



Evaluation of Waste Management at the Aradkouh Waste Processing Complex, Kahrizak, Tehran

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Received: 2025-10-29

Revised: 2026-02-14

Accepted: 2026-02-21

Initial Publish: 2026-02-23

Final Publish: 2026-09-01

Abstract

Over the past decade, numerous criticisms have been raised at the national, provincial, and local governmental levels regarding the mismanagement and inefficiency of the Aradkouh waste complex in Kahrizak, Tehran. However, these criticisms have not yet led to any decisive policy-making or concrete actions aimed at resolving this problem. In recent years, municipal authorities have repeatedly addressed issues related to the management of Aradkouh, and the complex has frequently been identified by relevant officials as one of the primary sources responsible for the capital city's unpleasant odor. The most important indicators for measuring and evaluating waste management performance at Aradkouh include the degree of damage control, the implementation of optimal management practices, and the realization of value-added generation from waste—often referred to as “dirty gold.” Accordingly, this study first conducted a comprehensive assessment of the waste generation cycle in Tehran, followed by an evaluation of waste management practices at the Aradkouh complex as the largest waste management facility in Tehran. Subsequently, strategic evaluation was carried out using benchmarking as the primary analytical method, while technology assessment and SWOT analysis were employed as complementary approaches. Overall, the findings indicate that, compared with global experiences, the current management approach suffers from major deficiencies, including weaknesses in waste control and separation (both at the source and due to incomplete processing at the destination), failure to achieve fully sanitary landfilling, lack of coherent and active infrastructure for energy production (including gas recovery, energy generation, and waste incineration), and the absence of a comprehensive strategic framework.

Keywords: Aradkouh, evaluation, optimization, waste, management

How to cite this article:

Samadi, S., & Ahmadian, R. (2026). Evaluation of Waste Management at the Aradkouh Waste Processing Complex, Kahrizak, Tehran. *Management Strategies and Engineering Sciences*, 8(5), 1-13.

1. Introduction

Urbanization, population growth, and industrial expansion have significantly increased the volume and complexity of municipal solid waste worldwide, transforming waste management into one of the most critical environmental and managerial challenges of contemporary cities. The rapid growth of urban populations has led to increased consumption patterns, resulting in greater waste generation and intensifying the need for efficient and sustainable waste management systems that integrate environmental protection, economic feasibility, and social acceptance [1, 2]. In megacities, waste management has

evolved beyond simple disposal functions and is now considered an integral component of urban infrastructure and sustainable development strategies, requiring systematic planning, technological integration, and institutional coordination [3, 4]. Inefficient waste management practices can result in severe environmental degradation, including soil contamination, groundwater pollution, and greenhouse gas emissions, particularly methane, which has a significantly higher global warming potential than carbon dioxide and contributes substantially to climate change [5, 6]. Consequently, modern waste management frameworks emphasize waste minimization, recycling, energy recovery,



and environmentally sound disposal to align with sustainability and circular economy principles [1, 7].

The transition from traditional linear waste disposal models toward circular economy approaches has introduced new paradigms in resource management, emphasizing waste as a valuable resource rather than a liability. Circular economy frameworks promote waste prevention, reuse, recycling, and energy recovery, thereby reducing reliance on landfills and minimizing environmental impacts [1, 8]. Waste-to-energy (WtE) technologies, including incineration, anaerobic digestion, and methane gas recovery, play a crucial role in this transformation by converting waste into usable forms of energy such as electricity and heat, thereby contributing to energy security and resource efficiency [9, 10]. These technologies not only reduce landfill dependency but also enable economic value creation from waste streams, supporting sustainable development and reducing greenhouse gas emissions [11, 12]. In addition, advancements in Industry 4.0 technologies, artificial intelligence, and smart waste management systems have enhanced waste monitoring, operational efficiency, and decision-making processes, enabling more efficient waste collection, sorting, and processing [8, 13]. These developments demonstrate that waste management is no longer solely an environmental function but also a strategic economic and technological domain.

Despite these advancements, many developing countries continue to face significant challenges in implementing sustainable waste management systems due to institutional, financial, technological, and social constraints. These challenges include insufficient infrastructure, limited investment, lack of regulatory enforcement, and low public participation in waste separation and recycling programs [14, 15]. Effective waste management requires coordinated governance, stakeholder participation, and long-term strategic planning to ensure sustainability and operational efficiency [16, 17]. In addition, behavioral factors, social norms, and public awareness significantly influence waste management outcomes, particularly in relation to waste segregation, recycling participation, and environmental responsibility [18, 19]. Therefore, comprehensive waste management systems must integrate technological solutions with institutional capacity building, community engagement, and regulatory frameworks to achieve sustainable outcomes [20, 21].

Globally, successful waste management models demonstrate the importance of integrated waste management strategies that combine advanced technologies, regulatory

enforcement, and economic incentives. Germany, for example, has developed one of the most advanced waste management systems in the world by implementing circular economy principles, strict landfill regulations, and widespread adoption of waste-to-energy technologies [11]. This approach has significantly reduced landfill dependency while increasing recycling rates and energy recovery efficiency. Similarly, modern waste management systems incorporate reverse logistics, resource recovery, and environmental diplomacy frameworks to address emerging challenges such as electronic waste and hazardous materials management [7, 22]. Waste management has also become increasingly linked to environmental governance, sustainability reporting, and climate change mitigation strategies, highlighting its importance in global environmental policy and sustainable development agendas [10, 12]. These international experiences demonstrate that successful waste management requires integrated planning, technological innovation, and effective institutional coordination.

In Iran, waste management has become an increasingly important issue due to rapid urbanization, population growth, and increasing waste generation rates, particularly in major metropolitan areas such as Tehran. Tehran, as one of the largest cities in the Middle East, generates thousands of tons of municipal solid waste daily, creating significant challenges for waste collection, processing, and disposal systems [23]. The complexity of waste management in Tehran is further exacerbated by urban expansion, changing consumption patterns, and insufficient infrastructure development to accommodate increasing waste volumes [2, 6]. Although various waste management initiatives have been implemented, including recycling programs, composting, and landfill management, challenges remain in achieving efficient and sustainable waste management outcomes [3, 4]. In addition, environmental concerns such as methane emissions from landfill sites, leachate contamination, and air pollution have raised serious concerns regarding the environmental and public health impacts of current waste management practices [5, 24].

The Aradkouh waste processing and disposal complex, located in the southern region of Tehran, represents the largest waste management facility serving the Tehran metropolitan area and plays a critical role in the city's waste management system. This complex includes waste processing facilities, composting units, landfill sites, and energy recovery infrastructure designed to manage and process large volumes of municipal waste [23]. However,

despite its strategic importance, the effectiveness and efficiency of waste management operations at Aradkouh remain subject to various operational, technological, and managerial challenges. These challenges include infrastructure limitations, technological inefficiencies, insufficient energy recovery, and gaps in strategic planning and resource utilization [3, 6]. Furthermore, the absence of integrated waste management strategies and limited investment in modern waste processing technologies may reduce the facility's ability to achieve optimal economic and environmental performance [20, 21]. The growing importance of sustainable waste management, energy recovery, and environmental protection underscores the need for systematic evaluation and strategic improvement of waste management facilities such as Aradkouh.

In addition to technological and infrastructural challenges, environmental and climate-related concerns further highlight the importance of improving waste management performance at large landfill sites. Landfill sites represent significant sources of methane emissions, which contribute to climate change and environmental degradation if not properly managed and controlled [5]. Methane recovery and energy conversion technologies provide opportunities to reduce greenhouse gas emissions while generating economic value and renewable energy, contributing to both environmental protection and energy sustainability [9, 10]. However, the successful implementation of these technologies requires effective management, technological integration, and supportive institutional frameworks to ensure long-term operational sustainability [11, 12]. Therefore, evaluating the performance and management effectiveness of major waste processing facilities is essential for identifying operational gaps and developing strategies for improvement.

Given the increasing importance of sustainable waste management, energy recovery, and environmental protection in urban environments, evaluating the effectiveness of waste management systems and identifying opportunities for strategic improvement have become essential priorities for policymakers and urban managers. Comprehensive evaluation approaches such as benchmarking, strategic analysis, and technology assessment provide valuable tools for assessing waste management performance and identifying best practices based on successful international experiences [1, 25]. These approaches enable the identification of operational inefficiencies, technological gaps, and strategic limitations while providing insights into potential solutions and

improvement strategies. Therefore, the aim of this study is to evaluate the waste management system of the Aradkouh waste processing complex in Tehran using benchmarking and strategic analysis approaches in order to identify existing gaps, assess operational performance, and propose optimal management strategies aligned with successful international waste management models.

2. Methodology

This study is applied in terms of objective and descriptive–analytical in terms of methodology. The research strategy is based on a combination of library studies, field observations, and the benchmarking technique.

Data Collection

The data required for this study were collected through two main methods:

a) Library Studies:

Scientific sources were reviewed, including reputable domestic and international journal articles, international reports (such as NASA reports, reports of the Tehran Waste Management Organization, and reports of Veolia Group), specialized books, and reliable databases. These sources were used to develop the theoretical framework, identify evaluation indicators, and select benchmark countries.

b) Field Studies:

Field data were collected through direct visits to the Aradkouh complex and observation of operational processes. In addition, semi-structured interviews were conducted with selected personnel and officials of the complex to supplement the information. Field observations included examination of processing lines, the composting site, the incineration facility, the anaerobic digestion facility, the landfill site, and the leachate treatment plant.

Data Analysis Method

Two main methods were used for data analysis: benchmarking and SWOT analysis, with technology analysis employed as a supplementary tool.

Benchmarking

Benchmarking is defined as a continuous process for measuring products, services, and operational practices against those of leading competitors or high-performing organizations (Owen & Rogers, 1999). The purpose of this method is to obtain information that contributes to continuous organizational improvement.

In this study, a three-level benchmarking model was used to evaluate the performance of the Aradkouh complex:

Level One: Self-Assessment

At this stage, the current status of the Aradkouh complex was documented in terms of technical specifications, operational processes (composting, incineration, anaerobic digestion, and landfilling), nominal and actual capacities, and economic productivity. This self-assessment was conducted based on field observations, review of internal reports, and comparison between documented data and operational realities.

Level Two: Comparative Assessment

In this stage, the performance indicators of the Aradkouh complex were compared with successful global benchmarks. The selection of benchmark countries was based on two main criteria:

- **China:** Due to its global leadership in waste-to-energy technologies and its role as the world's largest importer of recyclable waste, China was selected as a model for large-scale industrial waste processing (Veolia Group, n.d.).
- **Germany:** Due to its pioneering role in the circular economy and its "near-zero landfill" policies, Germany was selected as a model for source separation, public awareness, and integrated waste management systems [6].

This comparison was conducted in two domains:

- **Strategic Benchmarking:** Comparison of macro-level policies, comprehensive strategies, and management structures.

- **Functional (Process) Benchmarking:** Comparison of specific technologies and processes such as sanitary landfilling, sorting lines, energy recovery, and leachate control.

Level Three: Ideal State and Optimal Model Development

Based on the identified gaps between the current status of Aradkouh and the successful experiences of benchmark countries, an optimal waste management model for the Aradkouh complex was developed, and practical solutions adapted to local conditions were proposed.

Benchmarking is sometimes defined as "best practice benchmarking," which refers to the systematic search for the most effective operational methods in organizations recognized as leaders in their field and learning from their practices.

Benchmarking levels can also be presented from another perspective, as shown in Table 2.

Table 1. Levels of Benchmarking [

Level	Title	Elements
One	Self-Assessment	Measuring the organization's performance over time.
Two	Comparison	Comparing organizational performance with data obtained from various information databases based on organizational criteria and values; identifying areas requiring improvement and determining best practice standards.
Three	Partnering	Learning best practices and implementation tools and implementing necessary changes. Ideally, benchmarking is a reciprocal activity.

In this method, the process begins with identifying and defining the operational areas that require benchmarking. In the next step, the best benchmark option is identified. Subsequently, data are collected and analyzed to determine the characteristics of the selected activity or process. Finally, benchmarking is conducted at three levels—(1) self-assessment, (2) comparative assessment, and (3) ideal state—to evaluate the waste management practices of the Aradkouh complex.

SWOT Analysis

To complement the findings obtained through benchmarking and to provide a comprehensive understanding of the strategic position of the Aradkouh complex, SWOT analysis was employed. This method enables strategic planning by identifying Strengths, Weaknesses, Opportunities, and Threats (Wehrich, 1982). The SWOT matrix, as a tool for analyzing organizational

positioning and aligning internal and external factors, is one of the most widely used strategic analysis methods in management.

Kearns (1992) emphasizes that SWOT can either be a powerful managerial tool or a superficial and potentially misleading exercise. This outcome depends on the accuracy and rigor of decision-makers in integrating analyses of internal and external factors affecting the organization's future.

Accordingly, in this study, SWOT analysis was developed based on the following components:

Internal strengths and weaknesses were identified through field observations and self-assessment of the Aradkouh complex's performance.

External opportunities and threats were extracted through library studies, analysis of global experiences, and

examination of external environmental factors affecting waste management in Iran.

The SWOT analysis is presented in tabular form and serves as a foundation for developing improvement strategies in the conclusion section.

Technology Analysis

In addition to benchmarking and SWOT analysis, technology analysis was used as a supplementary tool to evaluate the technical and economic feasibility of the equipment and technologies employed at the Aradkouh complex. In this section, the status of key technologies such as incinerators, anaerobic digesters, and composting lines was compared with current global standards, and the causes of their inefficiency or failure were analyzed.

Study Population

The study population in this research is the Aradkouh Waste Processing and Recycling Complex, located in the Kahrizak district of Ray County, Tehran Province. This complex is situated at kilometer 23 of the old Tehran–Qom road and is recognized as the largest waste management facility serving the Tehran metropolitan area.

3. Findings and Results

3.1. Nominal Capacities:

The complex consists of 34 processing lines with a nominal daily intake capacity of 10,000 tons of municipal solid waste, including both wet and dry waste. Upon entering the processing lines, waste is transferred by loaders into hoppers and then conveyed via conveyor belts. During movement along the conveyor system, certain recyclable materials such as metal cans and plastic bottles are manually separated by workers and placed in designated storage areas. Additionally, ferrous metals are separated using magnetic separators installed along the conveyor belts.

Sanitary landfilling is implemented through trench excavation, final covering with stone powder, and the installation of drainage networks for leachate control.

Compost production is carried out through one operational line with a capacity of 500 tons per day, and an additional 12 new lines, each with a capacity of 250 tons, have been designed. Currently, compost refining and granulation are conducted within a site covering approximately 1,300 hectares. Compost is converted into granules with diameters less than 7 mm, classified as Grade 1 fertilizer, while granules larger than 7 mm are classified as Grade 2 fertilizer. Physical analysis of municipal solid waste in Iranian cities has shown that a high percentage of waste

consists of organic materials suitable for composting. Therefore, compost production is considered one of the most effective waste management and disposal methods in the country.

The leachate treatment facility covers an area of 3 hectares and has a treatment capacity of 1,400 cubic meters per day, while the actual daily leachate production at Aradkouh is approximately 400 cubic meters.

At the waste incineration facility, more than 200 tons of rejected waste from processing lines were incinerated and converted into electrical energy. At that time, of the total 3 megawatt-hours of electricity generated, only 75% was available for commercial sale, while the remaining 25% was consumed internally to support operational processes. The contractor responsible for this system was Tadbir Salamat Development Company, and the incineration system utilized Chinese technology.

The biogas facility—an anaerobic digestion unit with a nominal capacity of 300 tons of mixed waste per day and electricity generation capacity of 2 megawatt-hours—was commissioned and became operational in May 2013. Following its commissioning, more than 300 tons of mixed municipal waste from eastern Tehran were processed daily in this system.

3.2. Existing Conditions Based on Field Observations:

Field observations indicate that only approximately 8 processing lines remain operational, while the remaining lines have ceased functioning. Of these 8 lines, only 4 are currently active. Landfilling practices are only semi-sanitary, involving trench excavation, final stone powder covering, and drainage systems for partial leachate control. However, multiple leachate leakages have been observed, and during rainfall events, excessive leachate accumulation occurs due to inadequate final cover. Consequently, landfill environments remain largely uncontrolled, and proper waste compaction has not been achieved.

Although one 500-ton compost line and 12 additional 250-ton lines have been designed, compost refinement and granulation operations continue within the 1,300-hectare site, producing granulated fertilizer of varying grades based on particle diameter. The leachate treatment facility is currently non-operational due to the absence of a qualified contractor.

The incineration facility is also out of operation due to an accident involving the combustion chamber. Due to the lack of domestic technological capability for manufacturing

replacement components and the aging condition of the incineration infrastructure, Aradkouh management has been unable to restore the facility, rendering it completely inactive.

Similarly, the biogas facility, despite initial optimization efforts, remained operational for approximately two years and partially operational for an additional three years. However, due to deficiencies in system design and management, it is now completely inactive, and its infrastructure and equipment have been fully dismantled.

3.3. *Economic Value (Cost–Benefit) of Aradkouh:*

The current management approach at the Aradkouh complex lacks an economic orientation, and most of its economic capacities remain underutilized or inactive. Compost production and waste separation for recycling are outsourced to private contractors, who operate at minimal capacity levels. Observations conducted in the waste unloading areas indicate that the use of non-standard waste bags has created significant operational challenges. In contrast, in countries such as Canada, Japan, and South Korea, municipalities provide standardized waste bags to residents, facilitating effective waste separation at the source.

The use of appropriate separation bags and adherence to standardized procedures enable wet waste to be transported without excessive leachate generation while preserving dry waste integrity for recycling or disposal. Waste processing, separation, compost production, and electricity generation are implemented only for a portion of Tehran's municipal waste at the Aradkouh complex. Waste exceeding processing capacity is deposited in landfill storage areas for potential future processing.

Currently, refuse-derived fuel (RDF) production is not implemented at Aradkouh, methane gas recovery systems are not operational, and there is no dedicated medical waste incineration facility.

3.4. *Social Threats Resulting from Aradkouh Management:*

Based on field observations and verbal reports from relevant officials, certain areas within the Aradkouh complex have been identified as crime-prone zones, including incidents involving illegal weapons discoveries and the recovery of human remains.

Additionally, unpleasant odors caused by improper leachate management, inadequate landfill practices, and

insufficient odor control measures represent significant social and environmental impacts. The presence of stray dogs also poses health and safety risks to personnel and increases the potential spread of infectious diseases within urban areas.

3.5. *Strategic Trend Analysis:*

Several operational units at Aradkouh, including treatment plants and processing sites, have ceased functioning primarily due to outsourced management arrangements and now require infrastructure rehabilitation and technological modernization.

The waste incineration facility has been permanently shut down due to low operational efficiency, outdated infrastructure, lack of economic feasibility, and an explosion incident affecting key facility components. Negotiations are currently underway with Chinese companies for the construction of a new incineration power plant and waste processing facility within the Aradkouh complex.

3.6. *Energy Recovery System Using Anaerobic Digestion:*

With advancements in waste management practices in Tehran, energy recovery from waste became a strategic priority for municipal authorities. Various technological processes were evaluated in collaboration with academic and research institutions, resulting in the signing of a Build–Operate–Transfer (BOT) contract with a private company in late 2010.

This contract involved the construction and operation of an anaerobic digestion facility with a nominal capacity of 300 tons of mixed waste per day and electricity generation capacity of 2 megawatt-hours. The facility became operational in May 2013, receiving more than 300 tons of mixed municipal waste daily from eastern Tehran.

Typically, wet waste, following separation from dry recyclables, is transferred into digestion tanks. Through anaerobic fermentation processes, biogas is produced. The biogas undergoes moisture removal and purification to increase methane concentration, after which it is combusted to generate electricity. The residual sludge is used as a suitable raw material for high-quality compost production.

In 2014, due to optimization processes, the facility operated below full capacity and produced only 500 kilowatt-hours of electricity. Despite subsequent optimization efforts, the facility remained operational for only approximately two years and partially operational for

an additional period. It is currently fully inactive, and its infrastructure has been dismantled.

3.7. *Lack of Qualitative Development of Waste Incineration Facilities for Electricity Generation at Aradkouh:*

One of the primary barriers to the development of incineration facilities at Aradkouh is the high construction cost associated with non-localized technology and relatively

low electricity prices in Iran. Additionally, the absence of guaranteed electricity purchase tariffs represents a major structural limitation.

Although private sector participation could potentially overcome these barriers, successful implementation requires a comprehensive and integrated national waste management strategy, which currently lacks sufficient institutional commitment and implementation capacity.

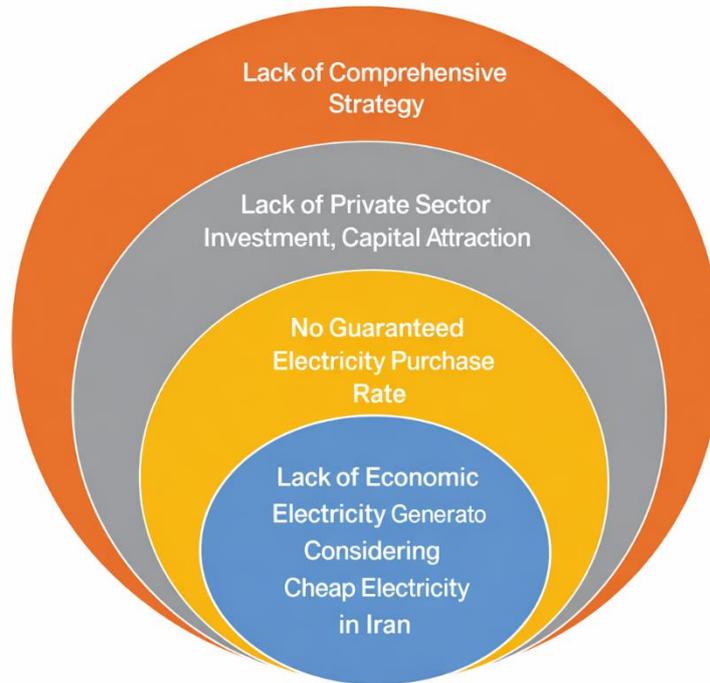


Figure 1. Lack of qualitative development of incineration facilities for electricity generation at Aradkouh.

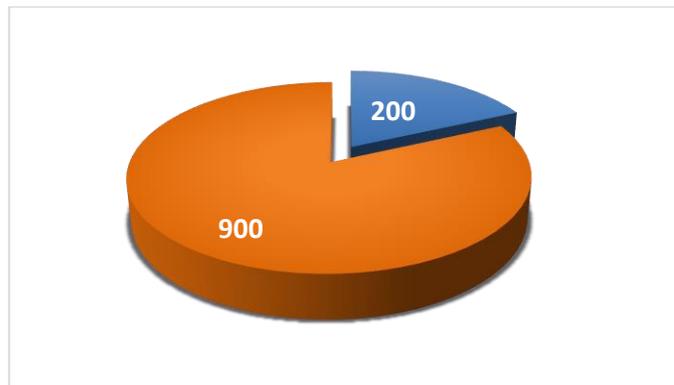


Figure 2. Benchmarking of waste incineration efficiency compared with a successful international benchmark (daily waste input volume in tons) [9] (Blue: Aradkouh Waste Incinerator (Year of construction: 2011); Orange: Maishima Incineration Plant, Osaka (Japan) (Year of construction: 2001)).

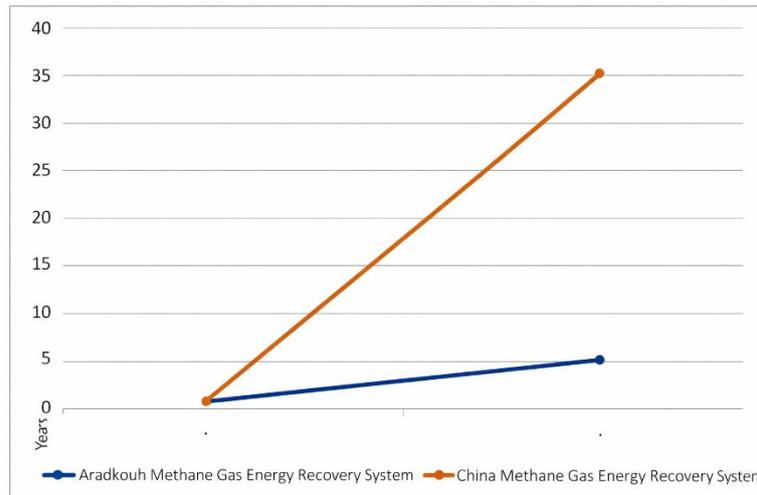


Figure 3. Benchmarking of energy recovery from methane gas compared with a successful international benchmark [24].

Table 2. Strategic Comparative Benchmarking – Alignment with Case Study Examples

Country / Facility Name	Main Strategy	Outcome
China / Veolia Group	Maximum economic efficiency; leachate treatment and commercial sale; methane gas control and commercialization; electricity generation and sale	40 million cubic meters of landfill gas are collected annually and used for energy/electricity generation; potential annual electricity production of 100,000 megawatt-hours from waste incineration facilities (Veolia Group, n.d.).
Iran / Aradkouh Waste Processing Complex, Kahrizak, Tehran	Absence of a primary strategic framework; fragmented and reactive management approach	Economic capacities remain largely inactive; increasing accumulation of waste; lack of long-term planning; increased environmental and social risks.

Table 3. Functional Benchmarking of Waste Landfilling

Aspect	Aradkouh	Laogang Landfill Site, China
Trench design	Hospital waste is handled with greater care compared to general waste	Primarily designed using deep excavation pits
Final landfill cover	Mostly filled with construction debris and stone powder	Covered with a protective impermeable layer to prevent rainwater infiltration

Table 4. Functional Benchmarking of Waste Sorting and Processing Facilities

Aspect	Aradkouh	Waste Processing Facility in China
Work environment	Lack of adequate facilities; poor sanitary and visual conditions; high potential for disease transmission	Controlled sanitary conditions and regulated work environment
Skilled workforce	Predominantly unskilled labor, including foreign workers	Skilled and semi-skilled technical workforce

Table 5. Ideal and Optimal Benchmarking Model for the Aradkouh Complex

Factor	Current Condition	Optimal Model – Successful Benchmark
Waste input control	High volume of incoming waste; absence of parallel processing facilities to reduce system load; lack of source reduction programs	Expansion of processing lines; improvement of workforce skill level; enhancement of occupational hygiene standards; implementation of source separation policies; enforcement of regulatory frameworks for waste separation (German model)
Landfilling method and landfill volume control	Waste accumulation and semi-sanitary landfilling practices; incomplete leachate control	Near-zero landfill strategy; economic utilization of waste prior to landfill disposal; fully sanitary landfill design with impermeable final covers to prevent rainwater infiltration and ensure effective leachate control (China model)

Table 6. SWOT Analysis of Aradkouh Waste Management

Factor	Description Based on Research Findings	Benchmarking Relationship (Comparison with Successful Models)	SWOT Classification
Strengths	High nominal capacity (daily intake of approximately 10,000 tons, 34 processing lines, and large composting facility); relative success in compost production (active lines and granulation systems); favorable geographic location (distance from urban center and large land area of approximately 1,400 hectares); existence of initial infrastructure (leachate drainage system and former biogas facility)	Comparable to large-scale facilities in China (Veolia Group; Laogang landfill); compost production capacity aligns with successful models in developing countries	Internal Strength
Weaknesses	Only approximately 4 processing lines operational out of 34 nominal lines; complete shutdown of incineration, anaerobic digestion, and leachate treatment systems; semi-sanitary landfill conditions (inadequate compaction and leachate leakage during rainfall); near-zero source separation; non-transparent contractor-based management structure lacking authority; shortage of skilled personnel and modern equipment	Significant performance gap compared with Germany (source separation rates exceeding 60–70% and minimal landfill reliance); China (leachate treatment exceeding 95% and high methane recovery efficiency); near-zero energy recovery efficiency compared with benchmark models	Internal Weakness
Opportunities	High potential for energy production from methane gas and refuse-derived fuel (RDF) using existing or upgraded technologies; potential for private sector participation (successful past BOT model and ongoing negotiations with Chinese companies); increasing demand for compost and organic fertilizers in agriculture; environmental and regulatory pressures (greenhouse gas reduction commitments and national environmental policies); availability of transferable advanced technologies (modern incineration systems and improved anaerobic digestion technologies); large and stable waste generation volume in Tehran	China model: commercialization of methane gas and treated leachate generating revenue; Germany model: mandatory waste separation and financial incentives reducing landfill volumes; circular economy opportunities through RDF and energy markets	External Opportunity
Threats	High methane emissions (previous NASA reports; contribution to air pollution and climate change); groundwater and soil contamination due to leachate leakage; widespread unpleasant odors resulting in public dissatisfaction and protests; social risks (crime-prone areas, stray dogs, and disease transmission risks); increasing waste generation exceeding system capacity; lack of political commitment and weak policy enforcement; high cost of rehabilitating outdated infrastructure without financial support	Global environmental regulatory tightening (European Union and German environmental standards); risk of international scrutiny and reputational damage; negative comparison with successful international facilities; risk of complete operational shutdown due to future technical failures or accidents (e.g., previous incineration system explosion)	

4. Discussion and Conclusion

The findings of this study revealed that despite the significant nominal capacity of the Aradkouh waste management complex, its operational performance remains substantially below its designed potential, reflecting structural, technological, and strategic inefficiencies in waste management implementation. The existence of 34 nominal processing lines with a designed capacity of approximately 10,000 tons per day demonstrates that the Aradkouh complex was originally conceived as a comprehensive waste management facility capable of addressing the needs of a megacity such as Tehran. However, field observations indicated that only a small proportion of these processing lines remain active, and many critical subsystems, including the waste incineration facility, anaerobic digestion unit, and leachate treatment plant, are currently non-operational. This discrepancy between nominal capacity and actual performance reflects a broader pattern observed in developing waste management systems, where infrastructure investments are not supported by

sustainable operational management, technological maintenance, and strategic planning frameworks [3, 6]. Similar findings have been reported in other developing urban contexts, where waste management infrastructure exists but operates inefficiently due to financial constraints, lack of technical expertise, and inadequate institutional coordination [12, 14]. The results of this study therefore highlight the importance of not only developing waste management infrastructure but also ensuring its long-term operational sustainability through effective governance, technical capacity, and maintenance strategies.

One of the most significant findings of this study was the limited effectiveness of waste-to-energy systems at Aradkouh, particularly the failure of anaerobic digestion and incineration systems to achieve sustained operational performance. Waste-to-energy technologies are widely recognized as critical components of sustainable waste management systems, enabling both energy recovery and waste volume reduction [9, 10]. However, the results of this study indicated that the anaerobic digestion facility at Aradkouh was operational only for a limited period and

subsequently became inactive due to technical design deficiencies, management challenges, and lack of sustained operational support. Similarly, the incineration facility was rendered inactive following technical failures and lack of technological capacity for maintenance and repair. These findings are consistent with previous studies indicating that the success of waste-to-energy systems depends heavily on technological reliability, institutional capacity, and financial sustainability [7, 11]. In contrast, successful international models, such as those implemented in Germany and other advanced waste management systems, demonstrate the importance of integrating waste-to-energy technologies within broader strategic waste management frameworks supported by long-term policy commitment and technical expertise [11]. The inability of the Aradkouh complex to sustain waste-to-energy operations therefore reflects systemic challenges related to technology transfer, maintenance capacity, and strategic planning.

The findings also revealed significant inefficiencies in landfill management practices, particularly in relation to leachate control, sanitary landfill design, and methane recovery systems. Although the Aradkouh complex has basic landfill infrastructure, including trench excavation and drainage systems, field observations indicated that landfill practices remain semi-sanitary, with inadequate waste compaction, incomplete leachate management, and absence of active methane recovery systems. These deficiencies have significant environmental implications, as landfill sites represent major sources of methane emissions and environmental pollution if not properly managed [5, 24]. Methane emissions from unmanaged landfill sites contribute substantially to global greenhouse gas emissions and climate change, highlighting the importance of methane capture and energy recovery systems [5]. Successful landfill management systems in advanced countries incorporate comprehensive leachate treatment, methane recovery, and engineered landfill design to minimize environmental impacts while maximizing resource recovery [9, 11]. The absence of such systems at Aradkouh indicates significant gaps in environmental management practices and technological implementation, which increase environmental risks and reduce opportunities for energy recovery and economic value generation.

Another important finding of this study relates to the limited implementation of waste separation and recycling practices, particularly at the source level. The results indicated that waste separation at Aradkouh is primarily conducted manually during processing, rather than through

systematic source separation programs. This finding reflects broader challenges in urban waste management systems, where insufficient public participation, lack of awareness, and absence of effective policy incentives limit recycling efficiency [15, 18]. Effective waste separation at the source is a critical component of sustainable waste management systems, enabling efficient recycling, reducing landfill volumes, and improving overall waste management efficiency [1, 20]. Countries with successful waste management systems, such as Germany, have implemented comprehensive source separation programs supported by public education, regulatory frameworks, and financial incentives, resulting in significantly higher recycling rates and reduced landfill dependency [11]. The lack of effective source separation at Aradkouh therefore represents a significant operational and strategic limitation, reducing the efficiency of waste processing and resource recovery systems.

The benchmarking analysis conducted in this study further highlighted the significant performance gap between Aradkouh and successful international waste management models, particularly in terms of strategic planning, technological implementation, and resource recovery efficiency. Successful waste management systems are characterized by integrated strategic frameworks that align technological infrastructure, regulatory policies, financial mechanisms, and institutional coordination [1, 21]. In contrast, the findings of this study indicate that waste management at Aradkouh is characterized by fragmented and reactive management practices, lacking a comprehensive long-term strategic framework. Similar findings have been reported in other developing waste management systems, where the absence of integrated planning and institutional coordination limits operational efficiency and sustainability [12, 16]. Strategic planning is essential for aligning waste management infrastructure, technological investments, and operational practices with sustainability goals, ensuring long-term efficiency and environmental protection [7, 8]. The absence of such strategic planning at Aradkouh therefore represents a critical barrier to achieving sustainable waste management outcomes.

The results of this study also revealed significant economic inefficiencies in waste management operations at Aradkouh, particularly in relation to energy recovery, resource utilization, and economic value generation. Although waste represents a potential resource for energy production and material recovery, the current waste

management system at Aradkouh fails to fully utilize this potential. Waste-to-energy technologies, methane recovery systems, and refuse-derived fuel production represent significant opportunities for economic value generation, energy production, and environmental sustainability [7, 10]. However, the absence of operational energy recovery systems at Aradkouh indicates that these opportunities remain largely unrealized. Previous studies have demonstrated that waste management systems that incorporate energy recovery and circular economy principles can significantly improve economic efficiency while reducing environmental impacts [1, 8]. The findings of this study therefore highlight the importance of transitioning from traditional waste disposal models toward resource-oriented waste management systems that emphasize energy recovery and economic value creation.

Furthermore, the findings of this study indicate that institutional and managerial factors play a critical role in determining waste management performance. The outsourcing of key operational functions without effective oversight, lack of technical expertise, and absence of long-term maintenance strategies contribute significantly to operational inefficiencies and system failures. Effective waste management requires strong institutional governance, technical capacity, and coordinated management practices to ensure operational efficiency and sustainability [19, 21]. Institutional capacity building, technical training, and organizational coordination are therefore essential components of sustainable waste management systems. Successful waste management systems are characterized by strong institutional frameworks, effective governance, and coordinated stakeholder participation, which enable efficient operation, technological maintenance, and continuous system improvement [1, 12].

In addition, the environmental and social implications of inefficient waste management practices at Aradkouh represent significant challenges for urban sustainability and public health. Poor landfill management, inadequate leachate treatment, and uncontrolled methane emissions contribute to environmental pollution, climate change, and public health risks [5, 24]. Waste management systems must therefore be designed and implemented in a manner that minimizes environmental impacts while maximizing resource recovery and economic efficiency. Sustainable waste management requires the integration of environmental protection, technological innovation, and strategic planning to ensure long-term sustainability [10, 20]. The findings of this study highlight the urgent need for strategic reform,

technological modernization, and institutional strengthening to improve waste management performance at the Aradkouh complex.

One of the main limitations of this study relates to the availability and accessibility of detailed operational data, particularly in relation to the long-term performance, financial costs, and operational efficiency of specific waste management technologies at the Aradkouh complex. Although field observations and benchmarking analysis provided valuable insights into system performance, the absence of comprehensive longitudinal operational data limited the ability to conduct detailed quantitative performance analysis. In addition, the study was limited to a single waste management facility, which may restrict the generalizability of findings to other waste management systems with different institutional, technological, and environmental conditions. Furthermore, some aspects of system performance were evaluated based on observational and qualitative assessments, which may be influenced by temporal operational variations and external factors.

Future research should focus on conducting comprehensive quantitative performance evaluations of waste management systems using operational, financial, and environmental performance indicators. Longitudinal studies examining the operational efficiency, economic performance, and environmental impacts of waste management technologies would provide valuable insights into system sustainability and performance trends. Comparative studies involving multiple waste management facilities across different cities and countries could also provide valuable insights into best practices and performance optimization strategies. In addition, future research should explore the role of emerging technologies, including smart waste management systems, artificial intelligence, and digital monitoring systems, in improving waste management efficiency and sustainability.

From a practical perspective, improving waste management performance at the Aradkouh complex requires the development and implementation of a comprehensive strategic waste management plan that integrates technological modernization, institutional capacity building, and environmental protection measures. Priority should be given to rehabilitating and upgrading existing waste-to-energy infrastructure, including anaerobic digestion and methane recovery systems, to improve energy recovery efficiency and economic sustainability. In addition, strengthening waste separation programs, improving landfill management practices, and implementing environmental

monitoring systems would significantly improve waste management performance. Institutional reforms, including improved governance structures, technical training programs, and enhanced operational oversight, would further strengthen waste management capacity and sustainability.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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