

Enhancing waste management sustainability in Kuwait's oil sector through artificial intelligence: A comparative analysis and framework development

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ABSTRACT

Waste management is a major sustainability challenge for oil-producing nations, especially in arid regions with low environmental resilience. Kuwait's oil sector generates massive amounts of produced water, drilling waste, sludge, contaminated soil, and emissions. This strains both local ecosystems and regulatory systems. Despite ongoing mitigation efforts, current practices remain reactive, fragmented, and lack advanced digital integration. This study explores how artificial intelligence (AI) can improve waste management sustainability in Kuwait's oil industry. We synthesized extensive literature on waste management across Kuwait, the Gulf Cooperation Council (GCC), and major global oil producers. Our comparative analysis shows that while waste streams are similar, there are significant gaps in treatment technologies, regulatory enforcement, and digitalization. Based on these insights, we developed an AI-driven sustainability framework tailored to Kuwait's operational and institutional context. The framework integrates digital sensing, AI analytics, regulatory alignment, and organizational readiness. It enables predictive monitoring, anomaly detection, optimized waste handling, and data-driven remediation. Findings show that Kuwait's main challenge is not the type of waste it produces, but its technological and institutional readiness. By adopting AI, Kuwait can shift from reactive waste control to proactive environmental governance, directly supporting Kuwait Vision 2035. Theoretically, this study bridges AI, sustainability, and oil-sector governance. Practically, it provides a scalable roadmap for AI adoption in resource-intensive industries.

Keywords: artificial intelligence, waste management, oil industry, sustainability, digital transformation.

INTRODUCTION

Kuwait is a major oil producer in the Middle East. It pumps about 3.15 million barrels per day—roughly 7% of the global supply (Sasu, 2025). The oil sector took off after the Mina Al-Ahmadi refinery opened in 1949. Since then, it has become a key driver of national growth, supporting industry, modernization, and global energy security (Al Salem and Thiemann, 2024; Alselahi et al., 2026). The Kuwait National Petroleum Company (KNPC) was founded in 1960. It oversees refining and sustainability efforts. Its mission: expand capacity while protecting the

environment (KOC, 2025). Despite its economic importance, Kuwait's oil industry faces growing environmental challenges (Al-Barood et al., 2024; Alameedy et al., 2026). The sector produces large amounts of hazardous solid, liquid, and gaseous waste. This happens across exploration, drilling, extraction, refining, and transport (Manikumar et al., 2024). Waste streams include produced water, brine discharge, drilling residues, oil sludge, contaminated soil, gas flaring emissions, sour gases, and greenhouse gases. These threaten soil, groundwater, marine life, and air quality (AlRukaibi and AlSalem, 2022). Produced water is the largest waste stream from oil operations in

Kuwait. It has high salinity, organic contaminants, dissolved hydrocarbons, and toxic heavy metals. Poor handling can lead to corrosion, scaling, ecosystem damage, and long-term health risks (Al-Mutairi et al., 2024; Rahman et al., 2026).

Globally, the oil and gas industry has increasingly focused on sustainability, circular economy practices, and reducing carbon intensity (Alzoubi, 2025; Muvel et al., 2025). Countries like Saudi Arabia, the UAE, Norway, Canada, and India have advanced their waste treatment, regulations, and environmental monitoring. This supports their climate goals and operational efficiency (Al-Mutairi et al., 2024; Al Salem and Thiemann, 2024; AlRukaibi and AlSalem, 2022). Kuwait, however, still faces several long-standing issues. These include aging infrastructure, high waste volumes, limited on-site recovery options, and environmental risks from soil contamination, oil lakes, and brine discharge (Al-Maheimid and Al-Mass, 2024; Sasu, 2025). These challenges show a clear need for better waste governance, modern treatment technologies, and data-driven decisions (KEPA, 2022).

AI has emerged globally as a transformative force for industrial sustainability. It offers predictive analytics, anomaly detection, optimization models, and real-time environmental monitoring (Bhatia and Malik, 2025; Janiesch et al., 2021w). In the oil and gas sector, AI algorithms improve reservoir management, drilling optimization, equipment maintenance, and operational safety (Alzoubi et al., 2024; Chen et al., 2025). Its potential use in waste management, like forecasting waste volumes, optimizing produced water treatment, automating waste sorting, detecting spills and leaks, and enhancing compliance monitoring, remains largely unexplored in Kuwait's context (Ming et al., 2024).

Although research on oil-sector waste management in Kuwait, the GCC, and other oil-producing countries is growing, most studies focus on waste characterization, treatment technologies, or regulatory challenges in isolation (Al-Hajri et al., 2025). Little attention has been given to AI as an integrated tool for waste management sustainability, especially within Kuwait's specific operational, regulatory, and environmental setting. More importantly, there is no consolidated, AI-driven sustainability framework for Kuwait's oil sector. Such a framework would systematically link technology, environmental governance, and organizational readiness

(Al-Barood et al., 2024). This gap limits both theoretical progress and practical guidance for policymakers and industry stakeholders who want to modernize waste management in line with national sustainability goals (Al-Kamzari et al., 2025). This study is also motivated by Kuwait Vision 2035, which places environmental sustainability, digital transformation, and oil sector modernization at the heart of national development (MOFA, 2026). To address this gap and guide the analysis, this study is driven by the following research questions:

RQ1: How do waste-treatment technologies, regulations, and digitalization levels compare across Kuwait, the GCC, and other countries?

RQ2: How can we build an AI-driven waste management framework that helps Kuwait's oil sector meet environmental goals and align with Kuwait Vision 2035?

This study fills that gap. It compares waste management practices in Kuwait, GCC countries, and major oil-producing nations like Russia, Canada, Norway, Iraq, and India. Through this literature-based comparison, the research identifies best practices, new technologies, and regulatory approaches. These can support Kuwait's shift toward more sustainable waste management. Using these insights, the paper proposes an AI-driven sustainability framework designed for Kuwait's oil sector. The main contributions of this study are:

- Review and critically assess Kuwait's current waste management challenges and practices across solid, liquid, and gaseous streams.
- Compare Kuwait's performance with regional and global peers, pointing out gaps and areas for improvement.
- Offer a comprehensive framework that integrates AI into Kuwait's waste management systems, with a focus on environmental sustainability, operational efficiency, and regulatory compliance.

The rest of this paper is structured as follows. Section 2 highlights the main waste streams and the environmental issues they create. Section 3 explains the methodology used in this study. Section 4 reviews the literature extensively. It covers Kuwait, GCC countries, and selected international oil-producing nations. It also provides an overview of AI applications relevant to waste management. Section 5 introduces the proposed AI-driven waste management sustainability

framework. It is tailored specifically to Kuwait. Section 6 discusses the implications of the findings. It also covers practical considerations and challenges related to adopting AI. Finally, Section 7 concludes the study and suggests directions for future research.

BACKGROUND

Major waste streams in Kuwait's oil industry

The oil industry in Kuwait generates many types of waste—both hazardous and non-hazardous. These come from extraction, drilling, refining, maintenance, and transport operations. Table 1 summarizes different types of waste in the oil industry in Kuwait.

Table 1 demonstrates that waste generation across Kuwait's oil sector is heterogeneous, spanning liquid, solid, gaseous, and contaminated-soil streams with different environmental and operational implications. Produced water represents a major wastewater stream requiring treatment and reuse, while drilling waste, refinery sludge, and contaminated soil require specialized recovery, treatment, or remediation approaches. Gaseous emissions and hazardous industrial wastes introduce additional air-quality, climate, and health concerns. These differences indicate that sustainable waste management cannot rely on a single treatment approach but requires waste-specific

strategies supported by effective monitoring, regulatory oversight, and resource-recovery practices.

Environmental and operational challenges

Kuwait faces several interlinked environmental challenges in managing these waste streams. First, many upstream facilities and refineries are decades old. Aging pipelines and storage tanks increase the risk of leaks, corrosion, and maintenance-related waste. Consequently, legacy contamination sites require continuous monitoring and remediation (Al-Mailem et al., 2017). Occupational exposure also warrants systematic assessment; although examining agricultural pesticide use, Novokhatska et al. (2024) show how inhalation and dermal exposure assessment can differentiate occupational risk pathways and inform safe-use requirements in hazardous environments (Novokhatska et al., 2024). Second, produced water volumes are rising as oilfields mature. Treatment plants often operate near capacity during peak cycles, stressing separation and reinjection systems. Furthermore, fragmented solid waste and thermal desorption facilities create logistical and regulatory bottlenecks (Al-Barood et al., 2024). Third, Kuwait's arid climate, shallow groundwater, and coastal zones are highly vulnerable to pollution. Spills disperse slowly in desert environments, causing persistent contamination. Similarly, marine areas near refineries and ports face risks from brine discharge, effluent leaks, and shipping activity (Al Salem

Table 1. Kuwait oil industry waste stream

Challenges	Description	Impact /effect
Produced water (Al-Maheimid and Al-Mass, 2024; Al-Mutairi et al., 2024; Al Salem and Thiemann, 2024)	A liquid waste containing both organic and inorganic materials, produces heavy oil with high H ₂ S content, low salinity brackish groundwater is used by KOC in its operations	Contamination and pollution of water sources, damage to production facilities and equipment, harm the marine ecosystem and the aquatic life
Oil sludge (Al-Mebayedh et al., 2023; Manikumar et al., 2024)	A mixture of oil and water and other thing that are found in the crude oil making it a hazardous material	Contain harmful material that result in health risk
Contaminated soil (KEPA, 2022)	It is the soil that is being contaminated with hazardous materials from the oil industry	Can lead to land pollution and health hazards if not properly managed
Gas Emissions and Air Pollutants (Al-Enezi et al., 2025; AlRukaibi and AlSalem, 2022; Healey, 2006)	Gas waste results from refining, combustion, and other processes within the oil production cycle When burned, fossil fuels release gases that become trapped in the atmosphere ⁷	Releases high levels of harmful gases including CO ₂ , sulfur dioxide, and nitrogen oxides, warming and climate change and severe environmental outcomes such as desertification and drought
Drilling waste (Al Salem and Thiemann, 2024)	Solid and liquid residues	Result in soil contamination that harm the plants
Solid industrial waste (Al-Enezi et al., 2025)	Catalysts, filter cakes, construction debris, packaging materials, industrial chemicals, and metal scrap	Present toxicity risks

and Thiemann, 2024). Fourth, limited real-time monitoring and fragmented data systems hinder early detection and informed decision-making. Inconsistent reporting across upstream and downstream operations further complicates predictive maintenance, leaving many facilities reliant on manual monitoring.

Sustainability dimensions and AI adoption in resource-constrained contexts

Sustainability is not just an extra theme in digital transformation. It is a core driver, especially in resource-limited and developing economies (Hamza and Karadas, 2025). In these settings, sustainable digital transformation goes beyond short-term efficiency gains. It focuses on long-term economic health, responsible resource use, and inclusive growth (Hamza and Karadas, 2025). Recent research shows that AI can support sustainability goals. It improves decision-making, optimizes resource use, and helps tackle complex environmental issues (Toderas, 2025). These benefits matter greatly in oil-dependent economies. There, environmental damage and resource depletion pose serious long-term risks. Studies on small and medium enterprises in resource-constrained settings show that digital leadership and AI use can boost sustainable innovation (Hamza and Karadas, 2025). This suggests that AI adoption is not purely technical. It depends on leadership, institutional readiness, and local context (Alzoubi, 2025).

Similarly, sustainability is often viewed through three interconnected lenses: environmental, economic, and social. Environmentally, AI monitoring can cut carbon emissions, reduce land damage, and protect biodiversity. It enables early contamination detection and better waste treatment (Chen et al., 2025). Economically, AI supports growth by streamlining operations, cutting downtime, and lowering long-term clean-up costs, without exhausting natural resources (Vuković et al., 2025). Socially, AI can improve transparency, regulatory accountability, and public awareness of environmental risks. This supports fair governance and trust (Singagerda et al., 2024). These sustainability dimensions are highly relevant to Kuwait's oil sector. As a resource-dependent economy going through digital modernization, Kuwait must balance environmental care with economic strength and social responsibility. The proposed AI-driven waste management

framework addresses all three areas. It combines preventive environmental controls, cost efficiency, and institutional capacity building.

Regulatory and institutional context

Kuwait has steadily expanded its environmental regulatory framework to strengthen oversight of the oil industry. The Environment Public Authority (EPA) enforces national environmental laws. It oversees waste classification and disposal standards. It also sets limits on emissions, effluent quality, soil contamination, and hazardous materials handling (Al-Enezi et al., 2025). In addition, both the EPA and industry operators maintain internal environmental management systems. These include ISO 14001 certification, spill-response protocols, produced water management plans, and continuous emission monitoring systems (Al-Maheimid and Al-Mass, 2024). Efforts such as the KERP, the Clean Fuels Project, and new produced water reinjection systems show a move toward better waste governance, energy efficiency, and pollution reduction (KOC, 2025). Despite these frameworks, gaps remain. Enforcement is not always consistent. Digital integration is limited. Advanced treatment technologies are still lacking. These shortcomings point to a clear need for modernization. AI-driven systems could help by improving monitoring, predictive capabilities, and integrated waste management planning.

METHODOLOGY

This study uses a theory-informed qualitative research design, as shown in Figure 1. It combines three elements: (i) a structured literature synthesis, (ii) cross-context comparative analysis, and (iii) conceptual framework development (Popay et al., 2006; Snyder, 2019). This design works well for multidisciplinary questions where evidence is varied and not suitable for meta-analysis. Still, it requires transparent and replicable synthesis procedures (Popay et al., 2006; Snyder, 2019). The study's logic is explanatory and policy-focused, not statistically generalizing. It aligns with comparative case-oriented approaches that use a small-to-medium set of cases to generate meaningful contrasts (George and Bennett, 2005). Methodologically, the paper follows an abductive analytic orientation. It moves back and forth between theoretical expectations and patterns found in the

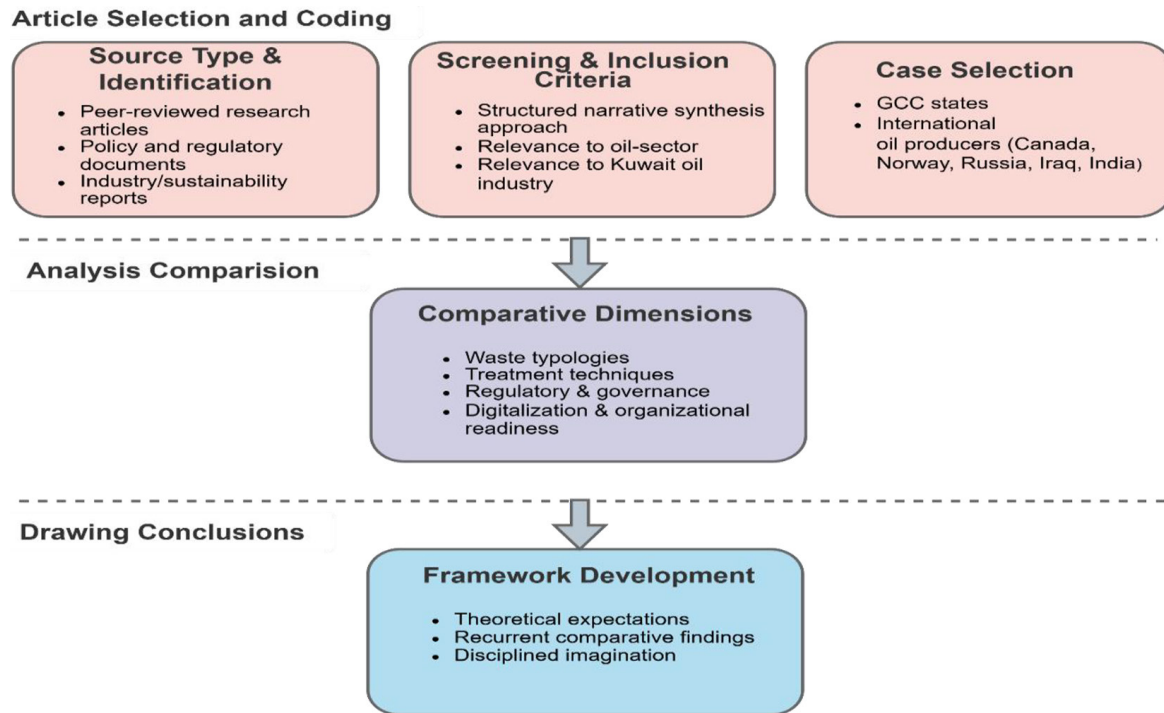


Figure 1. Research methodology

reviewed evidence. This helps refine categories, comparisons, and the final framework (Van Hulst et al., 2025). This approach is appropriate for conceptual work that aims to integrate governance theory with technology-enabled sustainability practices without reducing the analysis to either purely deductive theorizing or purely inductive description (Seawright and Gerring, 2008).

Source types and identification

The empirical foundation of the analysis is a corpus of peer-reviewed research articles, complemented by policy and regulatory documents and industry/sustainability reports where these provide necessary context on institutional arrangements, monitoring practices, and digitalization initiatives. Using literature review as an explicit research method is appropriate when the goal is to consolidate and interpret fragmented knowledge across domains and produce an integrative conceptual contribution (Snyder, 2019). To improve transparency and reduce ad hoc selection, this study adopts structured steps for searching, screening, and synthesizing evidence (Popay et al., 2006). Because the literature spans engineering, environmental science, policy, and governance, the synthesis uses narrative synthesis procedures designed for mixed evidence

types (Popay et al., 2006). This approach allows for systematic identification of common themes, such as monitoring gaps, enforcement challenges, and digital maturity. It also enables structured comparison across cases. At the same time, it preserves the interpretive depth needed for conclusions that are relevant to governance.

Screening and inclusion criteria

Rather than conducting a full systematic literature review (e.g., PRISMA), the study applied a structured narrative synthesis approach—appropriate when the evidence base includes mixed study designs, diverse outcome measures, and substantial contextual variation (Popay et al., 2006). Sources were included if they met the following three criteria. First, substantive relevance to oil-sector waste streams (solid, liquid, gaseous) and their management. Second, analytical relevance to governance, regulation, institutional capacity, or digitalization (not solely treatment chemistry/engineering). Finally, contextual relevance to Kuwait, GCC comparators, or major oil-producing international contexts used for benchmarking. This approach addresses the paper’s stated gap: moving beyond isolated treatment or regulatory discussions to an integrated AI governance-readiness framework (Seawright and Gerring, 2008).

Case selection and comparative rationale

Kuwait is treated as the focal case for good reason. It combines high environmental stakes—due to its arid and vulnerable ecosystem—with heavy oil-sector dependence. It also has explicit national commitments to sustainability and digital modernization (MOFA, 2026). Comparative cases were chosen purposively. The goal was to enable analytic contrast across institutional capacity and digitalization maturity. This follows established guidance on case selection in comparative research (Seawright and Gerring, 2008). Two comparator sets were used. The first includes GCC states—Saudi Arabia, UAE, Qatar, Oman, and Bahrain. These are “most similar” cases in terms of climate and hydrocarbon dependence. However, they differ in digital governance maturity. The second set includes international oil producers—Canada, Norway, Russia, Iraq, and India. These serve as contrast cases. Canada and Norway represent high regulatory stringency and advanced digital monitoring. Russia and India show mixed modernization trajectories. Iraq reflects severe institutional constraints. The comparative logic is structured and focused. The same core questions are asked for each case. This helps identify patterns in waste typologies, governance arrangements, monitoring infrastructures, and AI-readiness constraints (George and Bennett, 2005).

Comparative dimensions and coding schema

Guided by the theoretical framing—environmental governance, digital-era governance, algorithmic regulation, and sustainability transitions—the analysis compares cases along five recurring dimensions (Miles et al., 2014). These dimensions are: waste typology and scale, treatment and mitigation portfolios, regulatory and governance arrangements (including enforcement capacity), digitalization and monitoring maturity, and organizational readiness (skills, coordination, data governance) (Miles et al., 2014). Evidence was synthesized through iterative coding and theme development from textual materials. This follows qualitative analytic principles for condensing heterogeneous documents into comparable categories (Miles et al., 2014). The outputs were organized into cross-case matrices and summary tables. This makes the basis of comparison explicit and auditable.

Framework development procedure

The AI-driven waste management sustainability framework is developed through conceptual framework analysis. This involves identifying core concepts from multiple disciplines, specifying how they relate, and organizing them into a coherent structure (Weick, 1989). In line with abductive theorizing, the framework was refined iteratively. It moved between theoretical expectations, like governance capacity and algorithmic oversight—and recurring comparative findings, such as data fragmentation, monitoring gaps, and uneven enforcement (Van Hulst et al., 2025). To keep conceptual creativity in check and reduce arbitrariness, the framework followed a “disciplined imagination” approach. Several possible configurations were considered. They were then kept or rejected based on cross-case explanatory fit and alignment with the study’s research questions (Weick, 1989). The result is a framework that is theory-consistent, grounded in comparative evidence, and actionable for policy—not just aspirational.

Given the heterogeneity of the reviewed evidence, sources were interpreted according to their methodological strength, contextual relevance, and transferability to Kuwait rather than assumed to be directly comparable. Peer-reviewed empirical studies and documented industrial applications were distinguished from policy reports and descriptive sources, with the latter primarily used to establish contextual or implementation evidence. Cross-country findings were assessed against differences in regulatory conditions, infrastructure maturity, environmental characteristics, digital readiness, and organizational capacity. Accordingly, practices demonstrated in other countries were considered applicable to Kuwait only where their underlying technological and institutional requirements were compatible with the Kuwaiti context. This distinction informed both the comparative synthesis and the derivation of the proposed framework.

WASTE MANAGEMENT PRACTICES

Kuwait’s oil industry

Building on the structural challenges in Kuwait’s oil waste system, prior studies have examined regional and international technological

and regulatory responses. As extraction matures, handling becomes more difficult due to rising water–oil ratios (Al Salem and Thiemann, 2024; AlRukaibi and AlSalem, 2022). Research consistently highlights corrosion, scaling, storage limitations, and reinjection inefficiencies as persistent obstacles. Table 2 summarizes the tools/techniques used to manage the waste in the oil industry in Kuwait.

Table 2 reveals that Kuwait’s technological progress is uneven across waste streams. Resource-recovery approaches for produced water and drilling waste demonstrate movement toward circularity (Al Salem and Thiemann, 2024), whereas their implementation remains constrained by technical and operational limitations (Healey, 2006). Treatment technologies also involve different trade-offs: membrane-based systems can improve separation performance but require suitable operating conditions (Alqaheem, 2021), while bioremediation offers a less intensive treatment route but can be slow under Kuwait’s extreme climatic conditions (Al-Mebayedh et al., 2023; Kansour and Al-Mailem, 2023). Thus, the evidence does not indicate a universally superior

treatment approach; effectiveness depends on waste characteristics, environmental conditions, infrastructure, and operational capacity.

Advanced treatment and monitoring technologies offer important environmental benefits. Polymeric membranes support wastewater treatment (Alqaheem, 2021), while modified cellulose-based filtering materials combined with natural sorbents can enhance filtration and sorption of mechanical impurities, heavy-metal ions, and biological contaminants (Zahorodniuk et al., 2019). Remote sensing supports spill detection (Zakzouk et al., 2024), whereas bioremediation using native microbes provides an alternative for contaminated soil treatment (Kansour and Al-Mailem, 2023). However, their effectiveness is often limited by external factors (Al-Mebayedh et al., 2023). Bioremediation, for instance, is slow in extreme environments (Kansour and Al-Mailem, 2023). Remote sensing is constrained by weather conditions and satellite revisit times (Zakzouk et al., 2024). Furthermore, some solutions create secondary problems. Brine discharge can harm marine ecosystems. Chemical neutralization may leave behind residual toxins (Al-Mutairi et al., 2024).

Table 2. Tools used for oil waste management in Kuwait

Type of waste	Key tools / techniques	Main benefits	Key challenges
Greenhouse gas emissions (Al-Enezi et al., 2025; AlRukaibi and AlSalem, 2022; Healey, 2006)	Energy management systems, gas removal plants, fuel blend analysis	Reduce operational emissions, enable gas reuse, support renewable offset planning	Often prioritizes certification over deep circularity; public awareness gaps remain
Sour / low-sulfur gas (Alqaheem, 2021; KIPIC, 2024)	Polymeric membranes, refinery upgrades	Energy & cost savings; meets int’l specs; produces cleaner fuels	Low hydrocarbon yield: refining can result in net financial loss
Produced water and wastewater (Al Salem and Thiemann, 2024; Saad et al., 2025)	Reinjection, mineral extraction, RO/UF, flow monitoring	Enables reuse, supports circular economy, aids capacity planning	Purity issues, groundwater contamination risk, ammonia noncompliance
Desalination brine (Al-Mutairi et al., 2024; Saad et al., 2025)	Brine discharge, MSF/RO desalination	Lowers net carbon, supplies freshwater	Marine ecosystem harm; high carbon footprint of MSF
Chemical and thermal pollution (Al-Mutairi et al., 2024)	Neutralization, cooling systems, Mg-based treatments	Reduces toxicity & thermal impact; cuts acid corrosion	Incomplete neutralization risks marine life; maintenance demands
Hazardous and solid waste (KEPA, 2022)	Treatment centers, rehab sites	Enables waste tracking; reduces enviro risk	Groundwater pollution potential; methane/CO ₂ contamination
Oil-contaminated soil and marine spills (Al-Mebayedh et al., 2023; Kansour and Al-Mailem, 2023; Zakzouk et al., 2024)	Capping, bioremediation, soil washing, remote sensing	Removes contamination, uses native microbes, detects spills widely	High cost, slow process, sensor limitations, weather dependency
Drilling waste and byproducts (Al Salem and Thiemann, 2024; KNPC, 2025)	Salt precipitation, PCC use, APC optimization	Convert waste to products; improves yield/quality	Market-sensitive costs; calibration complexity
Petroleum system and off-spec products (Al-Enezi et al., 2025; KNPC, 2025)	1D modeling, APC monitoring	Confirms rock maturity; maximizes product quality	Limited modeling scope; model accuracy dependency
Biochemical oxygen demand (Alameedy et al., 2026)	Standard BOD testing	Measures treatment efficiency	5-day delay for results

Critically, the findings highlight a reliance on end-of-pipe treatment over preventive design. Many methods, such as capping oil lakes (Al-Mebayedh et al., 2023) or treating contaminated water (Saad et al., 2025), manage symptoms but do not address the root causes of waste generation. This is compounded by regulatory and economic pressures, where compliance (e.g., meeting KEPA standards (Saad et al., 2025)) can sometimes conflict with optimal environmental outcomes, and financial viability is sensitive to oil prices (Al Salem and Thiemann, 2024). The conclusion is that while the technological toolkit is robust, cross-sector collaboration and increased public awareness to move beyond compliance toward systemic resource conservation (AlRukaibi and AlSalem, 2022).

GCC oil industry

GCC states share similar climatic, geological, and operational characteristics with Kuwait, but vary in the maturity of their environmental and technological practices. Table 3 summarizes the tools used for waste management in the oil industry in GCC countries. Across the GCC, key strengths include strong reinjection and wastewater treatment systems, rapid adoption of digital technologies in Saudi Arabia and the UAE, centralized environmental governance, and growth in bioremediation and thermal technologies. However, challenges include dependency on aging infrastructure, costly ZLD systems, limited automation in waste handling, and gaps in real-time monitoring.

GCC nations—Saudi Arabia, UAE, Qatar, Oman, and Bahrain—leverage shared geological and operational contexts but differ in technological maturity and regulatory ambition. Saudi Arabia and the UAE lead with strategic investments: Saudi Arabia channels billions into low-carbon innovation and chemical recycling (e.g., via SABIC), while the UAE pioneers blue hydrogen production and enforces zero-flaring policies. Both integrate digital monitoring to enhance efficiency. Qatar employs thermal methods like pyrolysis and bioremediation for oil sludge, though energy intensity remains a drawback. Oman adopts nature-based solutions such as reed box systems for wastewater, prioritizing ecological compatibility over scale. Bahrain focuses on spill prevention through stricter transport monitoring. Common regional challenges include aging infrastructure, high costs of Zero Liquid Discharge (ZLD) systems, and limited

real-time data integration—particularly outside Saudi Arabia and the UAE.

International oil countries

To contextualize Kuwait's position globally, studies from selected oil-producing countries, Russia, Canada, Norway, Iraq, and India, provide insight into advanced practices and emerging solutions. Table 4 summarizes the types of waste in the oil industry in international countries.

International evidence indicates that differences in waste management performance arise not simply from the technologies adopted but from the institutional conditions surrounding their implementation. Norway combines closed-loop systems and water reuse with stringent regulation and specialized waste management partnerships, whereas Canada emphasizes recovery programs and heat-recovery applications. Russia demonstrates technically feasible approaches such as drilling-cutting reuse and thermal treatment, but fragmented regulation constrains their broader environmental effectiveness. These contrasts suggest that similar treatment technologies can produce different sustainability outcomes depending on regulatory enforcement, infrastructure maturity, investment capacity, and coordination among operators and environmental authorities.

AI in oil and waste management

The practical use of AI-driven waste management systems depends on many factors—technological, institutional, and socio-economic (Chen et al., 2025). Drawing on digital transformation and technology adoption research, several key drivers emerge. First, perceived usefulness and ease of use strongly influence adoption decisions (El-Bayaa et al., 2025). When AI systems clearly reduce costs, improve environmental compliance, and lower waste-related risks, organizations are more likely to invest. Second, public attitudes and social norms matter. Acceptance grows when environmental protection is seen as a national priority (Singagerda et al., 2024). Positive views of AI as a sustainability tool can speed up adoption across industry and regulation.

However, several barriers may hold back implementation. Financial limits are a primary obstacle. AI requires significant upfront spending on sensors, data infrastructure, cybersecurity,

Table 3. Tools used for oil waste management in GCC countries

Country	Type of waste	Tools used	Advantage	Disadvantage
Saudi Arabia	Greenhouse gas emission (ARAMCO, 2023)	1.5B sustainability fund for lower carbon solution	Funds innovation in emissions reduction and energy efficiency	High financial commitment, ROI on new technologies may be long term
	Produced water (Healey, 2006)	Separation, reinjection, treatment, and reuse in operations	Maintain reservoir pressure, reduce freshwater demand	High volume
	Oil and petrochemical (Alsaoud et al., 2025)	Chemical recycling by SABIC company	Reduce dependency on hydrocarbon resources	Infrastructural gaps, policy enforcement, high cost
United Arab Emirates	Greenhouse gas emission (Healey, 2006)	Blue hydrogen production (300 to 500kt/year) & global ammonia plant	Positions Abu Dhabi National Oil Company as future energy leader, create new revenue stream	High capital expenditure, global hydrogen market still developing
	Gas flaring (Saif-al-badi et al., 2025)	Zero flaring initiatives	Reduce wasted gas, lower emissions, improve efficiency	Implementation cost, needs advance monitoring
	Solid waste (Alhosani et al., 2025)	Public and private partnership	Reduce landfill dependency by converting industrial waste to energy	Requires government regulation and monitoring to maintain efficiency
Qatar	Operational responsibility (Healey, 2006)	Climate change strategy aligned with Paris agreement	Position company for long term global regulatory alignment	Strategy must balance with national economic dependence on hydrocarbons
	Oil sludge (Shahbaz et al., 2023)	Pyrolysis, gasification, bioremediation	Generates useful products (char, oil, syngas)	High energy demand (pyrolysis / gasification)
	Water waste from oil and gas extraction (Al-Muhtaseb et al., 2025)	Gravity separation	Removes aggregates and suspended solids	Limited to larger oil droplets, not effective for emulsified oil
Oman	Greenhouse gas emission (Healey, 2006)	Net zero by 2050 strategy	Comprehensive plan covering emissions, sinks, and efficiency	Very long timeline m dependent on future tech advancement
	Small scale oil spill (Al-Kamzari et al., 2025)	Mechanical, chemical, natural tools	Mechanical immediate contamination, chemical fast dispersion, natural low cost	Mechanical limited in rough seas, chemical harm the marine life, natural very slow
	Water waste (Al-Maskari et al., 2025)	Reed box treatment system	Uses plants, microorganism, and gravel to naturally filter and clean wastewater	Limited treatment capacity
Bahrain	Financial stability (Healey, 2006)	Cost control & economic diversification program	Ensure long term viability, reduce reliance on single revenue steam	Diversification is challenging for a small, oil dependent economy
	Oil spill (Rashed, 2025)	Spill control measures, stricter monitoring of raw material transport	Protects marine ecosystem, avoid biodiversity loss	Accidental spills still occur

and training (Vuković et al., 2025). In economies dependent on oil prices or with tight budgets, volatility can delay digital transformation efforts (Yaseen and Al-Amarneh, 2025). Institutional barriers also get in the way. These include fragmented data governance, lack of interoperability standards, and limited digital expertise (Singagerda et al., 2024). In addition, low public awareness and insufficient technical literacy can reduce acceptance. They may also hinder long-term system optimization.

Table 5 shows that the suitability of AI tools for oil-waste management depends on the type of decision they support and the quality of the underlying data and infrastructure. Predictive analytics

and anomaly detection primarily strengthen anticipation and early warning, while computer vision extends monitoring to visually observable waste and contamination conditions. Optimization methods add prescriptive capability by supporting resource allocation and operational decisions, whereas digital twins integrate real-time monitoring with asset-level analysis. AI-enabled compliance tools further connect technical outputs with regulatory processes. However, these benefits are conditional: data quality, model uncertainty, infrastructure requirements, cybersecurity, and regulatory complexity can limit performance. Accordingly, the evidence supports a complementary

Table 4. Tools used for oil waste management in international countries compared to the GCC

Countries	Type of waste	Tools used	Advantage	Disadvantage
Russia	Gas flaring, produced water (Al-Mailem et al., 2017)	Emerging hubs for clean technology research	Limited presence of independent waste management firms	Fragmented regulatory environment, inconsistent enforcement, lack of centralized waste tracking system
	Industrial waste (Tsareva and Tsarev, 2025)	Mamdani algorithm	Fuzzy control is most useful in EMS performance analysis	The adequacy of the IMS performance assessment
	Drilling cuttings (Illykh et al., 2023)	Land spraying	Simple minimal operations	High risk of pollutant migration
Canada	Used oil, filters, and containers from the automotive industry (InternationalTrade, 2023)	Used oil management association. two indicators resource recovery per vehicle and expenses	Actively pursuing multiple waste management strategies and environmental conservation measures	A lack of legislation in end-of-life vehicle management activities, a decreasing trend in RRPV across all jurisdictions
	Petroleum coke (Baritto et al., 2025)	Combustion of energy, limited industrial use	Provides low-cost fuel partial industrial use	High sulfur & metals, low market value
	Produced water (Aslani et al., 2025)	Heat exchange, heat recovery system	Lower greenhouse gas emissions	Heat loss in above ground pipeline
Norway	Waste streams, produced water (Al-Mailem et al., 2017)	Closed loop system, water reuse, waste to energy project, collaboration with specialized waste treatment contractors	Highly developed institutional framework, strict regulatory enforcement, consistent policy support	Achieving full circularity in complex offshore operations is challenging
	Gas flaring (Illykh et al., 2023)	Comprehensive legal framework	The regulatory framework is widely regarded as one of the most progressive	The Need to follow the regulation implemented by Norway
	Greenhouse gases (Bjerkkan et al., 2021)	Business model innovation	Companies can maintain their position in the oil and gas industry while simultaneously serving different customer	Low willingness to change among production companies because production is still profitable
Iraq	Produced water, drilling waste, oil sludge, gas flaring emissions (Al-Mailem et al., 2017)	Basic containment, third party disposal, limited pilot project	Pilot project like the Basra gas company demonstrates the economic	Severe infrastructure deficits, weak enforcement political instability
	Exploration stage risk (Obayes, 2025)	Geological surveys, drilling tools, SPSS based risk analysis	Identifies reserves before major investment	High uncertainty, costly drilling failures
	Naturally radioactive material (Alhamd et al., 2025)	Monitoring	Ensure worker safety	Doesn't eliminate hazard requires specialized infrastructure
India	Spent oil (Selvi et al., 2013)	Vacuum distillation with clay treatment, thin film evaporation, centrifuging / dehydration	High recovery rate (>90%), energy efficient (1/3 energy of crude refining conserves oil reserves)	High cost of collection, transportation energy intensive process
	Solid waste (Parashar and Thakur, 2024)	Recycling of metals	Safe disposal, decrease the need for extracting new assets	Health risk to human and wildlife
	Untreated biomass (Kaur et al., 2023)	Pyrolysis (350-550)	Produces char (up to 40.3wt% at 350), simple conversion	Lower yield and quality of bio-oil, char decreases at high temp

rather than stand-alone use of these technologies within an integrated waste management system.

Comparative analysis

Table 6 compares the benefits, limitations, environmental implications, digital requirements, and transferability of key waste management

approaches across the reviewed oil-producing contexts. The comparison is intended to assess not only technological performance, but also the conditions that shape implementation, including infrastructure maturity, regulatory capacity, digital readiness, and organizational capability.

Cross-study comparison reveals three important patterns. First, the evidence consistently

Table 5. The AI tools that are suitable for the oil waste management

Tool	Application	Advantages	Disadvantages
Predictive analytics models (Yaseen and Al-Amarnah, 2025)	Forecast equipment failure, oil output, waste volumes, and operational demand	Captures temporal dependencies; supports forecasting of waste volumes and operational conditions	Environmental uncertainty, vanishing gradient problems, more complex than simpler models
Anomaly detection (Azmi et al., 2024)	Safety enhancement, environment monitoring	Early detection of operational anomalies, improve safety and efficiency	High rate of false positives, effectiveness is dependent on the quality of the historical training data
Computer vision for waste detection (Morell et al., 2022)	Waste classification, sorting, and visual contamination detection	High accuracy in waste classification, recycle process, improve resource efficiency	Complex integration, high infrastructure cost
Optimization of waste handling (Wang et al., 2025)	Waste routing, treatment allocation, pipeline monitoring, leak detection, energy efficiency, and emission control	Supports resource allocation and operational decision-making; improves system efficiency	Computational complexity: sensitive to model assumptions, constraints, and uncertainty
Digital twin technology and real-time monitoring (Meza et al., 2024)	Monitor & manage the construction waste, predictive maintenance	Improves real-time visibility, asset optimization, and decision-making	Cybersecurity risks, data dependency, complexity dealing with high amount of data
AI-enabled environmental compliance (Amaliyah et al., 2025)	Automate the reports, policy and regulatory compliance, environmental and ethical supervision	Improves consistency of reporting and supports regulatory monitoring	Limited understanding of complex query, required continuous maintenance

supports resource recovery and preventive monitoring over disposal-oriented practices, although their effectiveness is context-dependent. Spent-oil recycling, for example, achieves high material recovery but remains sensitive to collection costs and workforce availability, whereas produced-water reinjection reduces surface discharge but requires substantial infrastructure and suitable geological conditions. Second, digitally enabled approaches offer stronger preventive capabilities than conventional treatment alone, yet their benefits depend on sensor reliability, data integration, cybersecurity, and institutional capacity. Third, differences between Kuwait, GCC countries, and more mature international systems appear to reflect governance and implementation capacity as much as technological availability. Consequently, transferability to Kuwait should be assessed through the combined consideration of technical feasibility, environmental benefits, infrastructure requirements, and institutional readiness rather than through the adoption of individual technologies in isolation.

The comparative analysis discloses that conventional waste-treatment approaches focus on end-of-pipe mitigation. Often require high capital investment and can create secondary environmental risks (Healey, 2006; Kansour and Al-Mailem; Selvi et al., 2013; Shahbaz et al., 2023). While mechanical and thermal treatments remain

essential, their limitations highlight the need for complementary digital approaches rather than replacement. The framework proposed in this study builds on this complementarity by integrating sensing, AI analytics, regulatory alignment, and organizational readiness.

FRAMEWORK DEVELOPMENT

The comparative synthesis identifies four recurring capability gaps that condition sustainable waste management performance: fragmented environmental data acquisition, limited predictive and prescriptive analytics, weak integration between operational monitoring and regulatory processes, and uneven organizational capacity for digital implementation. These recurring gaps provide the evidence base for the proposed framework. Accordingly, the framework comprises four interdependent pillars: (1) Digital and Sensing Infrastructure, addressing data availability and monitoring limitations; (2) AI-Enabled Analytical and Operational Engines, translating data into predictive and prescriptive decisions; (3) Environmental and Regulatory Integration, connecting operational intelligence with compliance and remediation; and (4) Organizational Readiness and Capacity Development, addressing the institutional and human capabilities required

Table 6. Comparative evaluation of waste management and sustainability approaches across oil-producing contexts

Approach / technique	Country context	Key benefits	Key limitations	Environmental effectiveness	Digital requirements	Transferability to Kuwait
Spent oil recycling (Selvi et al., 2013)	India (Selvi et al., 2013)	>90% recovery rate; 1/3 energy vs crude refining; conserves oil reserves	High collection cost; pollution risk; skilled labor shortage	High material recovery, moderate emission risk	Moderate regulatory oversight	High (requires stronger collection logistics)
Produced water reinjection (Alhosani et al., 2025; Healey, 2006)	Canada, Norway	Reduces surface discharge; enhances reservoir management	High infrastructure cost; geological dependency	High contamination prevention	Strong technical and monitoring systems	Moderate–High (needs infrastructure upgrades)
Pyrolysis / gasification (Al-Muhtaseb et al., 2025; Healey, 2006; Shahbaz et al., 2023)	India, GCC	Volume reduction; energy recovery potential	High char residue; emission control challenges; energy intensive	Mixed (depends on emission control)	High technical expertise	Moderate (requires emission control capacity)
Bioremediation (Kansour & Al-Mailem, 2023; Zakzouk et al., 2024)	GCC countries	Eco-friendly soil recovery; lower energy input	Slow process; climate-sensitive	Environmentally sustainable	Requires monitoring and lab capacity	High (suitable for desert-contaminated soil)
Zero flaring initiatives (Alhosani et al., 2025; Saif-al-badi et al., 2025)	GCC (Kuwait, UAE, Saudi Arabia)	Reduces emissions; aligns with global climate commitments	Requires infrastructure modernization	High climate mitigation impact	Monitoring & reporting systems	Already high priority in Kuwait
AI-based digital sensing & monitoring (Lakhout, 2025; Toderas, 2025)	UAE, Saudi Arabia	Real-time leak detection; predictive maintenance	High initial investment; cybersecurity risks	Preventive environmental protection	High digital governance maturity	High (aligned with Vision 2035)
Heat recovery systems (Aslani et al., 2025; Baritto et al., 2025)	Kuwait Refineries	Improves energy efficiency	Capital intensive	Reduces indirect emissions	Industrial retrofitting capacity	Already implemented

for sustained implementation. Figure 2 explains the synergy among the different framework components.

Digital and sensing infrastructure

Robust digital infrastructure is the foundation of AI-enabled waste management. Recent environmental monitoring studies further demonstrate the value of integrating spatial sensing technologies, continuous environmental monitoring, and data-driven environmental assessment to improve pollution detection and environmental decision-making in industrial settings (Ali et al., 2024). The comparative evidence, however, indicates that the critical distinction is not simply whether monitoring technologies are available, but whether they operate as an integrated environmental information system. Practices from Saudi Arabia, the UAE, Canada, and Norway demonstrate the value of real-time monitoring for predictive analytics, anomaly detection, and automated reporting (Al-Mutairi

et al., 2024; Chaterera-Zambuko, 2025; Chen et al., 2025). In contrast, Kuwait's system remains fragmented across KOC, KNPC, and subcontractors, with reliance on manual reporting and limited uniformity in data formats, sampling frequencies, and integration. This contrast provides the evidence base for the first framework pillar, which combines sensing, spatial monitoring, connectivity, and data integration rather than treating them as independent technological interventions.

Distributed sensor networks provide the first component by enabling continuous monitoring of produced water, drilling waste, and environmental parameters through smart flow meters and multi-parameter sensors (Bhatia and Malik, 2025). Such real-time data are also necessary for predictive analytics and mathematical optimization; without reliable inputs, optimization outputs can become unstable or unrealistic (Tascione et al., 2016; Tirkolaei, 2024). Spatial monitoring through UAVs, satellites, and thermal imaging complements fixed sensors where contamination

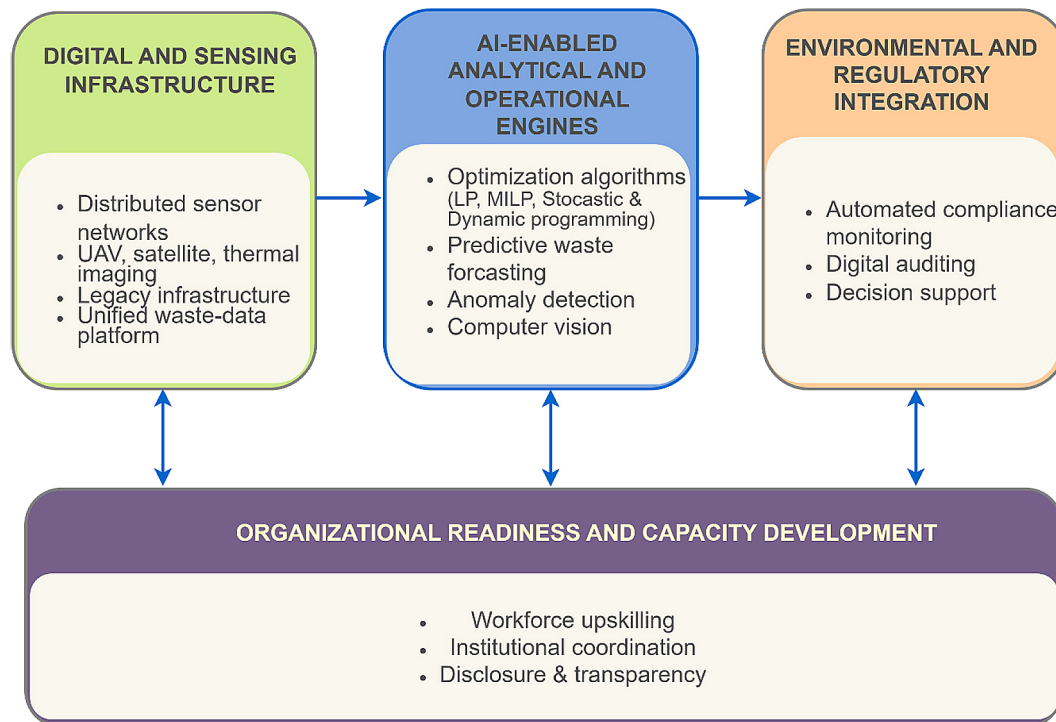


Figure 2. Evidence-derived AI-driven waste management sustainability framework for Kuwait's oil sector

is geographically dispersed or difficult to access. UAV-based vegetation indices and thermal imaging can identify indications of soil contamination (Al-Shammari et al., 2018; Dean et al., 2024), while Landsat and Sentinel support larger-scale oil-spill and soil-contamination assessment (Ashkanani et al., 2025). The two approaches are therefore complementary: sensor networks provide continuous point-based measurements, whereas remote sensing extends environmental visibility spatially.

Their effectiveness nevertheless depends on digital connectivity and integration. Legacy facilities with limited IoT connectivity cannot readily feed real-time observations into centralized analytical systems, making connectivity a prerequisite rather than a separate digital enhancement. Developments in IoT, cloud computing, AI, and standardized integration frameworks provide mechanisms for connecting heterogeneous and multi-vendor systems (Al-Hajri et al., 2025; Baranidharan et al., 2025), while digital twins can support data sharing, monitoring, and predictive maintenance (Tedstone, 2021). Low-power wide-area networks provide a potentially lower-cost retrofit option for legacy facilities (Al-Hajri et al., 2025).

The synthesis therefore points to a unified waste-data platform as the integrating component of this pillar. Combining sensor observations,

remote-sensing data, and facility-level information within a centralized environmental data system would provide the operational backbone for subsequent AI applications (Alselahi et al., 2026). For Kuwait, the principal requirement is consequently not the isolated adoption of additional sensors, UAVs, or digital platforms, but their integration into a common data architecture capable of supporting predictive, optimization, and regulatory functions across the oil-sector waste management system.

AI-enabled analytical and operational engines

Once digital infrastructure is in place, AI can enhance Kuwait's waste management operations (Alzoubi et al., 2025; Elbasi et al., 2025; Stewart, 2025). The reviewed evidence indicates, however, that these capabilities provide different but complementary forms of decision intelligence rather than interchangeable technological solutions. The second framework pillar therefore integrates predictive waste forecasting, anomaly detection, computer vision, and optimization into a predictive–prescriptive decision architecture.

Predictive forecasting and anomaly detection provide the anticipatory layer of this architecture. Machine-learning models such as Long

Short-Term Memory networks, XGBoost, and Random Forests can forecast produced-water volumes, sludge accumulation, drilling waste, and emissions patterns (Chen et al., 2025). Applications in Saudi Arabia and other oil-producing contexts demonstrate their potential for anticipating operational conditions and treatment requirements (ARAMCO, 2023; Yaseen and Al-Amarnah, 2025). Anomaly-detection techniques complement forecasting by identifying deviations in flow, pressure, emissions, and chemical signatures that may indicate leaks, tank overflows, abnormal contaminant concentrations, or unauthorized discharges (Alzoubiet al., 2024; Azmi et al., 2024). The distinction is important: forecasting supports planning before waste loads or events materialize, whereas anomaly detection provides early warning when actual operations deviate from expected conditions.

Computer vision extends these capabilities to spatial and visual waste characterization. CNN- and U-Net-based models can classify sludge characteristics, degrees of soil contamination, produced-water oil droplets, flare images, and waste-segregation streams (Morell et al., 2022). This capability complements sensor-based analytics where environmental conditions cannot be adequately represented by numerical measurements alone, particularly for contaminated land and heterogeneous waste streams. However, its applicability remains dependent on representative training data and image quality, making it complementary to rather than a substitute for sensor and laboratory measurements.

Optimization provides the prescriptive layer by translating predicted conditions into operational decisions. Importantly, the reviewed evidence shows that optimization should not be restricted to ML-based approaches. LP and MILP can support waste routing, treatment allocation, facility-capacity planning, and produced-water reinjection under operational and environmental constraints (Alameedy et al., 2026; Tirkolae, 2024), while multi-objective formulations enable economic and environmental objectives to be considered simultaneously (Tascione et al., 2016). Stochastic and robust optimization address uncertainty in waste generation and operational conditions (Al-Mutairi et al., 2026), whereas dynamic and two-stage approaches support time-dependent remediation, spill response, facility allocation, and routing decisions (Caramia et al., 2023; Wang et al., 2025). These methods therefore complement ML

rather than compete with it: ML identifies what is likely to occur, while mathematical optimization determines how available resources should be allocated in response.

The synthesis consequently supports an integrated engine in which forecasting anticipates waste conditions, anomaly detection identifies deviations, computer vision characterizes visually observable risks, and optimization selects operational responses. For Kuwait, the value of this pillar lies less in adopting individual algorithms than in connecting these capabilities to the common data infrastructure established under the first pillar, thereby shifting waste management from reactive treatment toward predictive and prescriptive decision support.

Environmental and regulatory integration

AI offers limited sustainability value if analytical capabilities remain disconnected from environmental governance and regulatory processes. The comparative evidence indicates that the distinction between technologically advanced and less integrated systems lies partly in whether environmental monitoring is linked to compliance, auditing, and corrective action. The third framework pillar therefore connects the analytical capabilities of the preceding pillars with three governance functions: automated compliance monitoring, digital environmental auditing, and remediation decision support. Evidence from Norway and Canada, where automated emissions-tracking systems feed into regulatory processes, illustrates the value of linking operational monitoring with environmental oversight (Baritto et al., 2025; Bjerkan et al., 2021).

Automated compliance monitoring provides the first connection between operational data and regulatory requirements. Environmental thresholds for gas flaring, effluent discharge, heavy metals in produced water, hydrocarbons in soil, and hazardous-waste classification can be embedded within monitoring systems to identify potential violations as they emerge (Ashkanani et al., 2025). Mathematical optimization can further incorporate environmental constraints directly into operational decisions, allowing economic and environmental objectives to be considered simultaneously (Caramia et al., 2023; Tirkolae, 2024). Robust approaches are particularly relevant where measurements or operating conditions are uncertain (Tascione et al., 2016). Thus,

regulatory integration shifts compliance from periodic reporting toward continuous, constraint-aware environmental management.

Digital environmental auditing complements real-time compliance by providing a broader assessment of facility performance and accountability. Experience from UAE refineries and Canadian oil-sands projects demonstrates the potential for digital systems to support remote assessment and reduce dependence on on-site inspection exclusively (Chaterera-Zambuko, 2025). However, automated monitoring and auditing identify deviations rather than resolve their environmental consequences; this creates the need for the third component, decision support for remediation programs. Decision-support systems can integrate site-specific environmental data and analytical models to compare remediation alternatives, prioritize contamination hotspots, estimate remediation timelines, and monitor progress (Alselahi et al., 2026). Such capabilities are particularly relevant to Kuwait's remediation programs, where contaminated sites require prioritization and sustained monitoring.

The synthesis therefore establishes a governance sequence in which automated monitoring detects potential non-compliance, digital auditing evaluates environmental performance, and decision-support systems guide corrective and remediation actions. For Kuwait, integrating these functions would help ensure that the sensing and analytical capabilities of the first two pillars translate into measurable environmental governance rather than remaining isolated technological improvements.

Organizational readiness and capacity development

Technology adoption depends on human and institutional readiness. The comparative evidence indicates that technical capability alone does not ensure effective digital transformation; its value depends on whether organizations possess the skills, coordination mechanisms, and governance capacity required to translate technological outputs into operational and environmental decisions. The fourth framework pillar therefore integrates three enabling conditions: workforce upskilling, institutional coordination, and public disclosure and transparency.

Workforce upskilling addresses the capability gap created by increasingly data-intensive waste

management systems. Advanced analytics and optimization require expertise in data analysis, operations research, mathematical programming, and uncertainty modelling (Tascione et al., 2016; Tirkolaee, 2024), while effective field implementation requires environmental and digital training (Bandeira et al., 2023). Evidence from Canada similarly emphasizes data literacy, AI monitoring, and digital maintenance among operators, engineers, and environmental personnel (Baritto et al., 2025). These findings suggest that workforce development should combine digital expertise with environmental and operational knowledge rather than treating AI skills as a stand-alone capability.

Institutional coordination is equally important because predictive and optimization outputs have limited practical value if organizational responsibilities remain fragmented. Effective waste management requires integration of human skills, work processes, organizational change, and technology (Alarifi et al., 2024), while coordination is necessary to translate analytical outputs into operational and regulatory decisions (Veres et al., 2025). For Kuwait, fragmented responsibilities among EPA, KOC, KNPC, and contractors therefore represent an implementation constraint alongside technological limitations. The framework consequently treats coordination not as an administrative addition but as the mechanism connecting operational intelligence, regulatory oversight, and organizational action.

Public disclosure and transparency complete this pillar by extending digital integration from internal decision-making to external accountability. Evidence indicates that consistent data-management practices and environmental disclosure can improve transparency and public understanding (Bandeira et al., 2023; Veres et al., 2025). However, greater data availability does not automatically produce trust; disclosure must be consistent, interpretable, and institutionally governed. Public reporting of environmental indicators, potentially supported by digital dashboards, can therefore complement internal monitoring while strengthening accountability for sustainability commitments.

The synthesis thus identifies organizational readiness as the enabling layer of the framework: workforce capability determines whether digital tools can be used effectively, institutional coordination determines whether their outputs lead to action, and transparency determines whether environmental performance remains accountable. Without these conditions, investments in sensing, AI, and

regulatory technologies risk remaining technically functional but institutionally underutilized.

Practical and theoretical implications

The proposed framework brings noteworthy practical implications for Kuwait's oil sector. From an operational standpoint, the integration of digital sensing networks, UAV monitoring, and centralized environmental data platforms offers a shift from responsive waste handling to proactive environmental management. Such an evolution would allow KOC and KNPC to detect leaks, rising contaminants, system irregularities, and flare anomalies early, thereby reducing environmental harm and operational downtime (Al-Hajri et al., 2025). In countries such as Canada and Norway, the deployment of digital twins, real-time sensors, and extrapolative analytics has been shown to improve waste-treatment performance, enhance compliance, and diminish unplanned shutdowns (Aslani et al., 2025).

Theoretically, this framework advances scholarly discussion on the convergence of AI and environmental engineering in the petroleum sector. Existing research in Kuwait and the GCC has extensively documented waste types and environmental pressures facing the industry (Al Salem and Thiemann, 2024). However, there is limited theoretical exploration of how digital systems could reshape governance models, compliance pathways, and sustainability strategies in oil waste management. By bringing together AI applications, environmental policy, and industrial operations, this study offers a conceptual model. It can inform future academic research and serve as a benchmark for other oil-producing nations pursuing modernization.

Also, the framework contributes to the theoretical literature on institutional readiness for digital transformation. Lessons from Canada and Saudi Arabia show that AI's value depends not just on technology. It also relies on governance structures, workforce skills, and alignment with environmental regulation (Chaterera-Zambuko, 2025). Thus, this paper positions AI not as a mere technical upgrade. It frames it as a systemic shift that calls for theoretical perspectives from sustainability science, organizational change, and digital governance.

Limitations and future research directions

Because this study relies mainly on secondary sources, evidence depth and metric comparison vary across countries. This limitation is typical in cross-national governance syntheses and is mitigated here through organized narrative synthesis procedures and explicit comparative dimensions. While this provides broad comparative insights, the absence of primary field data, such as operator interviews, real-time sensor records, or facility-level operational data, limits the empirical specificity of some observations. Moreover, the paper synthesizes AI applications based on international best practices. However, the readiness of Kuwait's existing infrastructure to support such technologies remains uncertain. Variability in network connectivity, data quality, and facility-specific configurations may affect how well the proposed framework can be implemented. AI is evolving rapidly. New models, tools, and regulatory frameworks may emerge that could enhance or modify the framework proposed here.

This paper has several promising paths for future research. First, empirical validation of the proposed framework through pilot projects at KOC and KNPC facilities would offer critical insights. It would help assess practical feasibility, model performance, and operational challenges. Such work would support decision-making at both institutional and national levels. Furthermore, more research is needed on cybersecurity and data governance. These issues will become increasingly important as Kuwait expands its reliance on connected environmental systems and real-time monitoring technologies. Another important path involves exploring how AI can support broader circular-economy strategies. Additionally, cross-disciplinary studies—drawing from social science, environmental law, and public policy—can help strengthen institutional readiness. This would better prepare Kuwait to support advanced digital technologies in the oil sector.

CONCLUSIONS

This paper examined the role of AI in improving waste management sustainability in Kuwait's oil sector. By reviewing extensive literature from Kuwait, the GCC, and international oil-producing countries, the paper highlighted several key themes. Although Kuwait generates waste

streams similar to those of other major petroleum-producing nations, its main challenges are different. They stem from limited digitalization, fragmented data collection, and a continued reliance on conventional treatment methods. Through a comprehensive comparative analysis and insights from advanced countries—like Canada, Norway, Saudi Arabia, and the UAE—the paper found significant opportunities for Kuwait. It can modernize its waste management systems and move toward a digitally enabled, sustainability-focused operational model.

The proposed framework provides a strategic plan to realize this transformation. The operational and governance aspects of waste management can be addressed through a comprehensive strategy that integrates digital and sensing infrastructure, AI-enabled analytical engines, regulatory integration, and organizational readiness and capacity development. Furthermore, this system is intended to support a transition from a reactive waste management approach to an automated, predictive, and optimization-driven environmental management practice. The paper also identifies institutional, technological, and structural barriers to adoption, despite the many benefits of using AI. These factors emphasize the necessity of creating technically sound AI projects that are also well grounded in the organizational and legal infrastructure of Kuwait.

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