engineering proceedings

MDPI

Proceeding Paper

Review on Leachate Treatment Methods in Morocco: Effectiveness and Limits †

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† Presented at the 8th edition of the International Conference on Advanced Technologies for Humanity (ICATH 2026), Rabat, Morocco, 15–17 July 2026.

Abstract

Several treatment methods for landfill leachate are employed in Morocco to manage both stored and newly generated effluents across controlled landfill sites. Accordingly, we sought to compile the majority of studies conducted on leachate treatment in 10 Moroccan landfills in order to compare their costs and removal efficiencies for COD, BOD, turbidity and heavy metals. The reviewed studies indicate that Moroccan landfill leachates are highly polluted, with COD levels reaching up to 95,000 mg/L, and that the applied treatment processes do not consistently meet Moroccan discharge standards.

Keywords: Moroccan leachate treatment; MBR; SBR; AOP; RO; coagulation flocculation

1. Introduction

In Morocco, the rapid demographic growth and the intensification of economic activity have led to a substantial increase in solid waste production, with approximately 4.5 million tons of urban waste and 800,000 tons of industrial waste dumped annually. Since the enactment of Law 28.00 on waste management and disposal in Morocco, and the support of the National Household Waste Program, 15 uncontrolled landfills had been closed by 2014, while seven controlled landfill sites were under development [1]. However, leachates generated by the majority of these landfills remain untreated, constituting a significant environmental problem [2]. Leachate is a highly toxic liquid produced by the percolation of rainwater through waste and the release of intrinsic water from the organic fraction [3]. This "landfill juice" is characterized by an extreme pollutant load, including high levels of organic matter (COD and BOD_5), massive concentrations of ammonia, mineral salts, and heavy metals, all of which pose severe threats to groundwater, surface water, and public health [4]. The composition of these effluents varies significantly from one landfill to another, depending on factors such as the age of the site, the nature of the collected waste and local climatic conditions [1]. Consequently, identifying effective and economically viable treatment methods adapted to the Moroccan context is now a priority for protecting natural resources and ensuring the sustainability of waste management infrastructure.

In this context, several studies have been conducted at various Moroccan landfill sites to identify appropriate treatment methods for leachates, while other investigations have focused on evaluating the effectiveness of treatment processes already implemented at some sites. Accordingly, the present study aims to compile and analyze research carried out at the

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Academic Editors: Brahim El Bhiri, Ayman S. Mosallam and Younes Karfa Bekali

Published: 18 November 2026

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following 10 Moroccan landfills: Fez, Mohammedia, Kenitra, Casablanca, Fkih Ben Salah, Oum Azza, Agadir, Kasba Tadla, Al Hoceima, and Taza. The objective is to compare the different treatment methods, their associated costs, and their efficiencies, while highlighting the constraints and limitations of each process, in order to draw on these findings to guide future research on untreated leachates from Moroccan landfills.

2. Search Methodology

In this research, a systematic literature search was executed using the following three scientific databases: ScienceDirect, Scopus, and Web of Science; the strategy started with applying the following key words: ("leachate" OR "landfill leachate" OR "Municipal wastewater") AND (treatment OR remediation OR purification OR management) AND (Morocco OR Moroccan). The initial search identified 1281 records in ScienceDirect, 119 in Scopus and 149 in Web of Science. Eligibility filters were applied to retain only open-access research articles while review papers were excluded, which reduced the number of records to 302 (210 from ScienceDirect, 48 from Scopus and 44 from Web of Science). Following the initial screening, 234 documents were excluded for the following reasons: the studies were conducted outside of Morocco, unrelated to the review objectives, or focusing exclusively on leachate characterization. Consequently, after removing duplicate records, 28 full-text articles met the eligibility criteria and were included in the review.

3. Landfill Leachate Characteristics in Different Sites in Morocco

Landfill leachates in Morocco are generally characterized by a very high pollutant load. In landfills such as Fez, Kasba Tadla, and Fkih Ben Salah, the studies have often used a young, acidic, or partially stabilized leachate with extremely high Chemical Oxygen Demand (COD) concentrations [5–7]. Conversely, sites like Al Hoceima and Casablanca exhibit stabilized leachates with more alkaline pH values (7.6 to 8.5) and lower BOD_5/COD ratios [8,9]. A distinct feature in coastal cities like Agadir is the exceptionally high electrical conductivity [10–12]. Heavy metals concentrations also vary; for instance, Kenitra shows significant levels of zinc [13], while Oum Azza is noted for its high aluminum content [14].

3.1. COD and BOD Variation in Moroccan Landfill Leachate

Moroccan landfill leachates reveal a lot of variability in terms of organic load, namely COD and BOD5 as presented in (Table 1). Extremely high values of COD and BOD5 were recorded in Fez, Fkih Ben Salah and Agadir, which represent highly polluted landfill leachates with younger age and inappropriate management [5,7,12]. The BOD5/COD ratio is an important metric for identifying landfill maturity. Young leachate from Mohammedia and Oum Azza exhibits high ratios (>0.5), indicating a high proportion of biodegradability [14,15]. Accordingly, mature landfill sites such as Casablanca have very low values for these parameters, indicating the presence of refractory compounds resistant to biological degradation [9]. Seasonal variability of leachate characteristics is obvious at Agadir due to industrial fish waste and evaporation in storage ponds [11]. Intermediate sites like Al Hoceima and Kenitra have semi-stabilized characteristics, such as moderate COD levels and BOD5/COD ratios [8,13].

https://doi.org/10.3390/engproc2026168007

Table 1. Summary of leachate characteristics by landfill.

Landfill	Leachate State	pH	COD (mg/L)	BOD_5 (mg/L)	EC (mS/cm)	Ammonia (NH4+) (mg/L)	Turbidity (NTU)	References
Fez	Young to Stabilized	6.2–8.0	3669–95,700	340–42,000	22.5–41.3	5000	141–3158	[5,16,17]
Al Hoceima	Stabilized	8.5	10,805	1530	29.3	4827	Not specified	[8]
Mohammedia	Stabilized/ Young	5.1–8.2	2473–58,880	400–24,000	10.3–48.4	4700	1305–2036	[15,18]
Casablanca	Stabilized	7.6	7680–22,000	300–8500	23.0–38.6	139	106–1007	[9]
Taza	Stabilized	7.35	5687–8245	4220–5220	24.05	48.4	Not specified	[19,20]
Kenitra	Stabilized	8.43	24,858–50,300	992–5000	14.2–25.0	910–2126	450–1865	[13,21]
Oum Azza	Intermediate	8.0–8.2	3850–7433	895–1260	15.9–30.8	Total Nitrogen TN: 725–1025	Not specified	[14,22,23]
Kasba Tadla	Fresh	4.49	26,720	Not specified	26.7	Not specified	2890	[6]
Fkih Ben Salah	Fresh	3.78	68,170	Not specified	32.67	Not specified	5190	[7]
Agadir	Young	3.1–7.1	3150–38,135	1000–18,062	13.1–115.3	47.7–229.5	620–2320	[11,12]
Moroccan Discharge Standards (MDSs)		5.5–9.5	500	100	2.7	Kjeldhal Nitrogen: 40	Not specified	[24]

3.2. Nitrogen and Turbidity Levels in Moroccan Landfill Leachate

The concentration of ammonia (NH4+) can be used as an indicator of the biological age of a landfill and to estimate its potential toxicity to aquatic life [19,21]. The ammonia concentrations vary greatly in Moroccan landfills; young leachates of Fez and Mohammedia have the highest concentrations, due to the rapid degradation of organic nitrogenous containing wastes such as food wastes [8,19], while Agadir leachates show lower ammonia concentration, possibly due to industrial wastes [12].

Turbidity is another important parameter because it indicates that high concentration of dissolved and suspended solids can interfere with treatment processes such as UV oxidation or membrane filtration [18]. Very high turbidity values are reached in Fkih Ben Salah and Kasba Tadla due to the high concentration of fine colloidal particles and organic matter in its fresh untreated leachate [6,7].

3.3. Mineral Load and Metallic Pollution of Moroccan Leachate

All inorganic analyses (Table 2) indicate a well-persisted mineralization with dominance of high concentrations of chloride (Cl-) as well as electrical conductivity. Chloride can reach levels greater than 3700 mg/L and 6000 mg/L in coastal cities such as Agadir and Casablanca, respectively, reflecting the dumping of industrial fish waste and the concentration effect of evaporation in storage ponds [9,12]. Heavy metals are one of the most dangerous toxic characterizations; Kenitra and Casablanca had the maximum toxicity based on heavy metal with a value of 100 mg/L for zinc and 35.7 mg/L for lead [9,13]. Chromium (Cr), a persistent pollutant at some sites such as Casablanca, Fez and Mohammedia (2.18 mg/L and 2.5 mg/L), reflects the particularities of local industrial or artisanal activities [5,15]. Oum Azza stands out for its relatively high aluminum content (3.82 mg/L) which sets it apart from other landfills in terms of its metallic pollution [14,22]. Table 2 summarizes the available data on the concentrations of heavy metals in landfill leachates; landfills for which no data were reported are not included in the table.

Table 2. Summary of heavy metal concentrations by landfill.

Landfill	Chlorides (Cl-) (mg/L)	Iron (Fe) (mg/L)	Chromium (Cr) (mg/L)	Lead (Pb) (mg/L)	Other Key Minerals/ Metals (mg/L)	References
Fez	6627	2.78	2.18	0.06	Zn (5.38), Cu (0.21)	[5]
Mohammedia	6204	36.01	2.50	0.53	Zinc (1.45), Copper (1.03)	[15,19]
Casablanca	6002	3.00	28.56	35.77	Nickel (16.63), Copper (9.54)	[9]
Taza	1000–1500	85.00	3.45	5.35	SS (16,000), Nitrates (13.1)	[20]
Oum Azza	3475	12.6 ± 1.15	Not specified	1.59	Aluminum (3.82), Copper (1.01)	[14,22,23]
Kenitra	5757–6571	Not specified	1.08	0.79	Zinc (100), Copper (0.70)	[13,21]
Agadir	675–3721	240.00	0.35	0.54	Zinc (6.20), Manganese (9.7)	[10,12]
Moroccan Discharge Standards	Active Chlorine: 0.2	5	2	1	Total Phosphorus (15), Zinc (5), Aluminum (10), Copper (2), Manganese (2), Nickel (5)	[24]

4. Methods of Landfill Leachate Treatment in Morocco

Leachate management is a critical challenge for Morocco's landfills due to their high organic and mineral pollutant loads, which pose significant risks to human health and the environment [10]. Hence, to compare and study the different methods of leachate treatment and their efficiency in Morocco, we tried to resume the various leachate treatment experiments and methods implemented or tested across ten major landfills in Morocco, focusing on their technical performance and economic viability.

4.1. Fez Elimination and Valorization Center (CEV)

The leachate in Fez is characterized by an extremely high organic load [5]. To address this, several treatment sequences have been tested as follows:

- Coagulation-Flocculation and Advanced Oxidation (AOP): A study utilized ferric chloride (FeCl3) followed by a combined H2O2-PS-US-UV-A system. This sequence proved highly efficient, achieving 97% COD removal, 97% absorbance reduction at 254 nm, and 99% color removal [16]. The operational cost for this combined system is estimated at 8.1 USD/m^3 [16].
- Biological Sequencing Batch Reactor (SBR) and Coagulation: A hybrid system combining an SBR biological stage with FeCl3 coagulation-flocculation achieved a 98% reduction in COD and 99.16% in BOD5 [17].
- Aerobic Treatment followed by Fenton Oxidation: Experimental results showed that a suspended growth bioreactor alone removed 41% of COD. When followed by a Fenton process, the global removal efficiency increased to 73% for COD, 99.5% for BOD5, and 94% for color [5].
- Coagulation and Bioadsorption: Using FeCl3 followed by adsorption on Cupressus sempervirens cones (cypress cones) removed 86% of COD and 96% of BOD5 under optimal conditions [25].

4.2. Al Hoceima Elimination and Valorization Center (CEV)

The Al Hoceima leachate treatment aims to meet strict discharge standards:

- Biological Pre-treatment and Reverse Osmosis (RO): The facility uses an activated sludge process followed by RO filtration. The biological stage alone abates approximately 66% of COD and 93% of ammonium [7]. The subsequent RO stage refines the effluent, bringing the total global COD removal to 99.3% and BOD5 to 97.4% [7]. The

permeate achieves Moroccan discharge standards but total nitrogen still represents a challenge for a full compliance [7].

4.3. Mohammedia Benslimane Landfill

Leachate treatment at Benslimane Landfill has focused on:

- Intensive Aeration: injection of continuous oxygen flow (16.75 kg/m^3/h) into 1 m^3 of leachate for 30 days [19]. It achieved high purification yields, specifically 73% for COD, 98% for BOD5, and 85% for Total Kjeldahl Nitrogen [19].
- Anaerobic–Aerobic Sequence: A study using an anaerobic biological process for 43 days followed by 30 days of aeration resulted in 75% COD removal and 66% BOD5 removal [15].
- Traditional Biological and Physicochemical Methods: The landfill also utilizes lime and ferrous chloride for settling, combined with a sand filter planted with reeds as a polishing step [19].

4.4. Casablanca (Mediouna Landfill)

Treatment strategies for Casablanca involved hybridizing physicochemical steps:

- Coagulation-Flocculation and PAC Adsorption: Combining FeCl3 coagulation with powdered activated carbon (PAC) adsorption resulted in 77% to 79% COD removal, 99.8% turbidity removal, and 99% color reduction [9]. The cost for the FeCl3 coagulation stage alone is estimated at 3.6 USD per m^3 [9].
- Coagulation and Bio-adsorption (PBP): A similar process using palm bark powder (PBP) as a bio-adsorbent reached 59% COD removal and 99% BOD5 removal [26].
- Coagulant Comparison: An evaluative study of three coagulants showed that lime achieved 66.25% COD removal, while FeCl3 and alum achieved 62.5% and 11%, respectively; FeCl3 was identified as the most cost-effective option [9,26].

4.5. Taza Uncontrolled Landfill

The focus in Taza has been on identifying low-cost materials for treatment:

- Infiltration-Percolation: Leachate was filtered through various natural media. Ash filters showed the highest efficiency with 91% COD removal and 94% BOD5 removal [20]. Clay filters also performed well, achieving 89% COD and 90% BOD5 reduction [27].

4.6. Oum Azza Landfill (Rabat-Sale-Kenitra)

Oum Azza has tested several advanced membrane-based configurations:

- Aeration and Reverse Osmosis: The standard industrial configuration utilizes aeration basins followed by RO, achieving 97% COD and 98% BOD5 removal [14].
- Membrane Bio-Reactor (MBR) and RO: An integrated MBR-RO pilot achieved strong organic matter reduction, with the MBR removing 76% of COD and the RO further polishing the effluent to reach a global retention of >95% for organic matter [22]. The operating cost for MBR/RO is estimated at 3.86 USD/m^3 [22].
- Hybrid Coag-UF/NF/RO: This system uses coagulation-ultrafiltration as a pretreatment to protect nanofiltration and RO membranes [23]. It achieved 99% salt rejection and 99% COD removal [23].

4.7. Kenitra (Ouled Berjal Landfill)

Researchers have experimented with innovative waste-to-treatment solutions:

- Coagulation and Red Brick Filtration: A novel method combining FeCl3 coagulation and filtration through red brick waste was tested, coagulation alone removed 81% of

COD, while the red brick filtration step further reduced the remaining organic load by 50% and turbidity by 71% [13].

4.8. Kasba Tadla Landfill

Research here centered on anaerobic digestion and solar-assisted methods:

- Up flow Anaerobic Sludge Blanket (UASB): This biological treatment achieved a 94% reduction in COD after 5 days, bringing the effluent near neutrality (pH ~6.87) [6].
- Forced solar evaporation: the test used inclined glass plates and showed that solar evaporation could reduce leachate volume faster than natural evaporation [28].

4.9. Fkih Ben Salah Landfill

Treatment studies prioritized finding the most effective chemical precipitate:

- Comparative Coagulation-Flocculation: A study compared lime, FeCl3, alum, and aluminum polychloride [7]. Lime was found to be the most effective, with optimized conditions (increased settling time and pH adjustment) leading to 90.27% COD removal, 90% turbidity removal, and 81.79% TSS reduction [7].

4.10. Agadir (Tamellast Landfill)

Agadir faces high salinity issues, influencing the effectiveness of standard treatments:

- Physicochemical Optimization: Current recirculation and sprinkler systems have proven insufficient [11,29]. Laboratory tests showed that FeCl3 alone removed 78.2% of COD. However, combining FeCl3 with a polyacrylamide flocculant increased removal to 97% for COD and 92% for turbidity [11].
- Bio-flocculant Trials: Using Opuntia cactus juice as a bio-flocculant with FeCl3 achieved 87% COD removal and 98.14% turbidity removal [29].

To sum up, Table 3 represents the treatment methods of the 10 landfills:

Table 3. Treatment methods and COD removal effectiveness.

Landfill	Experienced Methods	COD Removal (%)	Other Key Parameters	Estimated Cost	References
Fez	Coagulation-Flocculation + AOP (H2O2 -PS-US-UV-A)	97%	99% color removal; 97% absorbance reduction	8.1 USD/m^3	[16]
	SBR Biological + Coagulation-Flocculation (FeCl3)	98%	99.16% BOD5 removal; meets discharge standards	Not specified	[17]
	Aerobic Sequence + Fenton Oxidation	73%	99.5% BOD5 removal; 94% color reduction	Not specified	[5]
	Coagulation + Adsorption (Cupressus Sempervirens Cones)	86%	96% BOD5 removal; 93% color reduction	Not specified	[25]
Al Hoceima	Activated Sludge (Biological) + Reverse Osmosis (RO)	99.3%	97.4% BOD5 removal; 99% total phosphorus removal	Not specified	[7]
Mohammedia	Intensive Forced Aeration (Oxygen Injection)	73%	98% BOD5 removal; 85% TKN removal	~14.4 USD/m^3	[19]
	Anaerobic Biological + Aerobic Sequence	75%	66% BOD5 removal; 60% turbidity removal	Not specified	[15]
	Lime/Ferrous Chloride Settling + Reed-Planted Sand Filter	Not specified	Polishing step for residual pollutants	Not specified	[15,19]

Table 3. *Cont.*

Landfill	Experienced Methods	COD Removal (%)	Other Key Parameters	Estimated Cost	References
Casablanca	Coagulation (FeCl3) + PAC Adsorption	77–79%	99.8% turbidity removal; 99% color reduction	Not specified	[9]
	Coagulation + PBP (Palm Bark Powder) Adsorption	59%	99% removal; 90% color reduction	Not specified	[26]
	Coagulant Comparison (Lime vs. FeCl3 vs. Alum)	66% (Lime)	Substantial heavy metal removal (Cr, Pb, Ni)	3.6 USD/m^3 (FeCl3)	[9,26]
Taza	Infiltration-Percolation (Ash, Clay, and Mixed Filters)	91% (Ash)	94% BOD5 removal	Not specified	[20,27]
Oum Azza	Aeration Basins + RO (Industrial scale)	97%	98% BOD5 removal; 85% Pb removal	Not specified	[14]
	Membrane Bio-Reactor (MBR) + RO	>95%	98% TDS rejection; water suitable for reuse	3.86 USD/m^3	[22]
	Hybrid Coag-UF/NF/RO system	99%	99% salt rejection; 89% TSS removal	0.0019 USD/m^3 (energy)	[23]
Kenitra	Coagulation (FeCl3) + Red Brick Waste Filtration	81% (Coag)	Filtration adds 50% extra COD and 71% turbidity removal	Not specified	[13]
Kasba Tadla	UASB (Upflow Anaerobic Sludge Blanket)	94%	pH neutralized to 6.87; effective for fresh waste	Not specified	[6]
	Solar Forced Evaporation (Inclined Glass Plates)	Not specified	50% faster evaporation than natural methods	Not specified	[28]
Fkih Ben Salah	Comparative Coagulation (Lime as Best Coagulant)	90.27%	90% turbidity removal; 81.79% TSS reduction	Not specified	[7]
Agadir	FeCl3+ Polyacrylamide Flocculant	97%	92% turbidity removal; neutralizes pH	Not specified	[11]
	FeCl3 + Bioflocculant (Opuntia Cactus Juice)	87%	98.14% turbidity removal; ecological alternative	Not specified	[28]

5. Analysis of Limitations and Encountered Problems

Despite high removal efficiencies in laboratory settings, each site faces significant practical hurdles:

- Fez: the extreme organic load makes biological treatment alone insufficient. AOPs are effective but suffer from high operational costs and the production of massive volumes of ferric sludge [16].
- Al Hoceima: the main issue is nitrogen non-compliance in the permeate [8]. Additionally, the toxic RO concentrate is currently recirculated, risking accumulation of salts and pollutants in the landfill [8].
- Mohammedia: forced aeration proved ineffective for stabilized leachates since the organic matter becomes less biodegradable [19]. The cost of the treatment represents a further barrier to wide-scale implementation [19].
- Casablanca: its effluent is visually improved but still does not meet national discharge standards due to the complexity of the organic load [9]. Furthermore, the sludge generated due to the coagulation process is equal to 30% of the treated volume [9,26].
- Taza: the treatment method does not meet the MDS especially in terms of heavy metals, and the treated effluents affect seed germination, which makes it not suitable for irrigation or environmental discharge [6,28].
- Oum Azza: the center's storage basins are saturated (230,000 m^3), risking an overflow [21]. Membrane fouling is very common and requires expensive cleaning costs [22,23].
- Agadir: the very high salinity affects microbial growth, making standard biological treatment ineffective; plus, the salt removal remains more complicated [10–12,18].

- Kenitra: the removal of ammonia through coagulation is insufficient if the optimum dosage is not used, and the filtration using red bricks waste is only a complementary step of treatment [13].
- Kasba Tadla: the UASB process is very sensitive to temperature and initial pH, which requires close monitoring to avoid biological failure [6].
- Fkih Ben Salah: the site is not bottom-lined, which means that leachate infiltrates the soil before being collected for treatment [7].

6. Discussion of the Results

The comparison of the different treatment technologies can lead to the following conclusions:

Physicochemical treatments such as coagulation are very effective to remove heavy metals, turbidity and color and are technically simple to implement [9]. However, their major disadvantage is their inability to degrade the refractory organic matter of the stabilized leachate, which often leads to an effluent that does not comply with MDS; also, they produce a huge amount of toxic sludge which constitutes a major disposal burden [9].

Biological processes offer the most economical solution for treating young leachate. In fact, the UASB reactors are very efficient and need law installations; however, as leachate stabilizes, biological efficiency drops significantly [23]. Furthermore, the high ammonia levels can inhibit microbial activity, necessitating pretreatment stages [22].

Advanced technologies such as RO and AOPs can meet MDS, though they face critical limitations such as membrane fouling, high energy demand and the production of toxic concentrates [8,16].

Most of these treatment technologies generate large volumes of sludge or toxic concentrates, and the management of these byproducts remains the most critical environmental concern; in fact, for the RO concentrates, the toxic brine is often recirculated back into the landfill (the case of Al Hoceima landfill), which creates the problem of the accumulation of salts and refractory pollutants, increasing COD and ammonia levels in the raw leachate and rending the treatment system ineffective, or it is stored in large retention ponds (the case of Oum Azza landfill), which leads to a critical saturation, causing severe odor nuisances and risk of an overflow [8,23]. The sludge produced in large quantities as a result of the coagulation process is considered safe for disposal, but it requires more capacity in the landfill and risks the contamination of the leachate if it is not properly stabilized [7,30].

This comparative analysis confirms that the hybrid or combined systems are the only adequate solution for Moroccan landfills, such as biological pretreatment to remove biodegradable matter followed by reverse osmosis or AOP systems to remove refractory matter and heavy metals. A combined system like this one can ensure compliance and protect the expensive equipment.

7. Conclusions

In conclusion, the examination of the ten Moroccan landfills gives us a clear idea about the high threat to the environment caused by untreated leachate. Every site has its unique challenges, ranging from the extreme mineralization and salinity caused by industrial fish waste in Agadir to the massive organic loads in young leachate at Fkih Ben Salah and Kasba Tadla sites; the collected data demonstrate that conventional treatment methods such as simple natural evaporation or biological treatment are generally insufficient to achieve national discharge standards. However, the application of combined systems has proven high effectiveness, for example, combining biological pretreatments such as MBR, SBR and activated sludge with advanced technologies like RO or AOP has achieved pollution removal rates reaching 99%. Even though these advanced solutions guarantee

environmental compliance, they are often expensive and produce high polluted concentrates. Hence, the most promising solution for Moroccan landfills is a cost-effective and high-performance hybrid treatment system.

Author Contributions: Conceptualization, I.M., Y.R. and F.B.; methodology, I.M.; software, I.M. and Y.R.; validation, I.M., Y.R. and F.B.; formal analysis I.M.; investigation, I.M.; resources, Y.R. and F.B.; data curation I.M.; writing original draft preparation, I.M.; writing review and editing, I.M., Y.R. and F.B.; visualization, I.M.; supervision, Y.R. and F.B.; project administration, Y.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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