

Original Research

Quantifying Ecological Compensation for Cross-Regional Transfer of Industrial Hazardous Waste: A Case Study in Wenzhou, China

Yinfeng Xia¹*, Chao Wu², Guojin Sun¹, Yufeng Zhao¹

¹Nanxun Innovation Institute, Zhejiang University of Water Resources and Electric Power, Hangzhou, 310018, China

²Zhejiang Ecological Environment Group Co., Ltd, Hangzhou, 310012, China

Received: 23 October 2025

Accepted: 27 January 2026

Abstract

Industrial hazardous waste (IHW) comes in a wide variety of types and is difficult to dispose of completely on a local scale. Cross-regional cooperation is an effective way to achieve the optimal allocation of resources. This study constructs an ecological compensation framework for the cross-regional transfer of IHW, based on the generation and disposal status in Wenzhou, the utilization rate of disposal capacity, and the associated ecological environmental losses, development opportunity losses, and disposal costs. The results revealed that Wenzhou has sufficient capacity for IHW disposal, but the utilization rate is only 40%. Implementing the cross-regional transfer and disposal of IHW is conducive to utilizing the idle disposal capacity of Wenzhou and optimizing the resource allocation in the surrounding areas. Ecological compensation standards for various IHW were quantified. Among them, the incineration process requires the highest ecological compensation standard, which amounts to 1,629 CNY/t. The type of IHW with the largest disposal capacity in Wenzhou is HW17, and its recommended ecological compensation standard is 633.6 CNY/t. Full utilization of this disposal capacity can generate over 145 million CNY in ecological compensation income. This ecological compensation framework provides reasonable compensation standards and guidance for the cross-regional transfer of IHW and has strong applicability.

Keywords: industrial hazardous material, ecological compensation, ecosystem services value, cross-regional transfer, disposal capacity

*e-mail: xiayf@zjweu.edu.cn

Tel.: +86-571-8692-9060

°ORCID iD: 0000-0001-9457-2656

Introduction

Given their unique resource attributes and hazardous characteristics, industrial hazardous waste (IHW) falls within the category of solid waste subject to the strictest environmental supervision and attracts the greatest level of social concern [1, 2]. With the rapid development of China's economy, the rapid progress of urbanization and industrialization, as well as the continuous improvement of human living standards, the amount of various types of solid waste has been increasing year by year [3-5]. In recent years, the concept of "zero-waste cities" has been proposed and implemented in China [6, 7]. This also leads to a situation in which landfill-based IHW disposal faces bottlenecks in developed cities with scarce land resources. Wenzhou is an important city in the Yangtze River Delta region, with a population of nearly 10 million and a GDP of approximately 1 trillion CNY. However, nearly 80% of Wenzhou's land area consists of mountains and hills, making its land resources extremely precious. Therefore, promoting the joint construction and sharing of IHW recovery and disposal facilities and establishing the "resource management" concept becomes extremely important.

The cross-regional disposal of IHW is often accompanied by problems such as pollution transfer, environmental risk transfer, regulatory responsibility transfer, and the transfer of the "not in my backyard" sentiment [8]. To avoid unnecessary risk responsibilities, the local government of the receiving area often lacks enthusiasm to accept external solid waste, especially IHW. The resistance of local governments to the transfer of IHW to recovery and disposal reflects the lack of compensation for the transfer of environmental pollution responsibility. The establishment of a scientifically sound and rational ecological compensation mechanism constitutes the cornerstone of achieving cross-regional governance. Some cities in China have conducted in-depth explorations on the ecological compensation system for the cross-regional transfer and disposal of domestic waste and have achieved certain results [9-11]. However, there is still a lack of a theoretical basis for the ecological compensation of IHW.

Quantifying the compensation standard is the core for determining the amount of ecological compensation, and it is also the key to establishing an effective ecological compensation scheme [12]. It directly affects the scientific validity and implementation effectiveness of ecological compensation. The calculation methods of the existing ecological compensation standards for cross-regional transfer are mainly based on ecosystem service valuation, cost-benefit analysis, and opportunity cost methods [13-15]. Ecosystem service valuation can reflect the benefits of the ecological environment. This method realizes the monetization of ecosystem service functions, referred to as ecosystem service value (ESV). Costanza et al. (1997) classified the global biosphere ecosystem services into 17 categories

and estimated the functional values of all biosphere areas, such as water regulation, water supply, and soil and water conservation, based on existing international research [16]. The specific methods involve the equivalent factor method, the market price method, and the contingent valuation method, etc. [17-19]. The construction of IHW disposal facilities, whether it is a landfill, an incineration plant, or a recycling factory, will occupy and change the nature of the land, thereby causing damage to the surrounding ecological environment. On the other hand, cost-benefit analysis mainly consists of investment costs and ecological benefits [20]. At present, methods such as questionnaire surveys and indirect calculations are commonly adopted. IHW disposal facilities incur costs such as investment, operation, and depreciation, but they can also generate income through the recovery of resources and energy. Opportunity cost refers to the continuous cost resulting from the restriction of development opportunities due to environmental damage, both in the present and in the future [21]. In the cross-regional transfer and disposal of IHW, the opportunity cost is an important factor that cannot be ignored, as it directly affects the vital interests of residents.

In summary, the design of the ecological compensation system has already laid a certain foundation. However, no quantitative, technology-specific framework has been developed for the cross-regional transfer of IHW. As the cross-regional transfer of IHW involves transportation, storage, and centralized disposal, it faces problems such as ecological and environmental protection pressures and residents' health concerns in the receiving area, making it difficult to simply measure its value and increasing the difficulty of cost accounting for ESV. Meanwhile, the form of compensation will also affect the stability and reliability of the system. To fill this gap, this study attempted to propose an ecological compensation framework for the cross-regional transfer of IHW by integrating ecosystem service valuation, cost-benefit analysis, and opportunity cost. First, the necessity and feasibility of ecological compensation for the cross-regional transfer of IHW in Wenzhou were summarized and analyzed. Second, the ecological compensation standard was constructed by using ecosystem service valuation, cost-benefit analysis, and opportunity cost analysis. Finally, an ecological compensation system for the cross-regional transfer of IHW was developed based on IHW disposal capacity. It may provide valuable references and suggestions for China to break through the resource bottleneck, improve the disposal capacity of IHW, and achieve common prosperity in the region.

Materials and Methods

Study Area and Data Collection

Study Area

Wenzhou is a city located in the southeast of Zhejiang Province, China (N27°03'~28°36', E119°37'~121°18', Fig. 1). Wenzhou has a subtropical monsoon climate with four distinct seasons and abundant rainfall. The annual average temperature ranges from 17.3 to 19.4°C, and the annual precipitation is between 1,113 and 2,492 mm. As of 2024, the permanent resident population of Wenzhou is 9.85 million, the gross domestic product (GDP) reached 971.8 billion CNY, and the per capita GDP reached 99,106 CNY (equivalent to 13,919 USD). There were 9,291 industrial enterprises above designated size in Wenzhou, achieving an industrial added value (IAV) of 173.69 billion CNY, an increase of 10.2%. Therefore, industry in Wenzhou is still developing at a high speed, and the discharge of IHW will still show an increasing trend in the future.

Data Sources

The time span of this study is from 2022 to 2024. The basic statistical data of Wenzhou, such as the permanent resident population, GDP, per capita net income, and IAV, all come from the statistical yearbooks released by the Wenzhou Municipal Government. The data related to IHW, such as annual generation volume, generation types, disposal volume, incineration volume, and comprehensive utilization capacity, all

come from the Information Announcement on the Prevention and Control of Environmental Pollution by Solid Waste in Wenzhou. The market data, including the prices of landfill, incineration, and pollution emission rights trading, were obtained from the government pricing catalog published by the Development and Reform Commission of Zhejiang Province in 2022. The specific data source information is shown in Table 1.

Theoretical Basis

The main purpose of ecological compensation is to reduce or eliminate the negative impacts caused by human activities through compensation measures [22, 23]. In the field of solid waste resource utilization, it was extended to reward the negative impacts offset by resource utilization through compensation measures, thereby encouraging enterprises to undertake such ecological and environmental protection projects [24]. Therefore, it is of great importance to determine the ecological compensation standard. Based on this logic, the most crucial part of ecological compensation for IHW lies in accounting for the social harm cost caused by non-resource treatment and the expected benefits after resource utilization. As shown in Fig. 2, the cross-regional transfer of IHW involves many aspects, including incineration, landfill, and recovery, etc. The model for the cross-regional transfer of IHW includes the loss of ecological and environmental functions (LE), the loss of development opportunities in the surrounding areas of the disposal facilities due to environmental deterioration (LO), the disposal cost (CD), the dividends generated from the sale of resource



Fig. 1. Location of the study area.

Table 1. Related data sources.

Data category	Name	Data sources
Basic statistical data	Land area; the permanent resident population; GDP; per capita disposable income; IAV; per capita healthcare expenditure; population migration rate.	Statistical yearbooks of Wenzhou (2022, 2023, 2024)
IHW data	The total amount of IHW; the detailed amount of HW12, HW17, HW18, HW22, HW34, HW49; the disposal capacity of IHW; the number of disposal facilities; the amount of IHW transferred out; the amount of IHW transferred in.	Information Announcement on the Prevention and Control of Environmental Pollution by Solid Waste in Wenzhou (2022, 2023, 2024)
	Pollution emissions	Environmental Impact assessment reports (Wenzhou Xizilan Environmental Protection Technology Co., LTD, 2016; Zhejiang Ligao Environmental Protection Technology Co., LTD, 2016; Zhejiang Hetai Thermal Power Co., LTD, 2023; Yueqing General Industrial Solid Waste Landfill, 2020)
Market data	Benchmark price of emission rights trading; disposal fees of IHW	Zhejiang Province Pricing Catalogue (2022 Edition)
	Gross profit margin of IHW disposal enterprises; disposal cost of different disposal methods; product sales revenue	Shanghai Stock Exchange https://www.sse.com.cn/disclosure/listedinfo/regular/ (Shanghai Conglin Environmental Protection Technology Co., LTD 688370; Beijing High-Energy Dianchen Engineering Co., Ltd 603588) Shenzhen Stock Exchange http://www.szse.cn/disclosure/index.html (Dongjiang Environment Co., LTD 002672.SZ)
Reference data	Annual loss rate of ESV	[4]
	ESV of different land types	[27]

recovery and reuse (DR), and the gains from energy recovery and utilization (ER).

Calculation of Ecological and Environmental Losses

In this study, the loss of ecological and environmental functions was divided into two parts: ecological loss (LE_a) and environmental loss (LE_b). The former was used to measure the damage caused by IHW to the ecosystem, while the latter was used to measure the environmental pollution caused by the disposal of IHW. The specific Equation is as follows:

$$LE = LE_a + LE_b \quad (1)$$

Ecosystem service value (ESV) was used to quantitatively calculate LE_a . To ensure the operability of the model, cultivated land, forest land, wetland, water area, and green land (grassland) were selected as the accounting indicators. In this study, the weighted factor method is adopted to calculate ESV [25]. The weighted ESV is calculated by the following Equation.

$$ESV = \sum_k^n Z_k \times ESV_k \quad (2)$$

where k denotes the land use types; Z is the weight coefficient; ESV is the ecosystem services value, CNY/($\text{hm}^2 \cdot \text{a}$).

Therefore, the calculation formula for LE_a is as follows:

$$LE_a = \sum_i^n \frac{r_a \times ESV \times A}{G} \times Q_i \quad (3)$$

where i denotes the disposal types of IHW; r_a represents the annual loss rate of ESV of Wenzhou; A is the total ecological impact area of IHW disposal facilities, hm^2 ; G is the IHW disposal capacity of Wenzhou, t/a; Q is the amount of IHW, t/a.

The accounting indicators for LE_b include losses from air, water, noise, solid waste, and soil pollution, among others. Considering that the impact of noise is relatively small, and end-of-life disposal does not generate additional solid waste pollution, only the losses of air and water pollution were considered. China has established a trading system for pollution discharge rights. In this study, the calculation of environmental losses was based on the benchmark price of pollution discharge rights. Thus, the calculation Equation for LE_b is as follows:

$$LE_b = \sum_i^n \sum_j^m P_j \times E_{ij} \times Q_i \quad (4)$$

where j denotes the typical pollutants: SO_2 , NO_x , VOCs, COD, and $\text{NH}_3\text{-N}$, respectively; P is the benchmark price of pollution discharge rights, CNY/kg; E is the amount of pollutants generated by different disposal types, kg/t.

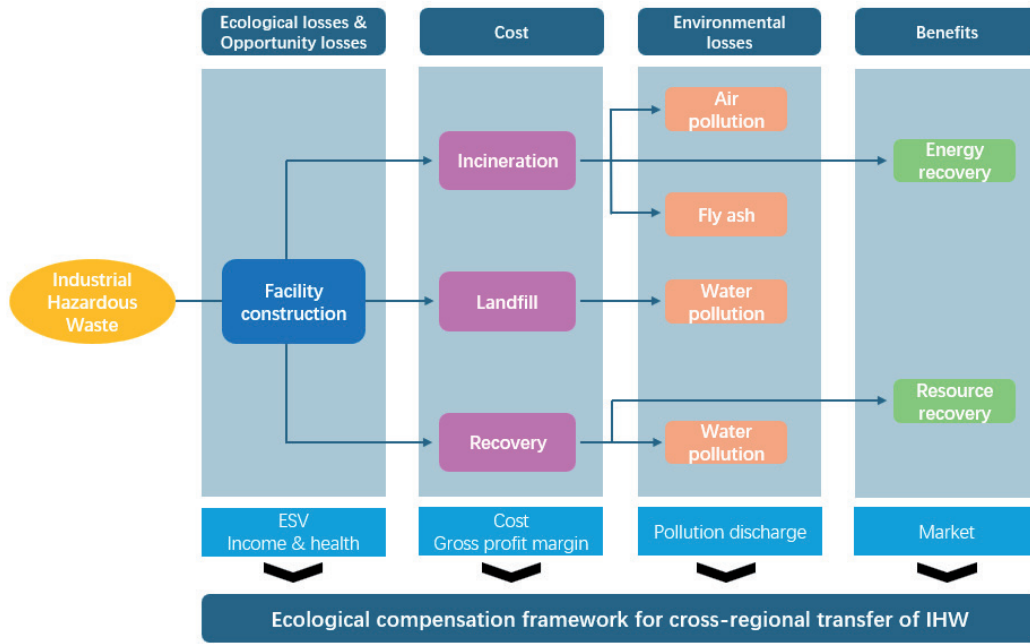


Fig. 2. Ecological compensation framework for cross-regional transfer of IHW.

Calculation of the Loss of Development Opportunities

This part of the loss can be measured by the opportunity cost method and the market value method [21, 26]. Specifically, it is possible to estimate the mobility of the regional labor force, the income levels of local farmers and urban residents, and the medical expenditures related to pollution (i.e., the loss of human health). The calculation Equation for *LO* is as follows:

$$LO = \frac{\rho \times A \times (r_p \times I_r + h \times e_m)}{G} \quad (5)$$

where ρ is the population density, p/hm^2 ; r_p is the population migration rate; I_r is the per capita disposable income of rural residents, CNY/p ; h is the health risk coefficient; e_m is the per capita healthcare expenditure, CNY/p .

Calculation of Costs and Benefits of IHW Disposal

Recovery, incineration, and landfill are three dominant disposal types of IHW. Apart from landfills, which offer no subsequent products, both recovery and incineration have products available for sale. Therefore, this part of the calculation will determine the costs and benefits based on the disposal types for different product categories. The disposal cost (*CD*) refers to the disposal costs of IHW without subsequent product sales. The calculating Equation is as follows:

$$CD = \sum_i^n r_{di} \times Q_i \quad (6)$$

where i denotes the types of IHW; r_d is the unit price required for different disposal types of IHW, CNY/t ; Q is the disposal amount, t/a .

The resource utilization of IHW generates both explicit economic benefits and implicit welfare gains. Explicit benefits arise from the sale of recovered resources, which provides direct revenue for enterprises. Implicit welfare gains are reflected in improvements to the urban environment through reduced waste emissions and lower costs associated with pollutant discharge penalties. The specific formula for *DR* is as follows:

$$DR = \sum_i^n \sum_l^m (R_l \times W_{il} \times Q_i) \quad (7)$$

where l denotes the products for sale; R is the revenue from the direct sale of item l , CNY/t ; W is the products generated from the recovery of IHW, t/t ; Q is the recovery amount of IHW, t/a .

Part of the IHW with calorific value can be incinerated to recover energy, thereby generating energy recovery benefits. The specific Equation is as follows:

$$ER = \sum_i^n V_i \times Q_i \quad (8)$$

where V is the economic value of the energy produced by incinerating per unit of the waste, CNY/t ; Q is the incineration amount of IHW, t/a .

Ecological Compensation Standard

In this study, ecological losses, environmental losses, opportunity losses, as well as revenue from resource sales and energy recovery during the disposal process of IHW were considered comprehensively. Suppose that

TL is the sum of all losses, which is taken as the total amount of the ecological compensation. The specific calculation model is as follows:

$$TL_i = \left[\frac{r_a \times ESV \times A}{G} + \sum_j^n P_j \times E_{ij} + \frac{\rho \times A \times (r_p \times I_r + h \times e_m)}{G} + r_{di} - \sum_l^m (R_l \times W_{li}) - V_i \right] \times Q_i \quad (9)$$

Therefore, the calculation model of the ecological compensation standard (S_i) is as follows:

$$S_i = TL_i / Q_i \quad (10)$$

where S is the ecological compensation standard for different types of IHW.

Results and Discussion

Current Status

In the past three years, the production of IHW in Wenzhou has shown a continuous growth trend. As shown in Fig. 3a), the annual generation of IHW increased from 470.4 kilotons in 2022 to 506.3 kilotons in 2023, then to 545.1 kilotons in 2024, with the annual growth rate exceeding 6%. In terms of output, the main types of IHW were, in order, surface treatment

waste (HW17), incineration residues (HW18), waste acid (HW34), waste circuit board (HW49), and copper-containing waste (HW22). Among them, both HW17 and HW49 have shown a significant year-on-year increase. The other three types of IHW, however, had years with both flat year-on-year growth and years of decline. The production of other types of IHW has shown a trend of decreasing year by year. Overall, the total amount of IHW generated in Wenzhou has been gradually increasing, but it is mainly concentrated in categories HW17 and HW49. The top five IHW categories account for over 85% of the total.

Meanwhile, the dominant type of IHW disposal in Wenzhou is recovery (as shown in Fig. 3b). The proportion of recovery showed a gradually increasing trend, ranging from 58.7% in 2022 to 59.6% in 2023 and 64.5% in 2024. The next dominant method is landfill, with proportions ranging from 33.1% in 2022 to 33.7% in 2023, then to 29.9% in 2024, showing a stable trend with a slight decline. Although incineration is also a common method for IHW disposal, its application in Wenzhou is not widespread. In 2024, only 2.7% of IHW adopted this method, but it is worth paying attention to in the future. Finally, every year, approximately 2.5% of IHW was stored for subsequent disposal. Although storage of IHW may lead to safety risks, the proportion remains relatively low [28]. As the amount of IHW generated continues to increase, the rates of recovery and landfill have remained relatively

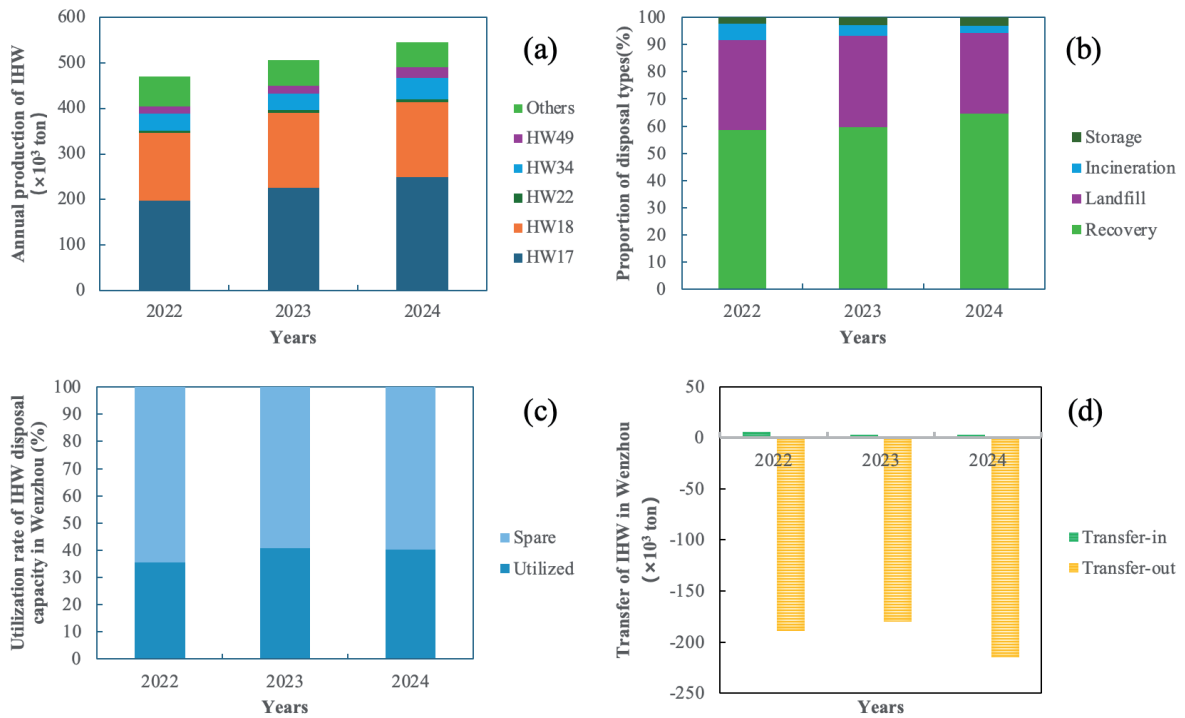


Fig. 3. The current situation of IHW disposal in Wenzhou.

a) the annual production of IHW in Wenzhou (HW17: Surface treatment waste; HW18: Incineration residue; HW22: Copper-containing waste; HW34: Waste acid; HW49: Waste circuit boards); b) the proportion of disposal types; c) the utilization rate of IHW disposal capacity in Wenzhou; d) the amount of IHW transferred cross-regionally.

stable, suggesting that Wenzhou has sufficient disposal capacity for IHW. However, there are still weaknesses in the disposal capacity for certain types of IHW. Fig. 3c) perfectly validates this hypothesis. The total disposal capacity of IHW in Wenzhou far exceeded its production amount. In 2024, it reached 826 kilotons/a, resulting in a utilization rate of disposal capacity of only 40.3%. This means a huge waste of resources, while also generating many cross-regional transfer demands. As shown in Fig. 3d), the total amount of IHW transferred out from Wenzhou to other regions was 21.5 kilotons in 2024, which accounted for only 3.9% of the total amount of IHW. On the other hand, the amount of IHW transferred in from other regions outside Wenzhou remained at a low level. The highest figure was 5.5 kilotons in 2022, which accounts for only 1% of the total disposal volume.

The Necessity of Cross-Regional Cooperation

The generation of IHW is closely related to the industrial structure of the city [29]. Wenzhou is one of the important industrial cities in the Yangtze River Delta region. Stainless steel and automotive components are important pillar industries in Wenzhou. The IHW emission intensity of a city can be measured by input-output analysis [30]. As shown in Fig. 4, the generation of IHW per billion IAV of Wenzhou was 1,771 t in 2024. It is far lower than the average levels in Zhejiang Province and China, which are 2,625 t and 3,210 t, respectively. Although there is a considerable gap compared to that of Beijing, overall, it is close to Shanghai and Hangzhou, which also have developed manufacturing industries. Compared with the typical heavy industrial city of Tangshan, the IHW emission intensity in Wenzhou is much lower. Meanwhile, Wenzhou has a strong disposal capacity of IHW, but most of it is idle, and the utilization

rate is only 40%, which results in a significant waste of resources. Therefore, Wenzhou has the necessary conditions to receive IHW transferred across regions.

The Ecological and Environmental Losses

In the ecosystem of Wenzhou, the forest, grassland, farmland, water area, and wetland ecosystems account for 61.10%, 0.67%, 12.90%, 4.41%, and 4.36% of the regional land area, respectively, a total of 83.44%. Each ecosystem has its corresponding ESV [31]. According to the distribution of the ecosystem and based on the area size, weight coefficients are assigned to the five major systems: forest ecosystem (forest land), grassland ecosystem (green land), farmland ecosystem (cultivated land), aquatic ecosystem (water area), and wetland ecosystem (wetland). Ultimately, a weighted ESV of Wenzhou can be obtained. The parameters for ecological loss calculation are shown in Table S1. The weighted ESV of Wenzhou is 37,450 CNY/($\text{hm}^2 \cdot \text{a}$).

The ecological and environmental losses caused by IHW are mainly based on ecosystem degradation and environmental pollution resulting from its disposal facilities [32, 33]. The distribution of IHW disposal facilities in Wenzhou is shown in Fig. S1. The ecological impact range is defined as the circular area of the radius of the influence range of air pollutants of a single disposal facility, that is, a circle with a radius of 2.5 km (an area of approximately 20 km^2). Given that the influence ranges of some disposal facilities overlap, after correction, the total affected area is 489 km^2 for all 30 disposal facilities. According to the report by Liu et al. on the profit and loss evaluation of the Wenzhou ecosystem, the annual loss rate of ESV of Wenzhou (r_a) was set at 1.16% [4]. From 2022 to 2024, there were 29, 29, and 30 disposal facilities of IHW in Wenzhou, respectively. Consequently, the IHW disposal capacity

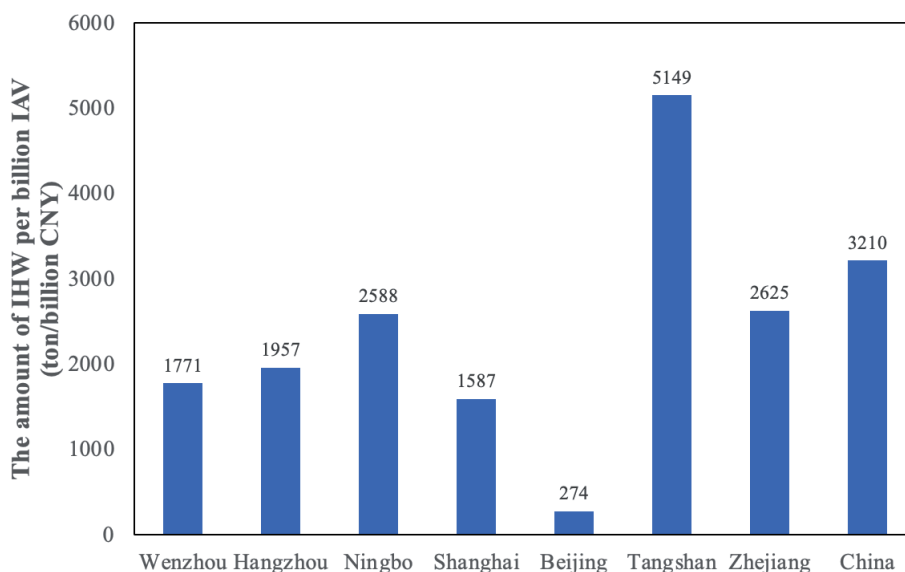


Fig. 4. Emission intensity of IHW in major cities in China, 2024.

Table 2. The ecological losses caused by IHW disposal in Wenzhou.

Years	Facility numbers	Influence area hm ²	Disposal capacity t/a	Ecological loss (LE_a) CNY/t
2022	29	47270	806,000	25.5
2023	29	47270	806,000	25.5
2024	30	48900	826,000	25.7
Average	29.3	47813	812,667	25.6

of Wenzhou was 812,667 t/a on average. Substituting this data into Equation (3), the ecological loss (LE_a) caused by IHW disposal facilities in Wenzhou can be obtained. The results were listed in Table 2. This means that the ecological loss caused by the disposal and utilization of IHW in Wenzhou was 25.5 CNY/t in 2024, and 25.6 CNY/t on average.

On the other hand, the environmental losses caused by IHW disposal mainly result from waste gas emission, wastewater discharge, and noise impact. Due to the difficulty in quantifying the impact of noise, it was not considered in this study. Three representative gaseous pollutants (SO_2 , NO_x , VOCs) and two typical water pollutants (COD, NH_3-N) were used as the basis for calculating environmental losses. According to the trading system for pollution discharge rights of China, these five pollutants were assigned specific benchmark prices, which can thus serve as an important reference for assessing environmental losses. In order to obtain the amount of pollutants generated by unit IHW during disposal, the authors investigated the environmental impact reports of relevant disposal facilities and obtained the following data, as listed in Table S2. Substituting

the data into Equation (4), the environmental losses (LE_b) caused by the IHW disposal each year can be obtained. As shown in Fig. 5, the amount of IHW locally disposed of in Wenzhou has been increasing year by year. Both landfill and recovery have seen significant growth, while incineration decreased from 27.8 to 14.3 kilotons/a. The pollution charge of recovery is the highest compared to the other two types, resulting in nearly 85% of the environmental loss originating from the local IHW recovery in Wenzhou. After estimation, the environmental loss caused by the disposal and utilization of IHW in 2024 was 0.86 million CNY, which was much smaller than the ecological loss caused. Therefore, the ecological and environmental losses (LE) caused by recovery, incineration, and landfill are 30.6, 28.1, and 26.1 CNY/t, respectively.

The Loss of Development Opportunities

The loss of development opportunities consists of two parts. One part is the potential increase in health expenditures for residents within the affected area of the IHW disposal facilities. The other part is the loss

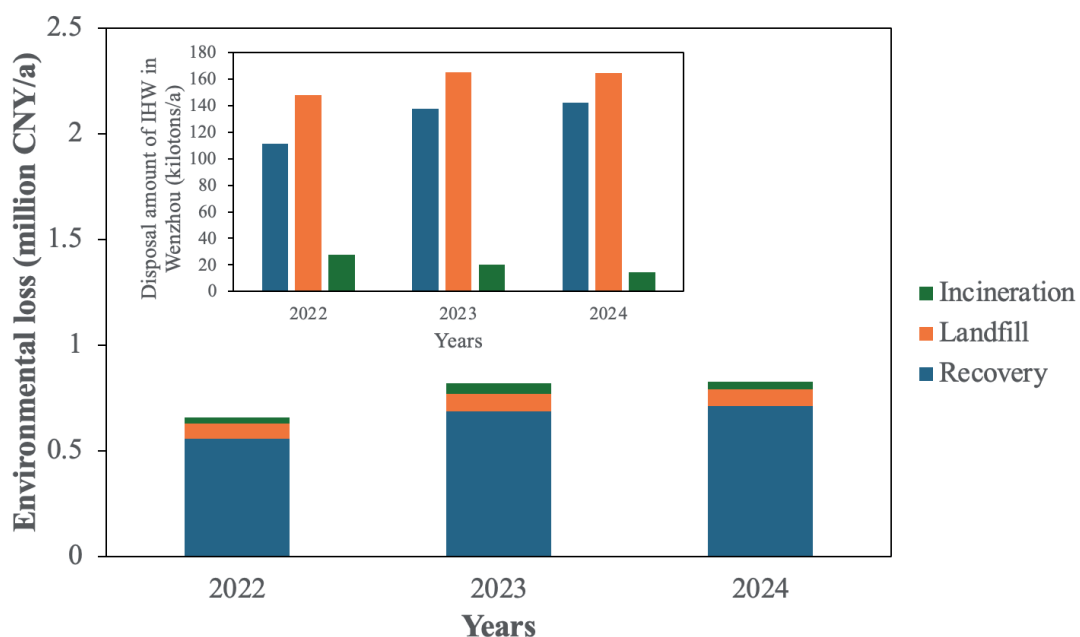


Fig. 5. The environmental loss caused by IHW disposal in Wenzhou.

Table 3. The loss of development opportunities caused by IHW disposal in Wenzhou.

Years	Influence area (hm ²)	Population density (p/hm ²)	Per capita disposable income (CNY/p)	Per capita healthcare expenditure (CNY/p)	Population migration rate (%)	Health risk coefficient	Loss of development opportunities (CNY/t)
2022	47,270	7.07	38,482	2,229	0.35	0.1	148.3
2023	47,270	7.07	41,622	2,296	0.35	0.1	155.6
2024	48,900	7.07	44,300	2,353	0.35	0.1	163.4

of job opportunities within that area. The concepts of population migration rate (r_p) and health risk coefficient (h) are introduced. In the past three years, the net migration rate of the population in Wenzhou was 0.35%. At the same time, the registered population in Wenzhou showed a slight downward trend, but remained relatively stable overall, at around 8.3 million. Therefore, the population density (ρ) is 7.07 p/hm². From 2022 to 2024, the per capita disposable income of rural areas (I_r) in Wenzhou increased from 38,482 to 44,300 CNY/a. On the other hand, the per capita medical expenditure (e_m) in Wenzhou increased slightly from 2,229 CNY in 2022 to 2,353 CNY in 2024. In the health risk assessment, an HQ (Hazard Quotient) less than 1 is considered acceptable [34]. As the maximum ground concentration compliance rate of pollutants within the compensation area is 10%, the health risk coefficient (h) in this study was set at 0.1. Substituting the data into Equation (5), the loss of development opportunities in Wenzhou can be obtained. The results are listed in Table 3. Based on the IHW disposal capacity of Wenzhou, the losses of development opportunities from 2022 to 2024 were 148.3, 155.6, and 163.4 CNY/t, respectively. The average annual growth rate of LO is approximately 5%. According to this trend, the projected LO for 2025 is expected to be 171.2 CNY/t. Based on this, in the subsequent calculations, LO will be set at 170 CNY/t.

Costs and Benefits of IHW Disposal

Different IHWs require different disposal methods, and they will result in completely different costs and benefits [35]. Therefore, the calculation of this part

is conducted based on different types of IHW. It has been previously mentioned that the proportions of the five major types of IHW in Wenzhou exceeded 85%. Therefore, the focus is on accounting for HW17, HW18, HW22, HW34, HW49, and paint waste (HW12). These six representative IHWs were classified into three disposal types: recovery, landfill, and incineration. By investigating the financial reports disclosed by similar disposal enterprises of listed companies in China, the costs and gross profit margins of IHW disposal were examined. The Development and Reform Commission of Wenzhou has set the corresponding disposal fees of IHW in Wenzhou. Considering that IHW disposal enterprises need a 25% gross profit margin to ensure stable operation of the business, this portion of the income needs to be considered as a cost during the calculation. The results are listed in Table 4. Among the three disposal types, landfill has no revenue from by-products, but its cost is relatively lower, so the gross profit margin is the highest, reaching 60%. Therefore, the net cost of landfill is negative. HW17 and HW22 mainly recover high-value zinc and copper, with relatively high by-product profits. However, the disposal costs are also the highest, and the gross profit margin is around 30%. HW34 mainly recycles products such as sulfuric acid and nitric acid, with relatively low costs and a gross profit margin of up to 43.8%. The disposal cost of incineration is relatively high, but the disposal fees set by the government are the highest, so there is still a decent gross profit margin. Since the revenue from incineration power generation is only 300 CNY/t, the net cost of incineration is the highest, reaching 1,433 CNY/t.

Table 4. The costs and benefits of IHW disposal in Wenzhou.

Disposal types	IHW types	Costs		Benefits		Gross profit margin (%)	Net cost (CNY/t)
		Disposal cost (CNY/t)	Profit cost (CNY/t)	Disposal fee (CNY/t)	Product sales (CNY/t)		
Recovery	HW17	3100	1733	2000	2400	29.5	433
	HW22	2800	1600	2000	2100	32.0	300
	HW34	900	800	1200	400	43.8	100
Landfill	HW18	1000	1333	2500	0	60.0	-167
	HW49	1000	1333	2500	0	60.0	-167
Incineration	HW12	2500	3033	3800	300	39.0	1433

Quantification of the Ecological Compensation Standard

Based on the above evaluations, the ecological and environmental losses, opportunity loss, and net disposal cost for different disposal types have been obtained. Then, the recommended ecological compensation standard for Wenzhou was provided. As shown in Table 5, the ecological compensation standards and their components for the six major types of IHW were presented. Among them, HW12, which is disposed of through incineration, requires the highest ecological compensation, reaching 1,629.09 CNY/t. This is partly due to the high cost of incineration disposal, and partly because the anti-incineration sentiment among the public is the strongest. The ecological compensation required for HW18 and HW49, which are disposed of through landfill, is the lowest, at only 31.13 CNY/t. This is due to the high charging fee, as well as the cost of landfill. The IHWs, HW17, HW22, and HW34, which can still be recycled, still need to be incentivized through ecological compensation. However, due to the differences in recovery processes and subsequent products, their ecological compensation standards also vary significantly. The ecological compensation standard for HW17 is the highest, at 633.60 CNY/t. HW22 follows with a standard of 500.60 CNY/t, while HW34 has the lowest standard of 300.60 CNY/t.

Compared to the reported standard based on emergy methods for phosphogypsum [24], which is 37.4 CNY/t for ecological and environmental loss, this study incorporates the same loss category but additionally monetizes opportunity cost, disposal cost, and technology-specific benefits, yielding a fully itemized and transferable compensation standard.

The Rationality of Ecological Compensation Standards

Since the construction of IHW disposal facilities may cause ecological damage and environmental pollution, which in turn affects the income and health of residents, there will be hidden costs associated with the disposal of IHW. As the transfer-out city of IHW, it avoids ecological damage and gains more development

opportunities. Therefore, reasonable ecological compensation is required for the transfer-in cities. This framework of ecological compensation covers losses of ecosystem and environment, loss of development opportunities, and the net cost of disposal.

The disposal facilities are fixed after their construction, so they have a continuous impact on ESV. Therefore, this impact needs to be distributed among the IHW they dispose of. Then the reasonable unit price is based on the disposal capacity of the disposal facility. When the disposal capacity is fully utilized, this cost will be minimized. In the past three years, the number of disposal facilities in Wenzhou has remained largely unchanged. In 2024, one more facility was added. Therefore, the total ecological loss in Wenzhou amounted to 21.42 million CNY in 2024, with a unit price of 25.6 CNY/t.

Meanwhile, whether it is recovery, incineration, or landfill, the disposal processes of IHW may cause secondary pollution. Therefore, this part of the pollutants should be regarded as cross-regional transfer, and it is reasonable to calculate and account for it through the trading of pollutant emission rights. Thus, the environmental loss was classified and calculated based on different disposal methods. The total amount of environmental loss caused by IHW disposal in Wenzhou was 2.18 million CNY in 2024.

The loss of development opportunities lies in the fact that the construction of IHW disposal facilities reduces the opportunities for residents to increase their income and increases the cost of maintaining health. Given that the locations of disposal facilities are usually chosen away from densely populated urban areas, rural residents are usually affected. Since it is difficult to separately count the population migrations caused by the construction of facilities, the overall population migration rate of Wenzhou is used as a substitute. The construction of factories often means the relocation of residents and the influx of migrant workers. Therefore, it is estimated that this loss exceeded 134.96 million CNY in 2024 and is still growing at a rate of 5% per year. This is also the reason why local governments are becoming increasingly cautious about building IHW disposal facilities.

Table 5. The ecological compensation standards for cross-regional transfer of IHW to Wenzhou.

IHW types	LE_a	LE_b	LO	CD	DR	ER	S
HW12	25.6	0.49	170	1733	0	-300	1629.09
HW17	25.6	5	170	2833	-2400	0	633.60
HW18	25.6	2.53	170	-167	0	0	31.13
HW22	25.6	5	170	2400	-2100	0	500.60
HW34	25.6	5	170	500	-400	0	300.60
HW49	25.6	2.53	170	-167	0	0	31.13

At present, the profits of IHW disposal enterprises mainly come from the income generated by the disposal fees. Although incineration and recovery can bring in sales revenue from by-products, it is far from enough to cover the fixed investment and depreciation, labor costs, transportation expenses, etc. According to the data disclosed by the China Securities Regulatory Commission for listed companies dealing with IHW, a 25% gross profit margin is the safety line for IHW enterprises to maintain their operations. Therefore, when calculating the net cost of IHW disposal, this factor needs to be taken into consideration. Incineration is the disposal method with the highest net cost, which is 1,433 CNY/t. Landfill is a disposal method with a negative net cost, thanks to its relatively high gross profit margin. Considering that landfill sites occupy land and have limited storage capacity, the cross-regional transfer for landfilling of IHW is not encouraged. Recovery generates different net costs depending on the types of IHW involved, so it is necessary to conduct classified calculations.

The purpose of ecological compensation is to encourage cross-regional cooperation, resource sharing, and maintain the healthy development of the IHW disposal industry. Therefore, the framework proposed in this study is reasonable, taking full consideration of the ecological service functions, residents' development opportunities, and the healthy operation of enterprises.

Benefits of Ecological Compensation

Based on the above analysis, there is still a significant amount of idle capacity for IHW disposal in Wenzhou, mainly concentrated in categories HW17, HW22, and HW34. As listed in Table S3, Wenzhou has the highest disposal capacity for HW17, reaching 483,400 t/a, with an idle rate of 48.5%. Based on the ecological compensation standard of HW17, which is 633.6 CNY/t, fully utilizing this disposal capacity can bring about 145 million CNY in economic benefits. In addition, there is also a disposal capacity of 57,600 t/a for HW22 in Wenzhou, but the idle rate has reached 88.2%. Therefore, fully leveraging this disposal capacity can also bring considerable economic benefits, amounting to 25.4 million CNY. The disposal capacity of HW34 has been well utilized at present, so cross-regional transfer is not encouraged. It should be noted that accepting IHW transferred from other regions not only generates substantial ecological compensation revenue but also helps improve the business conditions of the enterprises and promotes the healthy development of the industry.

Currently, the ecological and environmental losses, as well as the loss of development opportunities caused by IHW disposal, amount to nearly 160 million CNY each year in Wenzhou. Ecological compensation can cover these losses and help the government improve the local ecological environment and enhance the living standards of the residents.

Conclusions

This study conducts an in-depth analysis of the generation and disposal situation of IHW in Wenzhou, providing a feasible solution for future sustainable development. Based on ecosystem service value and market theory, a quantitative, technology-specific framework of ecological compensation for the cross-regional transfer of IHW was constructed. The ecological compensation standards range from 31.13 to 1,629.09 CNY/t, converting the technical differences into transparent price signals. This not only compensates for the losses incurred in the disposal of IHW but also provides a basis for decision-making for government guidance. By implementing the ecological compensation system to solve the problem of low utilization rate of IHW disposal capacity in Wenzhou, not only can considerable economic benefits be achieved, but a feasible solution can also be provided for the coordinated disposal of IHW in Zhejiang Province and even the entire country. Further empirical validation and policy refinement are required before a comprehensive ecological compensation system can be fully implemented.

(1) It is necessary to conduct a comprehensive analysis of the current situation of IHW generation and disposal throughout the province and even the entire country, and to seek appropriate resource allocation solutions.

(2) At present, there is no unified standard for ecological compensation for cross-regional utilization and disposal of IHW. The ecological compensation framework discussed in this study has certain universality in Wenzhou and even the Yangtze River Delta, but more scenarios are still needed to assist in its refinement.

(3) This study mainly discussed the most direct form of compensation, government financial fund compensation. However, the methods of ecological compensation are diverse. Besides innovating the ways of raising funds, various compensation methods, such as market compensation, policy compensation, and technical compensation, can also be considered.

Acknowledgments

This study was supported by the Nanxun scholar program (grant numbers: RC2024010802) and the Research Fund of Zhejiang University of Water Resources and Electric Power (grant numbers: xky2022008).

Nomenclature

CD – disposal cost
 CNY – Chinese Yuan
 COD – chemical oxygen demand

DR – dividends from recovery and reuse
 ESV – ecosystem service value
 GDP – gross domestic product
 HW12 – paint waste
 HW17 – surface treatment waste
 HW18 – incineration residues
 HW22 – copper-containing waste
 HW34 – waste acid
 HW49 – waste circuit board
 IAV – industrial added value
 IHW – industrial hazardous waste
 LE – ecological and environmental loss
 LO – opportunity loss
 USD – United States Dollar
 VOCs – volatile organic chemicals

Conflict of Interest

The authors declare no conflict of interest.

References

- CAMACHO J.A., RUIZ-PENALVER S.M., RODRIGUEZ M. Identification of Leading Hazardous Waste Generating Industries with High Improvement Potential in Spain. *Science of The Total Environment*, **731**, 139207, **2020**.
- DUAN H., HUANG Q., WANG Q., ZHOU B., LI J. Hazardous Waste Generation and Management in China: A Review. *Journal of Hazardous Materials*, **158**, 221, **2018**.
- GENG N., XIA Y., LU D., BAI Y., ZHAO Y., WANG H., REN L., XU C., HUA E., SUN G., CHEN X. The Bacterial Community Structure in Epiphytic Biofilm on Submerged Macrophyte *Potamogeton Crispus* L. and Its Contribution to Heavy Metal Accumulation in an Urban Industrial Area in Hangzhou. *Journal of Hazardous Materials*, **430**, 128455, **2022**.
- LIU R., LI J., HE G., FENG B., HUANG R., TIAN P., WANG L. Spatiotemporal variation and ecosystem service value assessment of green space system in Zhejiang Province, China. *Chinese Journal of Ecology*, **37**, 3119, **2018** [In Chinese].
- ZHAO J., RAO M., ZHANG H., WANG Q., SHEN Y., YE J., FENG K., ZHANG S. Evolution of Interspecific Interactions Underlying the Nonlinear Relationship between Active Biomass and Pollutant Degradation Capacity in Bioelectrochemical Systems. *Water Research*, **274**, 123071, **2025**.
- CHEN X., MA Y., FURST K., TAN Q., LIN W., SHI X., HUO J., LU X., LI J., LIN Y. Pathways to Zero Plastic Waste in Chinese Cities: Implications of Different Disposal Options under the Zero Waste Cities Policy. *Journal of Cleaner Production*, **463**, 142747, **2024**.
- LI Y., FU Z., LI J. Assessing the Policy Benefits of Constructing “Zero-Waste Cities” in China: From the Perspective of Hazardous Waste Lifecycle Management. *Science of The Total Environment*, **918**, 170184, **2024**.
- FERREIRA S., GALLAGHER L. Protest Responses and Community Attitudes toward Accepting Compensation to Host Waste Disposal Infrastructure. *Land Use Policy*, **27** (2), 638, **2010**.
- LI Y., CHEN X., FENG X., LV Y., ZHANG Z., QI Q. Investigation of the Allocation and Trading Strategy of Wastewater Emission Permits Considering Ecological Compensation. *Environmental Technology & Innovation*, **30**, 103103, **2023**.
- LIU C., LIU W., LU D., CHEN M., DUNFORD M., XU M. Eco-Compensation and Harmonious Regional Development in China. *Chinese Geographical Science*, **26**, 283, **2016**.
- SHANG W., GONG Y., WANG Z., STEWARDSON M.J. Eco-Compensation in China: Theory, Practices and Suggestions for the Future. *Journal of Environmental Management*, **210**, 162, **2018**.
- GUAN X., LIU W., CHEN M. Study on the Ecological Compensation Standard for River Basin Water Environment Based on Total Pollutants Control. *Ecological Indicators*, **69**, 446, **2016**.
- CAMPANHAO L.M.B., RANIERI V.E.L. Guideline Framework for Effective Targeting of Payments for Watershed Services. *Forest Policy and Economics*, **104**, 93, **2019**.
- CAO S., YU Z., ZHANG J., FENG F., XU D., MU X. Cost-Benefit Analysis of Ecosystem Services in China. *Ecological Engineering*, **125**, 143, **2018**.
- COSTANZA R., DE GROOT R., BRAAT L., KUBISZEWSKI I., FIORAMONTI L., SUTTON P., FARBER S., GRASSO M. Twenty Years of Ecosystem Services: How Far Have We Come and How Far Do We Still Need to Go? *Ecosystem Services*, **28**, 1, **2017**.
- COSTANZA R., D'ARGE R., DE GROOT R., FARBER S., GRASSO M., HANNON B., LIMBURG K., NAEEM S., O'NEILL R.V., PARUELO J., RASKIN R.G., SUTTON P., VAN DEN BELT M. The Value of the World's Ecosystem Services and Natural Capital. *Nature*, **387**, 253, **1997**.
- FERREIRA S., MARQUES R.C. Contingent Valuation Method Applied to Waste Management. *Resources, Conservation & Recycling*, **99**, 111, **2015**.
- XIE G., ZHANG C., ZHANG L., CHEN W., LI S. Improvement of the Evaluation Method for Ecosystem Service Value Based on Per Unit Area. *Journal of Natural Resources*, **30**, 1243, **2015**.
- DA MOTTA R.S., ORTIZ R.A. Costs and Perceptions Conditioning Willingness to Accept Payments for Ecosystem Services in a Brazilian Case. *Ecological Economics*, **147**, 333, **2018**.
- LOGAR I., BROUWER R., PAILLEX A. Do the Societal Benefits of River Restoration Outweigh Their Costs? A Cost-Benefit Analysis. *Journal of Environmental Management*, **232**, 1075, **2019**.
- ZHOU S., HUANG Y., HE H., ZHANG Z. Focusing on Structural Changes and Future Risks of Ecosystems: An Opportunity-Cost Based Ecosystem Service Account for Riparian Ecosystems and Its Case Study. *Ecological Indicators*, **158**, 111523, **2024**.
- ELOFSSON K., HIRON M., KACERGYTE I., PART T. Ecological Compensation of Stochastic Wetland Biodiversity: National or Regional Policy Schemes? *Ecological Economics*, **204**, 107672, **2023**.
- SHEN J., GAO X., HE W., SUN F., ZHANG Z., KONG Y., WAN Z., ZHANG X., LI Z., WANG J., LAI X. Prospect Theory in an Evolutionary Game: Construction of Watershed Ecological Compensation System in Taihu Lake Basin. *Journal of Cleaner Production*, **291**, 125929, **2021**.
- CAI W., LIU C., ZHANG C., MA M., RAO W., LI W., HE K., GAO M. Developing the Ecological Compensation

- Criterion of Industrial Solid Waste Based on Emergy for Sustainable Development. *Energy*, **157**, 940, **2018**.
25. ZHANG B., FENG Q., LU Z., LI Z., ZHANG B., CHENG W. Ecosystem Service Value and Ecological Compensation in Qilian Mountain National Park: Implications for Ecological Conservation Strategies. *Ecological Indicators*, **167**, 112661, **2024**.
 26. GENG J., LIANG C. Analysis of the Internal Relationship between Ecological Value and Economic Value Based on the Forest Resources in China. *Sustainability*, **13** (12), 6795, **2021**.
 27. LI J., ZHANG Y., ZHANG H., GONG H., LIU Y. The research of Spatio-temporal characteristics and influence factors of Wenzhou ecological resilience based on the potential-elastic-stability model. *Acta Ecologica Sinica*, **44**, 3253, **2024** [In Chinese].
 28. YANG P., ZHANG L.J., WANG X.J., WANG Z.L. Exploring the management of industrial hazardous waste based on recent accidents. *Journal of Loss Prevention in the Process Industries*, **67**, 104224, **2020**.
 29. JALIGOT R., CHENAL J. Decoupling municipal solid waste generation and economic growth in the canton of Vaud, Switzerland. *Resources, Conservation and Recycling*, **130**, 260, **2018**.
 30. MEYER D.E., LI M., INGWERSEN W.W. Analyzing economy-scale solid waste generation using the United States environmentally-extended input-output model. *Resources, Conservation and Recycling*, **157**, 104795, **2020**.
 31. LU Y., XU C., WANG X. A Novel Modification Framework for Evaluating Ecosystem Service Value in China's Five Major Freshwater Lakes and Their Surrounding Cities from 2002 to 2022. *Ecological Indicators*, **177**, 113711, **2025**.
 32. GAUR V.K., SHARMA P., SIROHI R., AWASTHI M.K., DUSSAP C., PANDEY A. Assessing the impact of industrial waste on environment and mitigation strategies: A comprehensive review. *Journal of Hazardous Materials*, **398**, 123019, **2020**.
 33. HONG J., HAN X., CHEN Y., WANG M., YE L., QI C., LI X. Life cycle environmental assessment of industrial hazardous waste incineration and landfilling in China. *The International Journal of Life Cycle Assessment*, **22**, 1054, **2017**.
 34. YAN F., LI N., WU R. Grey water footprint model of heavy metal based on the hazard quotient. *Ecological Indicators*, **162**, 112052, **2024**.
 35. NIINIMAKI K., PETERS G., DAHLBO H., PERRY P., RISSANEN T., GWILT A. The environmental price of fast fashion. *Nature Reviews Earth & Environment*, **1** (4), 189, **2020**.