Environmental Health Engineering and Management Journal. 2026;13:1694
http://ehemj.com
doi 10.34172/EHEM.1694

Environmental Health Engineering and Management Journal

Original Article

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Cost Cycle Analysis of Industrial Waste Management in Conventional and Smart Waste Management Patterns in Iran

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Abstract

Background: The industrial growth in recent decades has led to the production of significant amounts of industrial waste, leading to environmental and economic consequences, especially in developing countries. This situation has led to environmental pollution and health risks. In this study, the use of a smart industrial waste management system and its impact on waste management costs were investigated.

Method: Industrial waste quantity was investigated through field studies and official data, and the results were used for a comparative cost-benefit analysis of the current situation with scenarios for using the smart waste management model in a standard financial model.

Results: The results showed that the ratio of industrial waste production to the final product unit in the nonmetallic mineral, cellulose, food, textile, metal, and leather industries was 0.004, 1.88, 0.144, 0.027, 2.106, and 0.063%, respectively. The costs of industrial solid waste management in this situation were estimated at 11.42 USD/ton, which was reduced by 25.09% and 56.47%, respectively, through the use of two smart industrial waste management systems: a decentralized storage method and a centralized storage method.

Conclusion: Due to increased efficiency in waste collection and transportation, the costs of smart industrial waste management are much lower compared to the conventional method. Smart industrial waste management is a necessity for developing countries with financial limitations.

Keywords: Solid waste management, Industrial waste, Smart bin, Life cycle cost

Citation: Mohammadi H, Zardosht Z, Moein H, Hassani G. Cost cycle analysis of industrial waste management in conventional and smart waste management patterns in Iran. Environmental Health Engineering and Management Journal. 2026;13:1694. doi: 10.34172/EHEM.1694.

Article History:
Received: 28 July 2025
Revised: 19 September 2025
Accepted: 21 September 2025
ePublished: 9 February 2026

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Introduction

Government planning for economic growth and an increase in customer demand has led to the development of various industries, especially in developing countries (1,2). Also, economic competition in different countries has guaranteed the development of industries in the future (3,4). In this situation, globalization and industrialization have become the main priorities and goals for economic planners (4). However, various consequences of industrialization, including environmental pollution, are a serious concern (5,6). Energy consumption, air pollution, industrial wastewater, and industrial solid waste are important concerns related to industrial activities (7,8).

The production of significant volumes of solid waste is one of the consequences of urbanization and industrialization, which can have adverse effects on health and the environment (9-11). Industrial solid waste is an inevitable by-product in the production process (12); it includes two main categories: hazardous waste and non-hazardous waste (13). Non-hazardous waste includes boron sludge, slag, red mud, tailings, and other types of waste (14). However, hazardous industrial waste include solid waste that leads to environmental risk or human health problems (15). The production of industrial waste in 2013 in China was reported to be 32.8 billion tons (16). Also, there are reports of the production of 47,169 tons/year of industrial waste from 5,000 industries in Kuwait (17). Öncel et al 2017 reported the solid waste production ratio in plastic manufacturing industries in Turkey to be in the range of 11.5 to 100 kg/ton (18). Also, the production of industrial solid waste in an industrial area in Iran was reported as 64 tons/day (19). A significant portion of industrial waste may be generated by a few industrial activities. For example, Al-Khatib et al 2015 reported that about 48% of total industrial solid waste in Palestine is generated by the paper, pulp, furniture, and wood industries, while these industries account for only 3% of the industries operating in Palestine (20). In addition, the proportion of hazardous waste in industrial waste is also different. The study of 276 industries in Iran in 10 different categories showed that out of a total of 38,826 tons of industrial waste produced per month, 33,435 tons (86.1%) included hazardous waste. The ratio of hazardous waste in leather industries and chemical industries was 0.1% and 97.2%, respectively (21).

While various options are available for material and energy recovery from solid waste (22), one of the challenges of industrial solid waste management is the limited separation of components and the low recycling or reuse ratio, which has been reported in some literature as less than 20%(23). Environmental and health risks caused by industrial wastes and attention to the goals of sustainable development have led to a trend towards circular management of this type of solid waste (24). In this situation, the recycling potential is the distinguishing characteristic of industrial solid waste compared to other types of municipal solid waste. Therefore, reducing industrial waste management costs can lead to an increase in the financial balance of recycling.

The problems of conventional methods of industrial waste management, such as rapid filling of waste containers or non-filling of containers, lead to increased costs and irregular frequency of industrial solid waste collection (25). In recent years, the use of smart waste management has been considered to reduce the mentioned problems. Smart containers form the basis of smart waste management methods (26,27). The use of the smart garbage container system will lead to the diversity of the daily collection routes and the non-repetition of predefined routes. In fact, these conditions will increase efficiency and avoid moving and stopping between empty waste containers (28-30). Although the use of a smart waste management system has positive consequences, there are limitations to its implementation. An important limitation is the cost of smart waste management. The use of smart waste collection and transportation systems may increase investment costs, but in the long run, due to increased efficiency, it reduces wasted costs (31). This limitation is especially important for developing countries.

Industrial waste is a potential threat to the environment, especially in developing countries, due to technical and economic limitations in pollutant control. Also, the costs of industrial waste management in developing countries can be higher due to the lack of high-tech methods. However, there is a knowledge gap regarding the economic consequences of industrial waste and the impact of available management options on local costs. This study aimed to evaluate the impact of using smart waste management methods in reducing industrial waste management costs and to compare the cost reduction ratio in centralized and decentralized waste storage patterns. For this purpose, the cost of solid waste management was investigated in six industrial categories. Also, the differences in waste management costs in different smart industrial waste management scenarios were evaluated and compared with the current conditions.

Materials and Methods

Data gathering

This study was conducted in an industrial area in Iran. The industrial areas (zones) in Iran are clusters of industries supported by the government and located in complexes near cities (21,32). Various industries, including private industries and government industries, operate in industrial zones. The administrative management of the industrial zone and the provision of utilities such as electricity and water are the responsibility of the government, but the management of the activities of each factory is private. In all industrial zones in Iran, there is a Health, Safety, and Environment (HSE) department that provides services such as occupational health for workers and control of pollutant emissions. In this study, six classifications of industries, including nonmetallic mineral, cellulose, food, textile, metal, and leather industries, were evaluated in 2023. Industrial waste generation data in the studied industries were collected from official data recorded in the HSE unit in the industries. Further data on industrial waste management were gathered by interviewing the executive managers of the studied industries. This data collection method was consistent with the industrial waste management data collection methods used in previous studies in Iran and yielded similar results (21).

Data Analysis

Industrial waste management costs were estimated based on the financial model of waste management in Iran that was presented in previous studies (33). This financial model includes the cost analysis of the waste management hierarchy, including storage, collection, transportation, recycling, and disposal (34,35). The equations for estimating the cost of industrial waste management are shown in Table 1 (36,37):

Scenarios

Industrial waste management costs were estimated in three trial scenarios based on changes in storage and transportation conditions. The first scenario represented the current situation. In this scenario, the collection and transportation of industrial waste were done at regular intervals. As shown in Figure 1, the second scenario represented smart industrial waste management based on decentralized waste storage, and the third scenario represented smart industrial waste management based on centralized waste storage. Decentralized waste storage involves multiple storage containers distributed at specific distances, while centralized waste storage involves placing waste storage containers in one location. The unit cost for the sensor, data transmission system, and backend software was considered and applied in the equations based on the average prices in the Iranian market.

Results

Industrial waste quantity

The results of the waste quantity analysis in the six categories of studied industries are shown in Table 2. The results showed that the highest ratio of industrial waste production was in the metal industry, which was equal to 2.106% of the final product. At the same time, the ratio of industrial waste production to the final product in the cellulose and leather industries was 1.88% and 0.063%, respectively. Therefore, the production of industrial waste per 12000 tons of final product per year in the nonmetallic mineral, cellulose, food, textile, metal, and leather industries was estimated at 0.48, 226.32, 17.28, 3.24, 252.72, and 7.56 tons/year, respectively.

Cost analysis

The results of the estimated costs of the studied industrial waste management are shown in Table 3. The results showed that in the current situation, the highest cost in the waste management hierarchy is related to

Table 1. Details of used financial model

Equations	Formula	Parameters
1	$\text{ISWSC} = Cn\left(\frac{\text{Oc}+\text{Mc}}{\text{Py}}\right)$	ISWSC is the storage cost of industrial solid waste, *Cn* is the number of containers, *Oc* is the operating cost, *Mc* is the maintenance cost, and *Py* is the number of years of the project.
2	$\text{ISWCC} = LC\left(\frac{\text{Cn}}{\text{Ls}}\right)+Pc$	ISWCC is the collection cost of industrial solid waste, *Lc* is the cost for each labor, *Pc* is the personal protective equipment cost, and *Ls* is the standard labor number for collection.
3	$\text{ISWTC} = Trc\left(\frac{Wv}{Tv}\right)+Fc\left(\frac{\text{distance}}{\text{Trn}}\right)+Trn\left(\frac{Oc+Mc}{Py}\right)$	ISWTC is the transportation cost of industrial solid waste, *Trc* is the truck cost, *Wv* is the waste volume, *Tv* is the truck volume, *Fc* is the fuel cost, and *Trn* is the truck number.

Table 2. Calculated quantity of industrial waste in the studied industries in 2023

	Waste ratio (kg/ton final product)	Industry capacity (million ton/year)	Calculated waste generation (ton/year)
Textile industries	0.27	0.16	43.74
Leather industries	21.06	0.0044	9.35
Metal industries	0.63	85.70	53991
Nonmetallic mineral industries	0.04	342.84	13713
Cellulose industries	18.86	0.04	754.40
Food industries	1.44	8.74	12585.6

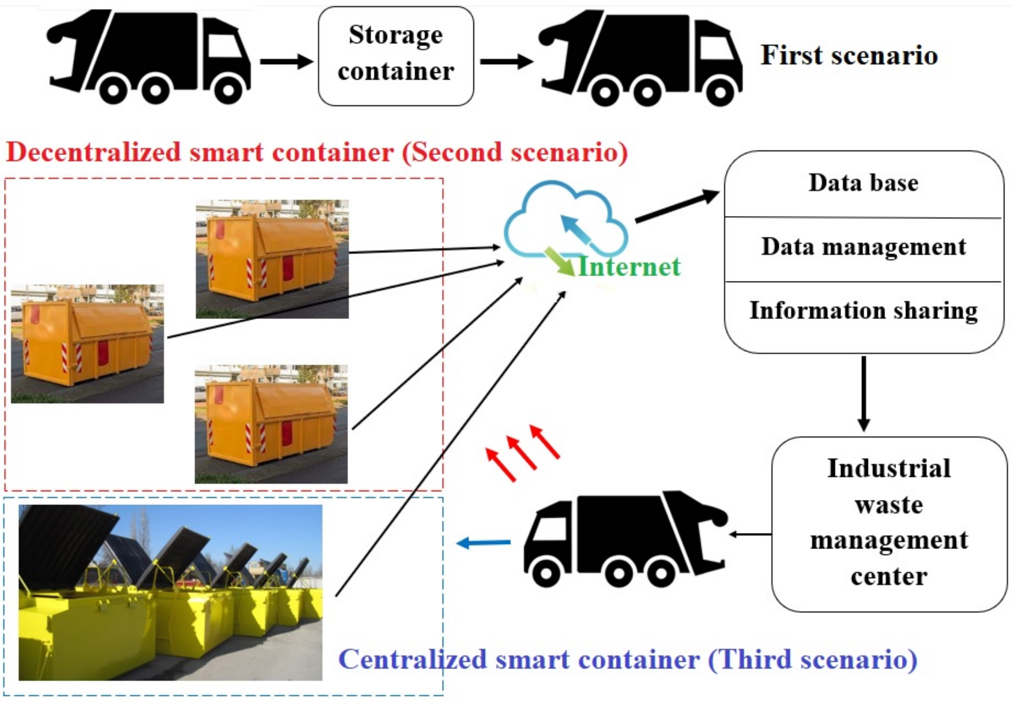

Figure 1. Details of industrial waste routes in the studied scenarios

transportation, which includes 53.7% of the total cost. As shown in Figure 2, the increase in storage costs in the second and third scenarios related to the development of smart containers was 23.4% and 36.7% higher than the first scenario, which represents the current situation. However, the reduction in transportation costs in the second and third scenarios compared to the first scenario was 28.4% and 62.8%, respectively (Table 4). In fact, smart

Table 3. Details of waste generation and management costs in the studied industries in 2023

		Textile industries	Nonmetallic mineral industries	Leather industries	Cellulose industries	Food industries	Metal industries
Waste production (ton/year)		42.72	13374.92	8.90	733.36	12274.88	52659.52
Cost per ton of waste	Storage			0.73			
	Collection			4.57			
	Transportation			6.12			
Storage cost (USD/year)		31.93	10010.49	6.82	550.71	9187.48	39413.43
Collection (USD/year)		199.89	62668.41	42.72	3447.60	57516.19	246738.87
Transportation (USD/year)		267.68	83923.56	57.22	4616.92	77023.87	330424.92
Total		499.51	156602.46	106.77	8615.24	143727.55	616577.22

Table 4. Details of industrial waste management cost in the studied scenarios in 2023 (USD/year)

		Textile industries	Nonmetallic mineral industries	Leather industries	Cellulose industries	Food industries	Metal industries	Total
S1	Storage cost	31.9302	10010.49	6.8255	550.712	9187.488	39413.43	59200.87
	Collection	199.8918	62668.41	42.7295	3447.608	57516.192	246738.87	370613.70
	Transportation	267.6888	83923.56	57.222	4616.928	77023.872	330424.92	496314.19
	Total	**499.5108**	**156602.46**	**106.777**	**8615.248**	**143727.552**	**616577.22**	**926128.76**
S2	Storage cost	54.28134	17017.833	11.60335	936.2104	15618.7296	39413.43	73052.08
	Collection	29.98377	9400.2615	6.409425	517.1412	8627.4288	246738.87	265320.09
	Transportation	40.15332	12588.534	8.5833	692.5392	11553.5808	330424.92	355308.31
	Total	**124.41843**	**39006.6285**	**26.596075**	**2145.8908**	**35799.7392**	**616577.22**	**693680.49**
S3	Storage cost	111.7557	18018.882	23.88925	1927.492	17456.2272	43354.773	80893.01
	Collection	7.995672	7833.55125	1.70918	137.90432	6390.688	123369.435	137741.28
	Transportation	10.707552	10490.445	2.28888	184.67712	8558.208	165212.46	184458.78
	Total	**130.458924**	**36342.87825**	**27.88731**	**2250.07344**	**32405.1232**	**331936.668**	**403093.08**

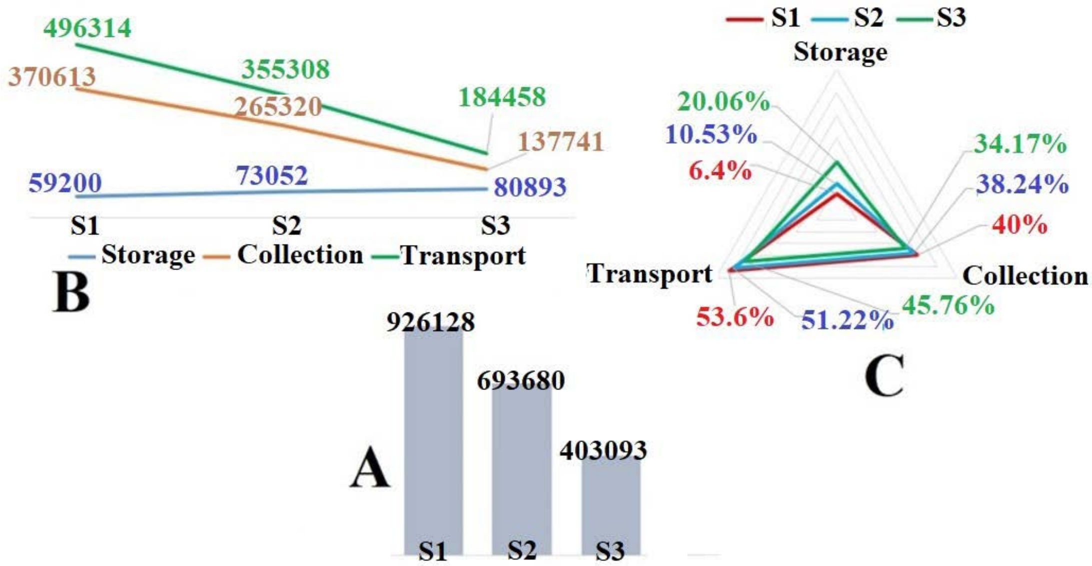

Figure 2. Cost analysis of studied scenarios (S1-S3), A: total cost in studied scenarios (USD/year), B: trend of cost change in management stages (USD/year), C: ratio of management stages in total cost

equipment in containers that send the volume of stored waste in the container to the waste management center requires investment in network development, sensor installation, and a data transmission system. However, reducing truck movements and avoiding their visits to containers that are not yet full reduces waste collection and transportation costs.

However, investing in the development of smart containers leads to a reduction in collection and transportation costs as well as a reduction in the cost of truck maintenance. Therefore, in developing countries such as Iran, although providing investment for smart industrial waste management is a limitation, reducing the operational costs of waste management in a smart method can be a strength that ultimately leads to improving the financial balance of waste management. Also, due to the growth of specialized skills in the past decades, skilled human resources are one of the potential resources for applying the smart industrial waste management method in developing countries, including Iran.

Discussion

The production of industrial waste in different countries and in different industries does not have the same pattern (8,13,14). The production of industrial waste depends on the type of industry, available technology, quality of operation, and waste reduction programs that are supported by the government (14). Therefore, the production of industrial waste has temporal and spatial variation, which is evident in previous reports. For example, the results of the analysis of the quantity of waste in the Shams Abad industrial zone in Tehran showed that 1428 tons/day of solid waste was produced in this area, 80% of which (426048 tons/year) was related to the metal industry and 0.005% was related to the medical equipment industry (30.3 tons/year) (38). In another example, an assessment of the quantity of industrial waste in an industrial zone in Yazd, Iran, which included 252 industrial units, showed that 65 tons/day, with a volume of 519 cubic meters of industrial waste, was produced in this area. Glass and paper (32%) and metals (21%) accounted for the largest portion of the studied industrial waste (19). In addition, industrial development in Iran in recent decades has led to the development of industries in urban environments. For example, a study of one of the urban areas of Tehran showed that 292 small and 15 large industrial units were active in this area, producing 4,850 tons/year of industrial waste. The highest share of industrial waste in this urban area of Tehran was produced by machinery manufacturing industries, at 2,282 tons/year (39). Considering the lack of a centralized industrial waste management system and a comprehensive monitoring program, industrial waste management in Iran involves irregular storage (dumping in industrial zones) and irregular collection, which has led to increased costs of industrial waste management (21,32). The results showed that the third scenario leads to a reduction in industrial waste management costs by 56.47%, while the reduction in industrial waste management costs in the second scenario was calculated to be 25.09%. This cost reduction was due to the reduction in the costs of collection and transport of industrial waste, which is one of the main aims of smart waste management (40). According to national laws in Iran, industrial waste management is the responsibility of the producer (39). Therefore, private companies providing waste management services collect industrial waste (19). In addition, the significant potential of industrial waste recycling has led industries to pay attention to the reuse or sale of solid waste to material recovery facilities (MRF) (21). Therefore, the use of smart industrial waste management in the studied scenarios will be effective in reducing the costs of recycling and disposal of industrial waste. In the first scenario, which represents the current conditions of industrial waste management, industrial waste collection trucks collect waste from containers at regular intervals, usually daily. This method is less efficient than the smart waste management method for reasons such as fast filling of containers due to improper capacity design, sudden filling due to changes in the production process, and reduction of stored waste due to unforeseen interruptions in industrial production (25,41).

The problems caused by the inefficiency of the current solid waste collection structures have led to the development of smart waste management (41). Compared to the current method, which includes one operational part (trucks), the smart industrial waste management method consists of three operational parts, including smart containers, an information network, and trucks. Smart containers use sensors to notify the waste management center that the container is full through the information network, which then sends the data to the trucks for waste collection (29). One of the most important consequences of a smart industrial waste management system that leads to cost reduction is the prevention of trucks traveling on repetitive routes and moving towards empty containers (28, 42). Reduction of waste management costs using smart systems for municipal solid waste has been reported in several cases. For example, reducing the collection delay time from 55 minutes to 18 minutes and increasing the average container fill ratio from 72% to 89% have been reported with the replacement of the traditional waste management system with a smart system (29). However, the increased costs associated with the development of smart containers and information networks may be considered as a limitation for the use of smart systems (42).

The expansion of the number and activity of industries in Iran, as a vast country, and the limitations in human resources and government budgets, make monitoring industrial waste management a challenge for government organizations responsible for environmental protection and health. Scattered and irregular data on the quantity of industrial solid waste are among the first limitations. In this situation, the environmental and health risks from industrial waste are high. The diversity of pollutants in the composition of industrial waste, including heavy metals, oil and petroleum compounds, solvents, and other pollutants, can lead to soil and water resource pollution (43). Even transferring part of industrial waste to landfills can lead to an increase in the concentration of these pollutants in the leachate, which is an environmental threat (44). Therefore, the development of the smart industrial waste management system can lead to the creation of complete and systematic data on the quantity of industrial solid waste and its trends. Therefore, in the smart industrial waste management method, the possibility of transferring hazardous industrial waste to municipal waste landfills is reduced. Also, due to the importance of proper treatment methods for hazardous industrial solid waste and the use of hazardous waste landfills, a smart waste management system can facilitate the monitoring of industrial solid waste management processes.

This study had strengths and limitations that can be considered in future studies. Predicting the economic consequences of using a smart industrial waste management system in two scenarios was a strength of this study. Considering several types of industries with different waste generation ratios to the final product was another strength of this study. However, evaluating the indirect pollutant cycle in industrial waste management in the studied scenarios was a limitation of this study. Therefore, considering the results of the study, the following are suggested by the authors to reduce industrial waste management costs:

The ratio of industrial waste production to the final product unit for each industry in the industrial zone should be calculated.

The capacity of the containers should be designed based on the calculated quantities.

The use of centralized storage should be prioritized by designing a central storage station.

The smart industrial waste management system should be developed as a necessity in industrial zones.

The data from the smart collection system should be used for database preparation and planning by decision makers.

Changes in the pollutant cycle in solid waste management in the conventional and smart systems can be investigated in future studies.

Conclusion

The status of industrial waste management in an industrial zone in Iran in 2023 was studied, and the effect of using a smart waste management system on reducing its costs was evaluated. The results showed that industrial waste production in six categories, including nonmetallic mineral, cellulose, food, textile, metal, and leather industries, was 37.56, 2.06, 34.48, 0.119, 147.9, and 0.025 tons/day, respectively. In the current situation, the cost of waste management in the total studied industries was estimated at 926128.76 USD/year. The use of a smart industrial waste management system in two scenarios, including decentralized storage and centralized storage, reduced management costs by 25.09% and 56.47%, respectively. In addition to reducing the costs of industrial waste management, the smart system can be helpful in providing a database of industrial waste, which is one of the current limitations of industrial waste management in Iran. The use of a centralized smart system can prevent the waste of time and money due to trucks moving between empty containers. The use of smart industrial waste management systems is an environmental necessity for developing countries and provides better monitoring by environmental protection organizations and local decision-makers.

Acknowledgements

The authors gratefully acknowledge the financial support given by the Yasuj University of Medical Sciences, Yasuj, Iran (grant number: 4020034; ethical code: IR.YUMS.REC.1402.041).

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Funding acquisition: Ghasem Hassani.
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Writing–review & editing: Hamed Mohammadi, Zahra Zardosht, Hossein Moein, Ghasem Hassani.

Competing interests

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Ethical issues

The Research Ethics Committee of Yasuj University of Medical Sciences, Yasuj, Iran, approved this study (ethical code: IR.YUMS.REC.1402.041).

Funding

The authors gratefully acknowledge the financial support given by the Yasuj University of Medical Sciences, Yasuj, Iran (grant number: 4020034)

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