositions and concentrations in surface water, groundwater and leachate within the same city showed high consistency, which implied that the regional sources of contamination and migration pathways were homogenous. The total concentrations of sulfonamides, tetracyclines, and macrolides in raw leachate from some landfills in northern Zhejiang Province, China, ranged from 0.98 ng/L to 90.3 ng/L, 1.90 ng/L to 50.6 ng/L, and 146 ng/L to 383 ng/L, respectively, which were lower than those in the present study (Xue XD et al., 2021).

4.2. Risk assessment

Surface water and groundwater are common sources of water for residents, so an ecological risk assessment of surface water and groundwater in the three cities was carried out. After determining the PNEC, the ecological risk of several cities could be assessed by calculating the RQ value. From the calculation results, it can be seen that most of the results were lower than 0.1 and there was no ecological risk, while the RQ value of amoxicillin in one surface-water sample in City P was greater than 1, presenting a high ecological risk. By analyzing the concentration of pollutants in City P, it was found that the antibiotic and hormone content in surface water was very high, which requires attention to local pharmaceutical medical waste management.

The 32 target substances have been highly detected and used for correlation analysis. As shown in the figure, the positive correlation indicates homology, and these drugs share a common pollution source, which is more consistent with previous studies. It shows the correlation between the selected points and targets, although most of the correlated substances exhibit low concentrations, and the local pollution is not evident.

Principal component analysis (PCA) was used to analyze the sources and contributions of target substances. As shown in Fig. 5, the first two principal components (PC1 and PC2) explained 43.3% and 13.8% of the total variance, respectively. The low significance and high similarity of the three city points indicate that the three cities share similar pollution profiles and sources. Fig. 5 shows the loadings plot, where the closer the variables are, the stronger the positive correlation coefficients are, and since the co - occurring compounds may have similar sources, the antibiotics and hormones in Cities S and P may be from common sources, whereas City X exhibits an additional contamination source. Fig. 5d shows the cluster analysis dendrogram in the water bodies of the three cities. The dendrogram grouped the points

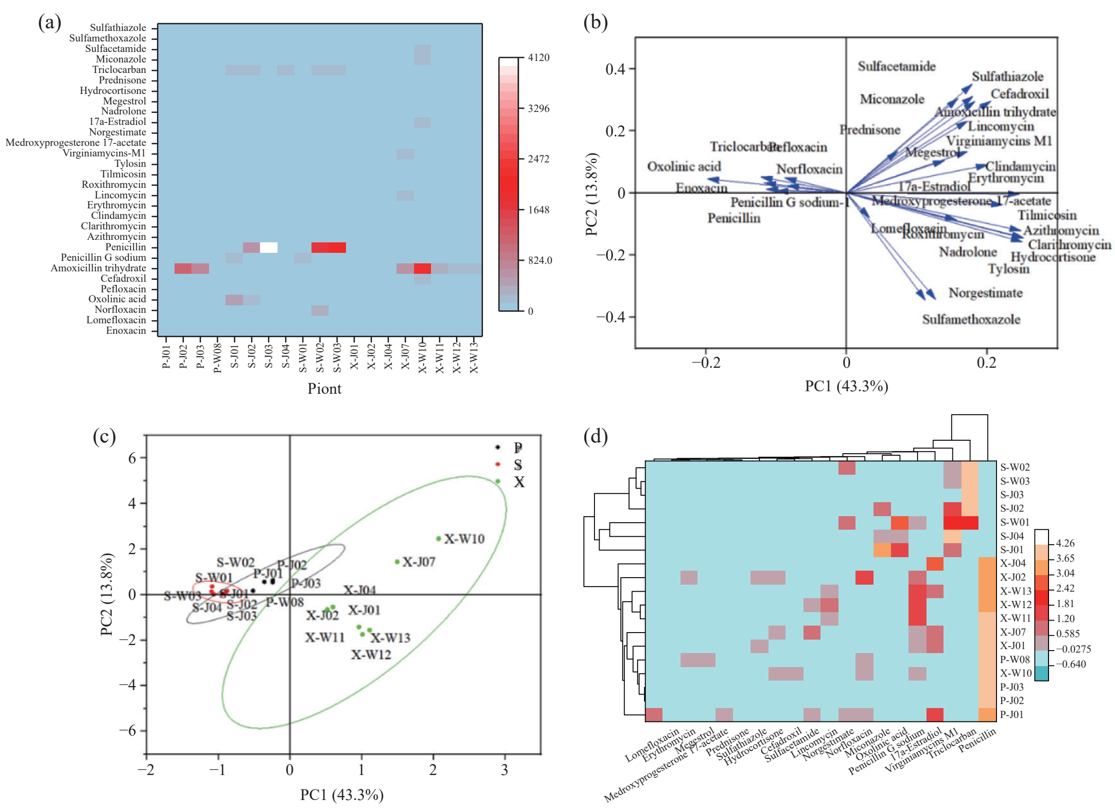

Fig. 5. Risk assessment cluster diagram. a–Correlation hotspot analysis plot; b–Load plot of antibiotics and hormones in three municipal waters; c–PCA plot of samples of antibiotics and hormones in three municipal waters; d–Cluster analysis tree plot of antibiotics and hormones in three municipal waters.

into clusters, which was almost consistent with the actual point distribution, indicating that the correlation between the points in the same city is good, and the similarity of the three places is high and has a positive correlation, which can be echoed with the results of PCA calculations; in terms of the categorization of the compounds, it is close to the same as the results of the grouping of PCA.

5. Conclusions

The main conclusions are as follows:

(i) Distribution characteristics of target pollutants: In the three cities, the maximum value of amoxicillin in the surface water of City P was 1171 ng/L, and the maximum concentration of amoxicillin in the groundwater was 81.9 ng/L; the maximum concentration of penicillin in the surface water of City S reached 410 ng/L, and the maximum concentration of norfloxacin in the groundwater reached 374 ng/L. The maximum concentration of lincomycin in the surface water of City X reached 201 ng/L, and the maximum concentration of amoxicillin in the groundwater reached 224 ng/L.

(ii) Spatial transport correlation of pollutants: Azithromycin, lincomycin, and amoxicillin trihydrate were highly detected in the surface water and groundwater in the three cities. Meanwhile, the target contaminants in the three water bodies of the landfill site have high similarity, indicating that the waste leachate and surface water have a great influence on the pollution of the groundwater.

(iii) Ecological risk assessment results: Based on the risk quotient (RQ) assessment, most of the points of antibiotic pollutants in the study area are at a low ecological risk level. However, special attention should be paid to one landfill in City X, whose amoxicillin RQ value is greater than 1, presenting a high ecological risk, suggesting that this site may pose a potential threat to the local ecosystem and the production and living environment of residents.

This study systematically reveals the accumulation pattern and ecological risk of antibiotics and hormones in the groundwater of the landfill, which not only provides key data support for the research on the traceability of pollution, migration mechanism and long-term health effects, but also lays a foundation for the improvement of the regional groundwater hydrological and environmental monitoring system and the construction of the whole chain of pollution prevention and control system, which will help the ecological protection and sustainable management of the groundwater.

CRediT authorship contribution statement

Yi Huang conceived of the presented idea. Yi Huang, Xuan Dong and Zhu Rao performed data analysis and summarization. Zhi-yuan Ma and Xi-zhao Tian conducted field surveys and sample collection. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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Supplementary dataset

Supplementary data (Table S1) to this article can be found online at doi: 10.31035/CG20250076.

References

Abd El-Salam MM, Abu-Zuid GI. 2015. Impact of landfill leachate on the groundwater quality: A case study in Egypt. Journal of Advanced Research, 6(4), 579–586. doi: 10.1016/j.jare.2014.02.003.

Abdel-Shafy HI, Ibrahim AM, Al-Sulaiman AM, Okasha RA. 2024. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. Ain Shams Engineering Journal, 15(1), 102293. doi: 10.1016/j.asej.2023.102293.

Abiriga D, Vestgarden LS, Klempe H. 2020. Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry. Science of the Total Environment, 737, 140307. doi: 10.1016/j.scitotenv.2020.140307.

Chen YL, Jiang CX, Wang YL, Song RR, Tan Y, Yang YY, Zhang ZL. 2022. Sources, environmental fate, and ecological risks of antibiotics in sediments of Asia's longest river: A whole-basin investigation. Environmental Science & Technology, 56(20), 14439–14451. doi: 10.1021/acs.est.2c03413.

Cheng DL, Ngo HH, Guo WS, Chang SW, Nguyen DD, Liu YW, Wei Q, Wei D. 2020. A critical review on antibiotics and hormones in swine wastewater: Water pollution problems and control approaches. Journal of Hazardous Materials, 387, 121682. doi: 10.1016/j.jhazmat.2019.121682.

Crystal YO, Luo YL, Duangthip D, El Tantawi M, Benzian H, Schroth RJ, Feldens CA, Virtanen JI, Al-Batayneh OB, Diaz ACM, Vukovic A, Pavlic V, Mfolo T, Daryanavard HA, Gaffar BO, Shamala A, Foláyan MO, Early Childhood Caries Advocacy Group (ECCAG). 2024. A scoping review of the links between early childhood caries and clean water and sanitation: The Sustainable Development Goal 6. BMC Oral Health, 24(1), 769. doi: 10.1186/s12903-024-04535-9.

Davies J, Davies D. 2010. Origins and evolution of antibiotic resistance. Microbiology and Molecular Biology Reviews, 74(3), 417–433. doi: 10.1128/MMBR.00016-10.

Duong HA, Phung TV, Nguyen TN, Phan Thi LA, Pham HV. 2021. Occurrence, distribution, and ecological risk assessment of antibiotics in selected urban lakes of Hanoi, Vietnam. Journal of Analytical Methods in Chemistry, 2021, 6631797. doi: 10.1155/2021/6631797.

Feng L, Cheng YR, Zhang YY, Li ZW, Yu YC, Feng L, Zhang S, Xu LJ. 2020. Distribution and human health risk assessment of antibiotic residues in large-scale drinking water sources in Chongqing area of the Yangtze River. Environmental Research, 185, 109386. doi: 10.1016/j.envres.2020.109386.

Frieri M, Kumar K, Boutin A. 2017. Antibiotic resistance. Journal of Infection and Public Health, 10(4), 369–378. doi: 10.1016/j.jiph.2016.08.007.

Gaston L, Lapworth DJ, Stuart M, Arnscheidt J. 2019. Prioritization approaches for substances of emerging concern in groundwater: A critical review. Environmental Science & Technology, 53(11), 6107–6122. doi: 10.1021/acs.est.8b04490.

Jafari Ozumchelouei E, Hamidian AH, Zhang Y, Yang M. 2020.

Physicochemical properties of antibiotics: A review with an emphasis on detection in the aquatic environment. Water Environment Research, 92(2), 177–188. doi: 10.1002/wer.1237.

Joakim Larsson DG, Flach CF. 2022. Antibiotic resistance in the environment. Nature Reviews Microbiology, 20(5), 257–269. doi: 10.1038/s41579-021-00649-x.

Lee KH, Noh J, Khim JS. 2020. The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities. Environment International, 137, 105528. doi: 10.1016/j.envint.2020.105528.

Li CQ, Li LX, Ren YJ, Zhao JH, Huang G, Zhou SY, Liu LP, Jiang JS, Liang F. 2024. Determination of 35 antibiotics in surface water by high performance liquid chromatography-tandem mass spectrometry with online solid-phase extraction and large-volume injection. Rock and Mineral Analysis, 43(6), 945–956. doi: 10.15898/j.ykcs.2024 04050076.

Liu K, Gan C, Peng YE, Gan YQ, He J, Du Y, Tong L, Shi JB, Wang YX. 2024. Occurrence and source identification of antibiotics and antibiotic resistance genes in groundwater surrounding urban hospitals. Journal of Hazardous Materials, 465, 133368. doi: 10.1016/j.jhazmat.2023.133368.

Ma JW, Cui YB, Li AM, Zhang WJ, Ma CD, Luosang ZM, Chen ZB, Zhao K. 2021. Tracking macrolides, sulfonamides, fluoroquinolones, and tetracyclines in sludge treatment wetlands during loading and resting periods. Separation and Purification Technology, 279, 119599. doi: 10.1016/j.seppur.2021.119599.

Niu Y, An S, Chen K, Qin JJ, Liu F. 2023. A review of current status and analysis methods of antibiotic contamination in groundwater in China (2012—2021). Rock and Mineral Analysis, 42(1), 39–58. doi: 10.15898/j.cnki.11-2131/td.202210120192.

Pan CY, Bao YY, Xu BT. 2020. Seasonal variation of antibiotics in surface water of Pudong New Area of Shanghai, China and the occurrence in typical wastewater sources. Chemosphere, 239, 124816. doi: 10.1016/j.chemosphere.2019.124816.

Parvin F, Tareq SM. 2021. Impact of landfill leachate contamination on surface and groundwater of Bangladesh: A systematic review and possible public health risks assessment. Applied Water Science, 11(6), 100. doi: 10.1007/s13201-021-01431-3.

Rouhani A, Bradák B, Makki M, Ashtiani B, Hejcman M. 2022. Ecological risk assessment and human health risk exposure of heavy metal pollution in the soil around an open landfill site in a developing country (Khesht, Iran). Arabian Journal of Geosciences, 15(18), 1523. doi: 10.1007/s12517-022-10792-1.

Salma U, Nishimura Y, Tokumura M, Hossain A, Watanabe K, Noro K, Raknuzzaman M, Amagai T, Makino M. 2025. Occurrence, seasonal variation, and environmental risk of multiclass antibiotics in the urban surface water of the Buriganga River, Bangladesh. Chemosphere, 370, 143956. doi: 10.1016/j.chemosphere.2024.143956.

Samadder SR, Prabhakar R, Khan D, Kishan D, Chauhan MS. 2017. Analysis of the contaminants released from municipal solid waste landfill site: A case study. Science of the Total Environment, 580, 593–601. doi: 10.1016/j.scitotenv.2016.12.003.

Seifrtová M, Nováková L, Lino C, Pena A, Solich P. 2009. An overview of analytical methodologies for the determination of antibiotics in environmental waters. Analytica Chimica Acta, 649(2), 158–179. doi: 10.1016/j.aca.2009.07.031.

Tuts L, Rasschaert G, Heyndrickx M, Boon N, Eppinger R, Becue I. 2024. Detection of antibiotic residues in groundwater with a validated multiresidue UHPLC-MS/MS quantification method. Chemosphere, 352, 141455. doi: 10.1016/j.chemosphere.2024.141455.

Wu HX, Liu RJ, Liu GJ, He M, Arif M, Li FM, Si W, Yue Z, Hu H. 2024. Unveiling antibiotic contamination in surface water: A study of the Huaihe River Basin's Huaibei Plain, a significant Chinese herbal medicine planting region. Science of the Total Environment, 933, 173125. doi: 10.1016/j.scitotenv.2024.173125.

Xue XD, Chen BH, Wang H, Fang CR, Long YY, Hu LF. 2021. Antibiotics in the municipal solid waste incineration plant leachate treatment process. Chemistry and Ecology, 37(7), 633–645. doi: 10.1080/02757540.2021.1924695.

Ying JL, Qin XP, Lang H, Guo JY, Xiong L, Zhang ZH, Liu F. 2022. Determination of 37 typical antibiotics by liquid chromatography-triple quadrupole mass spectrometry. Rock and Mineral Analysis, 41(3), 394–403. doi: 10.15898/j.cnki.11-2131/td.202111060168.

Yu KN, Wang RZ, Liu DD. 2023. A review of rapid detections for emerging contaminants in groundwater. Rock and Mineral Analysis, 42(6), 1063–1077. doi: 10.15898/j.ykcs.202302080018.

Yu X, Sui Q, Lyu SG, Zhao WT, Liu JG, Cai ZX, Yu G, Barcelo D. 2020. Municipal solid waste landfills: An underestimated source of pharmaceutical and personal care products in the water environment. Environmental Science & Technology, 54(16), 9757–9768. doi: 10.1021/acs.est.0c00565.

Zainab SM, Junaid M, Xu N, Malik RN. 2020. Antibiotics and antibiotic resistant genes (ARGs) in groundwater: A global review on dissemination, sources, interactions, environmental and human health risks. Water Research, 187, 116455. doi: 10.1016/j.watres.2020.116455.

Zhang R, Yang S, An YW, Wang YQ, Lei Y, Song LY. 2022. Antibiotics and antibiotic resistance genes in landfills: A review. Science of the Total Environment, 806, 150647. doi: 10.1016/j.scitotenv.2021.150647.

Zhou P, Zeng D, Wang XT, Tai LY, Zhou WW, Zhuoma QD, Lin FW. 2022. Pollution levels and risk assessment of heavy metals in the soil of a landfill site: A case study in Lhasa, Tibet. International Journal of Environmental Research and Public Health, 19(17), 10704. doi: 10.3390/ijerph191710704.