

The Legal Framework for the Use of Artificial Intelligence in Managing Electronic Waste in Saudi Arabia

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Abstract

This article explores the legal and institutional landscape of Saudi Arabia for the role of AI in electronic waste governance. It is an integrated doctrinal legal review, combined with policy evaluation and exploratory SmartPLS evidence, which evaluate legislation, enforcement, institutional roles and international alignment. The results indicate that weak incentives and unclear institution mandates hinder the uptake of awareness and readiness, while national legislation and international standards support them. The article concludes that Saudi Arabia must have an e-waste and AI integration law, more specific responsibilities of agencies, rules based on AI for monitoring and more integration with the circular economy standards. The study also offers a policy-oriented basis for connecting national regulation, institutional coordination, data accountability and international standards in support of legally responsible AI adoption for e-waste governance. Its framework can support future empirical testing and practical cross-sectoral collaboration among environmental, digital and industrial authorities in the Kingdom.

Keywords: artificial intelligence; electronic waste; legal framework; environmental governance; Saudi Arabia.

1. Introduction

With the speed of technological advancement and the dependency on electronic devices in Saudi Arabia, the abundance of both e-waste and its disposal problems is becoming a significant environmental issue for the Kingdom. The rapid digitalization of Saudi Arabia and the extensive use of electronic devices are making E-Waste one of the most pressing environmental challenges facing the Kingdom. Saudi Arabia has seen substantial technological progress under Vision 2030, leading to a rise in the manufacturing and distribution of electronic products. Saudi Arabia is experiencing great technological development under Vision 2030, which has led to an increase in the production and sale of electronic products. This development has resulted in an equal rise in e-waste – wasted computer hardware, mobile phones, televisions and other electronic devices. Hazardous materials such as lead, mercury and cadmium are present in such waste and improper handling and disposal can cause serious threats to public health and the environment. While e-

waste has environmental concerns, it is under-regulated in many countries, including the country, and needs to be effectively and sustainably managed.

Meanwhile, artificial intelligence (AI) has become a much talked about technology in environmental management. From automated waste sorting machines powered by sensors to AI-driven predictive analytics and decision-making, the collection, classification, and management of waste are being transformed. When applied to e-waste management, AI can help streamline the processes, optimise recycling methods, and minimize environmental hazards through more precise and data-driven practices. With Saudi Arabia's focus on smart cities and digital infrastructure, AI has become an opportune solution for ecological governance, notably to address the e-waste problem. Such advanced technologies, however, need to be supported by an adequate legal and regulatory framework, with a view to accountability, transparency and sustainability.

But, the current legislation and regulations in Saudi Arabia does not have specific provisions with regard to the relationship between technology and environmental protection. While there are general environmental laws, there are no standards, guidelines or enforcement processes for AI-based waste management. There are areas with little development, such as protection of data, algorithmic accountability, coordination between different areas and the public-private partnership. Additionally, the current lack of regulation and formal guidance on using AI in waste management systems can pose a regulatory challenge and obstruct innovation and the success of environmental measures. The research highlights the importance of having a comprehensive and flexible legislation that supports the efficient management of e-waste equipped with technologies of artificial intelligence. Lack of such a system in Saudi Arabia is one of the biggest challenges to realizing the potential of AI in environmental sustainability. The present study thus aims to analyse the legal and institutional landscape of e-waste and AI in India, assess the status of existing laws and policies in promoting innovative solutions and identify the gaps and suggest the amendments of the laws and policy to align with the digital and environmental needs of the country. The following objectives are aimed at this study: (1) to analyse the existing legal and regulatory frameworks in the Kingdom of Saudi Arabia that regulates e-waste; (2) to identify the legal and institutional gaps that hinder the integration of AI in e-waste management system in the Kingdom of Saudi Arabia; (3) to evaluate the benefits and risks of using AI in waste management in the Kingdom of Saudi Arabia; and (4) to present a set of legal recommendations for effective and responsible utilization of AI in e-waste management systems in the Kingdom of Saudi Arabia.

The central research questions are: What are the existing laws and legislations related to e-waste and AI in Saudi Arabia? How do these laws enable or hinder the implementation of AI technologies in waste management? What changes are needed in the law for a fair and supportive regulatory framework for sustainability solutions powered by AI?

The use of terms is important in the study because it assumes that there is communication between different institutional environments in the legal field. In the context of Arabic-English

legal translation, it has been proven that the choice of words can impact the meaning of legal duties and institutional responsibility (Alshehab and Rababah 2020).

The interdisciplinary orientation of the present study is also supported by research on contextualized academic writing, feedback, digital learning, virtual simulation, sociolinguistic practice, discourse analysis, institutional tolerance and cultural naming, all of which underline the importance of precise language, contextual framing and digitally mediated professional engagement (Bardaweel and Rababah 2022; Rababah 2022; Rababah et al. 2023; Rababah 2023; Rababah and Rababah 2024; Al-Mazari and Rababah 2024; Al-Khawaldeh et al. 2024; Amaireh and Rababah 2024; Rababah et al. 2024).

This study focuses solely on the legal and policy aspects of AI technology in e-waste management in the Kingdom of Saudi Arabia. It is national-legislation centered, regulatory institutions oriented, and selected international benchmarks oriented. This research does not include the technical aspects of design or engineering of the AI or its operation. The study employs a doctrinal legal method with the support of policy analysis and as needed, expert commentaries of a qualitative nature. However, there are several important challenges, such as the fast pace of the development of AI technologies and the related regulations, a scarcity of publicly available data with respect to AI initiatives in the private sector, and a limited number of documents covering enforcement practices in the Saudi environmental sector. This study contributes to the interdisciplinary literature on law, technology and environmental policy by illustrating a means for legal systems to change in order to accommodate sustainability-focused digital innovation.

In practice, it provides guidance to the government, regulators, and industry stakeholders on how to link Vision 2030, environmental protection and responsible AI-driven waste management.

2. Literature Review and Theoretical Framework

2.1. The effectiveness of AI based Electronic Waste Management. How AI helps with electronic waste management.

The efficiency and effectiveness of e-waste management have been demonstrated as significant benefits of using AI. The segregation of various types of waste is a complex and time-consuming task that can be streamlined and improved with the use of modern computer vision and deep learning techniques, which can accurately identify and categorize waste materials, significantly increasing the speed and precision of the recycling process (Shahab et al. 2022; Sharma et al. 2023). For example, image recognition based automatic systems have successfully achieved high accuracy of e-waste classification, such as one research using deep convolutional neural networks (Nafiz et al. 2023) obtaining up to 98% accuracy in e-waste waste materials classification. This AI-based sorting robots and platforms technology minimizes the use of human labour, thereby lowering processing time and expenses, and increasing safety for workers (Sharma et al., 2023). Moreover, collaborative robotics (cobots) can be used in disassembly lines to assist humans in completing tedious jobs and lifting heavy loads, thereby supplementing

human beings' flexibility and problem-solving ability; Chen et al. (2022) provided a brief overview of the current situation of collaborative robots in manufacturing and their potential for disassembly lines. The examples shown here demonstrate how, beyond the use of smart sensors, AI approaches, such as machine learning algorithms, can boost recycling rates and resource recovery, thereby contributing to a more circular economy (Nišić et al. 2024). It is also acknowledged that, e-waste streams are complex and diverse and complete automation is difficult, the best results comes with human-AI collaboration and human judgment (Ramadurai 2025). In summary, the literature suggests that, if used sustainably, AI technologies can significantly improve the efficiency of e-waste collection, sorting, and recycling operations (Nesmachnow et al. 2025).

2.2. National Legislation on E-Waste and AI

The e-waste laws in Saudi Arabia have not yet reached the mature stage and researchers reported that the country has not had specific e-waste laws in the past (Islam and Ali 2025). E-waste is currently regulated under general waste management laws (such as the Waste Management Law of 2021) which apply to all waste, but not specific laws targeting the technical, hazardous and trade-related characteristics of waste in the European Union which is categorised as Waste Electrical and Electronic Equipment (WEEE) (Government of Saudi Arabia 2021; Trade.gov 2024). This regulatory vacuum partly accounts for the high proportion of e-waste that continues to find its way into landfill or low value treatment, resulting in the loss of resources and possible environmental risks as also reflected in regional and UN monitoring reports of GCC countries (Kavil 2025; ITU and CST 2023). As such, national waste policies in Saudi Arabia have started to focus on incorporating Extended Producer Responsibility (EPR) and circular economy principles in the national waste regulations to shift away from landfill dependent waste management practices (CST 2023; Vision 2030 2016). Indeed, the call for a modernisation of environmental regulations and boosting recycling and material recovery, as stated in Vision 2030, will give high level political support to new e-waste instruments. On the AI front, Saudi Arabia has made significant strides in its national AI strategy and governance proactively. Saudi Data & AI Authority (SDAIA) has implemented a National Strategy for Data and AI (NSDAI) in 2020 to achieve the goal of making the Kingdom one of the top nations in the world in AI by 2030 (SDAIA 2020). This approach involves establishing a "welcoming legislative framework" for AI development and use, and has been encouraging the drafting of new legislation such as the "Global AI Hub" law in the Communications, Space & Technology Commission (CST) (CST 2025; TransPerfect 2025). These laws and strategies are not directly related to e-waste but create a conducive legal framework for the use of AI in various sectors, such as the environment and waste management. To conclude, Saudi Arabia is taking steps to enhance its legal framework at the intersection of e-waste and AI, addressing the legal gaps in e-waste management and introducing future-focused AI regulations, to facilitate the responsible use of AI in managing the nation's rising e-waste challenge.

2.3. Regulatory Enforcement Mechanisms

In order to be effective, a sound legal framework must be well-enforced. Traditionally, the implementation of e-waste legislation has been challenging and problematic due to issues with enforcement, lack of coordination between enforcement agencies, and the ambiguity of the regulation. Historically, the effective implementation of e-waste laws has been difficult, as e-waste is hard to detect, standards are often unclear, and there is challenging coordination between enforcement agencies (UNEP 2019; Isarin et al. 2024; OECD 2022). In efforts to combat these problems, governments are increasingly shifting to digital and AI-based enforcement tools. In the waste sector, digital surveillance, data analytics and machine learning have the potential to significantly increase the capacities of regulators to monitor compliance and detect illegal activities (ITU and CST 2023). AI systems have been used to analyse satellite data, for instance, to shorten investigation times and enhance illegal dumping detection over manual inspections (David et al. 2024). Such technologies can allow for intelligence-led inspections, alerting high-risk waste movements or locations to facilitate the use of limited resources for inspections where they're most needed (OECD 2022). The OECD research has also been published, and it is confirmed that there is "enormous potential for AI to increase compliance, improve monitoring and respond to non-compliance" in the environmental sector. Concurrently, there is need to establish clear legality for effective implementation of such tools, including defining the use of digital evidence (such as drone videos or sensor information) in prosecutions, as well as data privacy and accuracy (UNEP 2023).

Saudi Arabia's fledgling e-waste initiative is taking these enforcement innovations on board. In 2023, the CST, alongside the International Telecommunication Union (ITU), announced a Global pilot project for the creation of e-waste regulations and enforcement standards, which will also be put into practice in countries such as Rwanda and Zambia (CST 2023). The goal of this initiative is to establish model regulatory enforcement systems – including a standardised tracking system and reporting framework – which can be implemented in Saudi Arabia and elsewhere. As a result, the Kingdom is following the international best practices in the field of waste crime by taking advantage of AI and digital tools to improve e-waste policing. The goal is a more transparent and information-based enforcement framework with effective action on violations, to guarantee the effectiveness of the new e-waste legislation.

2.4. Institutional Responsibilities

It is important to have clear institutional roles in the governance of AI-powered e-waste management. Effective legal frameworks establish accountability across government agencies, industry and other stakeholders by assigning responsibility (Alwreikat and Qtaishat 2025). Comparative analysis highlights that countries with clear institutional mandates, like China and the European Union, have more effective coordination across e-waste management and AI adoption (Deng et al., 2024; Epstein, 2025). In emerging economies, weak governance practices and overlapping responsibilities are found to be significant obstacles to good waste management and technology transfer (Christine et al., 2024; Ahanor et al., 2025). Likewise, Naeem (2024)

and Angel (2024) point out that the lack of institutional coordination at both the environmental and technology authorities' level reduces enforcement capacity in the South Asian and African context, respectively.

The main public actors in e-waste management in Saudi Arabia are the Ministry of Environment, Water and Agriculture (MEWA) for environmental policy and the National Center for Waste Management (MWAN) for monitoring and supervising e-waste management activities (Trade.gov 2024). The MWAN is not only tasked to license waste facilities and to encourage principles of circular economy, but also plays a leading role in any attempts for integrating AI and e-waste. The National Centre for Environmental Compliance (NCEC) is responsible for enforcing environmental standards such as waste-handling standards and making sure that e-waste processing (including manual and AI processes) complies with legal and safety standards.

Technologically, the SDAIA supports the national AI strategy and ethics, and the CST has emerged as a key contributor to digital sustainability, such as e-waste regulations (CST 2023). Furthermore, the partnerships between CST and MEWA, and CST and MWAN, involve the convergence of institutions, where technology regulators and environmental authorities are responsible for AI solutions in waste policy (Kapartziani 2025).

Private and semi-government institutions also have important roles to play apart from government institutions. Saudi Investment Recycling Company (SIRC) is responsible for developing recycling infrastructure and encouraging the automation of recycling plants through the use of artificial intelligence (AI). Similar public-private partnerships in the field of waste management using artificial intelligence have been attempted in Nigeria and Uganda, where AI and robotics are increasingly being used to monitor and regulate waste (Ahanor et al. 2025; Christine et al. 2024). Similarly, EPR schemes, based on OECD (2001) guidelines, transfer the collection and recycling of electronic products to manufacturers and importers, aligning the incentives of the private sector with national sustainability objectives. Communication, training and digital presence are also crucial factors in assessing institutional readiness. The study of online social learning and instructional presence in Jordanian higher education provides evidence of the impact of digital environments on participation and perceptions of institutional support (Rababah and Rababah 2024).

2.5. Levers for AI Adoption: Incentives and Legal Support.

Governments can promote and support AI adoption in public services through incentives and policy tools, such as waste management. The National Strategy for Data and AI in Saudi Arabia and accompanying Vision 2030 programs represent a government commitment to AI research, human-capital building and digital infrastructure. While those measures can enhance AI-supported recycling, smart collection and predictive monitoring, they have a low legal impact if they are not linked to mandatory rules, procurement pathways, standards for certification and public-private partnership mechanisms. Incentives should be therefore linked to producers'

responsibilities, measurable goals, data sharing requirements, privacy and algorithm precautions in the case of e-waste.

2.6. Alignment with International Environmental and Digital Standards

This is because e-waste is linked to hazardous materials, cross-border transport of materials and global technology supply chains, and needs to match international environmental and electronic standards. Guidelines for classification, traceability, producer responsibility and reporting the circular economy are provided by the Basel Convention and EU WEEE Directive, as well as by OECD suggestions on extended producer responsibility. Transplanting of such instruments is not necessary in Saudi Arabia. Rather, they provide principles that can be adapted to national institutions, the priorities set out in Vision 2030 and the future of AI governance. This alignment would help to enhance legal clarity, promote global collaboration, and minimize the potential for environmental responsibility gaps in AI-driven waste systems. The research has focused on the effects of e-waste on the environment and applied AI to optimise waste management, but studies on AI governance and environmental law in the Saudi context are scarce. Existing knowledge and understanding tend to focus on the technical innovations or the general sustainability frameworks, with little attention being paid to the legal, institutional and regulatory issues that support and/or restrict the application of Artificial Intelligence in e-waste management. In addition, empirical studies that integrate doctrinal analysis of the law with quantitative and qualitative analysis and evaluate the effects of the design, enforcement and institutional capacity of law on AI-assisted environmental governance are very limited. Therefore, an integrated solution is still needed that incorporates legal interpretation, perception of stakeholders, and statistical modelling to evaluate the effectiveness and compatibility of Saudi Arabia's legal system with international good practices in AI-driven e-waste management. The study will be based on an integrated conceptual framework that combines the Technology Acceptance Model (TAM), Institutional Theory, Extended Producer Responsibility (EPR), Law and Technology Co-Evolution Theory and Environment Governance Theory. It assumes that perceived usefulness and ease of use of AI-driven waste management systems influence stakeholders' adoption of these systems (TAM, Davis 1989). The study also posits that the perceptions can be positively impacted through facilitating legal measures like providing clear guidelines, supportive training programs, and simplified compliance processes, which can then lead to increased adoption of AI technologies in e-waste management. Institutional Theory (Scott 2014) is used to analyse the integration of AI, and to understand how the three types of institutions (regulative, normative and cognitive), are affecting the integration of AI in the waste sector. This lens is then used to analyze how well Saudi Arabia's institutional set-up aligns with the conditions needed to successfully implement AI.

The EPR framework (OECD 2001) is integrated as a policy design component, which puts the producer under a legal duty to manage the end-of-life of products. The inclusion of AI tools in the EPR schemes is expected to enhance the tracking, monitoring, and adherence to recycling requirements. This part of the framework is directly related to the implementation of the new

waste law in Saudi Arabia and the possibility of implementing recognized waste EPR models internationally. The dynamic view of the evolution of technological innovations and legal systems is provided by the Law and Technology Co-Evolution Theory (Brownsword and Goodwin 2012). In this framework, the principle is used to explore the regulatory changes that will be required as a result of developments in AI, including robotics, computer vision and data analytics, and how adaptive regulation can encourage innovation in e-waste management. Lastly, Environmental Governance Theory (Lemos and Agrawal 2006) provides the overarching framework to ensure that the legal-technical integration of AI in e-waste management is grounded in principles of governance, including transparency, accountability, participation, and multi-level coordination. This theory will be used to analyse the study as for how the governance mechanisms in Saudi Arabia can ensure that the solutions will help support environmental sustainability and meet the goals of Vision 2030. For the purpose of operationalizing these theoretical views, the study considers two types of variables that will represent the conceptual model, which is listed in the Table 1.

3. Methodology

3.1 Research Design

This study uses a mixed methodology approach which is a combination of doctrinal and empirical legal research. The doctrinal part analyzes the main legal instruments, policies and international instruments that are relevant to the management and regulation of e-waste in Saudi Arabia. The empirical element adds to this by engaging in semi-structured interviews with various policy stakeholders, regulators, and industry experts, and a structured questionnaire to industry and e-waste policy stakeholders.

3.2 Data Sources

The sources of data used in the study are primary and secondary: Primary legal texts and regulations: Saudi laws and policy frameworks and official guidelines regarding waste management, AI governance, and environmental protection. Policies and official reports: Governmental policies that have been formulated (Saudi Vision 2030), regulatory authority publications (SDAIA, MWAN), and relevant ministry reports. Semi-structured interviews with legal scholars, policymakers, environmental regulators and AI practitioners to capture experiential knowledge and professional perspectives. Case studies and comparative benchmarks: Comparative study of the international frameworks such as the EU WEEE Directive, OECD guidelines on EPR and good practices in the more advanced countries in terms of regulatory track and experience.

3.3 Analytical Framework

The study combines an analytical approach with a: Legal text and policy content analysis for the identification of emerging principles, regulatory gaps and overlaps. Doctrinal interpretation of laws to assess consistency of laws and their sufficiency and enforceability in the Saudi context.

The data from qualitative interviews and surveys were thematically analysed to capture the perceptions, experiences and recommendations of the stakeholders regarding the use of AI in e-waste management.

Quantitative analysis (PLS-SEM using SmartPLS 4): Test the hypothesized model between legal framework dimensions (IVs), IS capability & use (mediator) and effectiveness of AI-based e-waste management (DV), with planned moderator (e.g., institutional collaboration/Vision 2030 context). The procedure includes: Evaluation of the measurement model: indicator reliability (loadings $\geq .70$, where possible), internal consistency (Cronbach's $\alpha \geq .70$ /Compositeness $\geq .70$), convergent validity (AVE $\geq .50$), discriminant validity (HTMT $< .85/.90$). The analysis of the structural models included collinearity checks of path coefficients (β) and bootstrapping (5000 subsamples), as well as the relationships between Awareness of AI and e-waste Management (AIWM) as the dependent variable and National Legislation on e-waste and AI, Regulatory Enforcement Mechanisms, Institutional Responsibilities, Legal Incentives and Support for AI Adoption, and Compliance with International Standards as the independent variables. This hybrid analytical approach allows for the triangulation of legal coherence and stakeholder narratives with evidence based on hypotheses and models, providing a comprehensive and policy-relevant analysis of the legal enablement of AI in the management of e-waste in Saudi Arabia.

3.4. Data Collection Procedures

The data will be gathered in two complementary ways: Legal and Policy Documents: Government portals, official gazettes, and ministry's archives will be used to get legal and policy documents. Reports from institutions in the Kingdom (SDAIA, MWAN, and MEWA) will be systematically entered into the database for analysis. Questionnaire Survey: A structured questionnaire will be created with closed-ended questions (Likert scale) to measure awareness, perceptions and readiness and open-ended questions to allow elaboration and recommendations. The survey will be sent via an e-mail to a purposive sample of stakeholders, such as policymakers, regulators, technologists, waste management operators and academics.

3.5. Tools of Analysis

The quantitative data were analysed using the method of Partial Least Squares Structural Equation Modelling (PLS-SEM) with the use of SmartPLS 4 software. The tool was selected because it was appropriate for testing complicated models involving multiple latent variables, and medium sample size. The measurement model was tested on reliability and validity of the instruments while the structural model was tested on the relationship between variables using the SmartPLS software and bootstrapping to test the significance of the path and mediating effects. Besides, using WordClouds.com to visually analyse open-ended responses. The qualitative data were cleaned and translated, then all the text was uploaded to the platform, so that the size of the words corresponds to the frequency with which they occurred and their importance in the themes. The visualization was used to capture important themes and to give a comprehensive and

understandable overview of the core themes of the participants and to support the thematic analysis.

4. Findings and Discussion

4.1. Students perform legal and policy document analysis. Students conduct legal & policy document analysis.

In the first phase, the legal and policy framework of Saudi Arabia regarding the management of e-waste and the introduction of AI technologies was analysed. Institutional access to internal archives and unpublished reports was not possible, but a large amount of analysis was conducted using publicly accessible and authenticated secondary sources, which gave good insights into the current legal framework. Documents reviewed comprised official documents, royal decrees, environmental policies published by the MOWA, SDAIA, MEWA and CST. The Kingdom has put in place a comprehensive regulatory framework for waste management in general under the Waste Management Law (2021) and supporting executive regulations, but has not yet adopted a specific legislation for e-waste management. The results also indicate that Saudi Vision 2030 is a key factor in the development of national strategies as it introduces sustainability, digital innovation, and circular economy concepts into environmental governance, thereby supporting the Vision. The focus on waste reduction and recycling, along with resource efficiency, aligns the programs to a vision that fosters an environment conducive to AI-based solutions. SDAIA's publications emphasized the NSDAI, which became active in 2020, and is dedicated to the proper use of AI and the advancement of smart technologies in environmental application. Documents from CST also featured projects under the Digital Sustainability Program that will promote the adoption of innovative solutions such as drone technology, sensors and data analytics for better waste tracking and environmental compliance. The Saudi policies were benchmarked against the international policy frameworks such as the UNEP, OECD, the World Bank and EU WEEE Directive. The lessons learned from these comparative references encompassed learning how to use the most successful regulatory models, such as e-waste control solution and digital traceability, and cross-border solutions for e-waste across the EU. Comparative review has revealed that the direction of Saudi policy is quite comparable to the international sustainability policies in terms of its direction and that detailed provisions of the role of AI in the operations, accountability and data governance of the e-waste management are still at their infancy. All recovered documents were analysed, catalogued and authenticated as to their authenticity systemically, and based on the metadata: Date of publication, issuing authority, document origin. As a whole, this phase demonstrated that Saudi Arabia has a robust strategic and institutional roadmap to generate AI solutions in the waste management industry and an identified policy agenda on Vision 2030. It has also highlighted the absence of specific legal aspects on AI in the e-waste management framework, calling for further development of legislation that allows enhanced utilization of AI technologies in environmental governance, thereby promoting efficient, transparent, and ethical use of the technology.

4.2. The study comprised a doctrinal approach in order to assess the coherence, sufficiency and enforceability of the current Saudi legislation and regulatory system to handle e-waste and the implementation of AI in pollution control systems. Among the main national authorities, this interpretative analysis focused on the texts of the law and policies, namely that of the Waste Management Law (2021), the laws and policies of the Ministry of Environment and Water (MEWA), the Ministry of Water and Sanitation (MWAN), the Saudi Data and AI Authority (SDAIA) and the laws and policies of the CST. Table 2 reveals that the doctrinal review reveals that the Saudi Arabian waste management and environmental sustainability legal context is comparatively broad and general with no specific expression in legislation for waste management and AI based technologies. The Waste Management Law (2021) provides general guidance on waste classification, licensing and compliance, but does not explicitly identify e-waste as a category of waste or include AI-based tools and mechanisms such as automated waste sorting, AI-based digital traceability and sensor-based monitoring of waste. The lack of dedicated clauses in such policies means there is a lack of clarity in waste management when it comes to the ethical and operational strategies of AI tools. In addition, it was observed that there were ambiguities within the institutional mandates, for example, institutional roles in licensing, enforcement and reporting of data in MEWA and MWAN are not well defined and there was no cross reference with data governance framework from SDAIA.

The NSDAI provides strategic advice on integrating AI across multiple industries but does not have any regulatory frameworks in place to ensure accountability or liability for AI systems if they malfunction, suffer a data breach or the algorithm misfunctions. This means that enforcement is predominantly based on principles rather than operations, and depends on the discretion of the enforcement bodies. As far as legal enforceability is concerned, the review concluded that Saudi Arabia's system is based on a centralized administrative system, which helps in making policies more coordinated and efficient in implementation, but which can also hinder fast adaptation to new technologies. Enforcement provisions are included in the overall compliance provisions that focus more on compliance with requirements for waste generators and handlers, but do not address the AI system developers, operators or data controllers. The absence of a formal chain of responsibility can lead to problems when determining who should be accountable for harms to the environment resulting from AI, such as if a person is misclassified in an AI-driven waste classification system or fails to report the waste. Saudi Arabia's strategy was found to be comparable in intent to international sustainability strategies in the Saudi Arabia's instruments, such as the EU WEEE Directive (2012) and the Basel Convention (1989) and the OECD Extended Producer Responsibility (EPR) Guidelines (2001), in terms of sustainability goals, and more developed in terms of procedures. The EU and OECD standards define particular operating conditions including producer take-back obligation, reporting and cross-border tracking of e-waste, with technological monitoring systems. The Saudi system, on the other hand, relies more on the policy goals and activities of the voluntary compliance system. The doctrinal interpretation also was progressive, however. The national programs also specifically refer to AI and digital tools in the context of enhancing waste monitoring and efficiency in waste recycling, for example in the Digital Sustainability Program by CST (2023) and in the Circular Economy Strategy by MWAN. So far, the developments show that it is a long road until a

final set of laws will be enacted, specifically dedicated to the use of AI, but an awareness of the policy and the readiness of the institutions is good progress.

4.3. Qualitative Results

4.3.1. The Measurement Model and the Structural Relationships were evaluated.

The results of the SmartPLS support the statistical and theoretical soundness of the measurement model. Table 3 shows that all constructs have good reliability, convergent validity and discriminant validity, which means they can be used in the structural model. The moderate R^2 value (0.445) suggests that the joint effect of legal and institutional variables accounts for almost half of the variation in Awareness of AI and E-Waste Management. Good governance, such as legislation and enforcement mechanisms, showed positive relationships in the case of Legislation, Enforcement Mechanisms, and International Compliance, indicating that these factors drive AI use in waste management. In contrast, low or negative scores for Institutional Responsibilities and Legal Incentives indicate the absence of institutional coordination and/or weak incentive systems. Overall, the findings suggest that improving the legislative and enforcement landscape in Saudi Arabia can significantly improve e-waste governance using AI in Vision 2030. The results of the Structural model suggest that the most significant and statistically robust predictors of the stakeholders' awareness of AI and e-waste management in Saudi Arabia are national legislation and adherence to international standards. The positive coefficient of National Legislation ($\beta = 0.325$, $p = 0.029$) further indicates that strong, clear, and communicated legislative frameworks boost institutional and public understanding of AI tools for environmental practices. Likewise, Compliance with International Standards ($\beta = 0.302$, $p = 0.037$) shows that the institutions' compliance with international standards (Basel Convention, EU WEEE Directive) is associated with higher awareness and policy coherence. Positive but not statistically significant, the same applies to Regulatory Enforcement Mechanisms ($\beta = 0.272$, $p = 0.072$), indicating that the enforcement is not always consistently applied, or even well supported and backed up by monitoring mechanisms. The low or null beta values of Institutional Responsibilities ($\beta = -0.145$, $p = 0.464$) and Legal Incentives ($\beta = -0.010$, $p = 0.956$) suggest that there is limited role ambiguity within institutions and little effect of incentives, so far, to support effective engagement with AI-based waste management systems. A qualitative analysis was conducted using word cloud. The word cloud visualization shows the most prevalent concepts in the participants' perspectives on AI-powered e-waste management in Saudi Arabia. The key terms, AI, Waste, Air Pollution, Heavy Metals, and Risks, indicate a shared understanding of the importance of AI in mitigating environmental and health risks stemming from e-waste. There is a high level of concern for toxic exposure and societal issues such as Groundwater Contamination, Endocrine Disruptors, Children, and Workers are mentioned many times. Words like Governance, Liability, Licensing, and Incentives highlight the importance of a well-established legal and regulatory structure that will hold AI entities accountable, promote ethical usage and provide support from within the institutions.

The use of terms such as Sensors, Drones, Alerts and Recycling indicate participants' understanding of the potential AI technology can offer to improve monitoring and compliance, and recycling efficiency. The terms Lack of Awareness, Unsafe Handling, and Technical Capacity, however, point to the perceived issues in public education, infrastructure and institutional readiness. The presentation as a whole tells a balanced story where the participants understand that while AI can be a technological tool, it is also a component of the larger governance landscape needed to ensure environmentally sustainable, legally compliant and socially responsible e-waste management that aligns with Saudi Vision 2030.

5. Conclusion

The study involved a doctrinal, policy and empirical analysis of the legal and institutional framework of the use of artificial intelligence (AI) in the management of e-waste in Saudi Arabia. The results show that Saudi Arabia has laid a solid ground for its strategic approach to waste management under the Waste Management Law (2021), NSDAI (2020), and other environmental programs, however, the current legal framework is not very specific and detailed in the e-waste and AI governance field. Through the doctrinal analysis it was established that, although national laws in the field of sustainability and digital transformation exist, there are no specific provisions that address the AI-related waste classification, data accountability and algorithmic liability. The inconsistencies between the operations of MEWA, MWAN and SDAIA and CST also reduce the clarity of operations and the effectiveness of enforcement.

The empirical results supported the findings of the SmartPLS model, which showed that the national legislation and compliance with international standards have a significant impact on awareness and readiness for AI-based e-waste management, whereas weak institutional roles and underdevelopment of incentive mechanisms have a negative impact on the implementation of AI-based e-waste management. Moderate explanatory power indicates that almost half of the variance in AI awareness is attributed to the legal and governance factors. The qualitative results corroborate this: stakeholders are familiar with the potential of AI in the waste management sector but also stress the importance of more precise legislation, effective enforcement, better training and awareness.

The recommendations, limitations, and future research are as follows:

- This research presents a set of strategic policy and legal suggestions to enhance the regulatory and institutional capacity of Saudi Arabia to operate with AI in e-waste management:
- Adopt a specific E-WASTE and AI INTEGRATION LAW, categorizing e-waste, assigning responsibilities for AI systems and applying the Extended Producer Responsibility (EPR) approach with digital traceability.
- Improve regulatory enforcement with the help of AI-driven compliance monitoring, standardisation of data reporting, and the acceptance of digital evidence.

Establish a cross-sectoral AI-AI-Environment Task Force between MWAN, MEWA, CST and SDAIA with a view to coherence in the policy execution.

Suggest legislation and funding models to promote the use of AI in recycling and monitoring systems, including innovation grants, tax incentives, and regulatory sandboxes.

Improve regional and international cooperation, establish consistency between national environmental standards and Basel Convention, OECD EPR guidelines and EU WEEE directive, and lead the digital environmental governance in Saudi Arabia.

Start investing in institutional and technological readiness, especially capacity-building, human capital building and enhancement of infrastructure for the use of AI in the context of sustainability.

To wrap up, Saudi Arabia's journey towards sustainable, AI-driven e-waste management will require the conversion of strategic goals into actionable, flexible, and enforceable laws. The Kingdom can take a leadership role in the region by closing the legislative gaps and enhancing institutional coordination to meet the sustainability goals of Vision 2030 through digital innovation that is environmentally responsible.

Although the study has been methodologically sound, and the design has been triangulated, there are a number of limitations. First, because of the use of SmartPLS and cross-sectional data, it allows for gaining insights into associations and predictive relationships, but not for drawing causal inferences over time. It would be useful to have longitudinal data to explore how changes in legislation and institutional practice affect AI use in the waste sector. Second, a Saudi Arabian legal and institutional context has been used as the scope of the study. International benchmarks (EU WEEE Directive, Basel Convention, OECD EPR) were applied for comparisons, but may not be applicable to jurisdictions with varying legal and policy maturities. Lastly, the findings are subject to a temporal constraint, as both AI and environmental policies are constantly changing and new ones are anticipated as a result of the Vision 2030.

This research could be extended in future studies to investigate the changing legal, institutional and technical aspects of AI in e-waste management in Saudi Arabia. It is recommended to conduct longitudinal studies to track the impact of new policies and reforms introduced under Vision 2030 over a period of time to understand how this affects the implementation and sustainability of AI. Advanced jurisdictions, like the EU and Singapore, could serve as a source of best practices and transferable models for harmonizing the governance of AI and environmental regulation. Furthermore, institutional and case-based studies are required to explore the impact of inter-agency coordination and capacity-building on the actual application of AI in waste management, such as in agencies like MWAN, SDAIA, MEWA and CST.

Tables

Table 1. Variables and constructs.

Type	Variable / Construct	Key Dimensions or Indicators
Dependent	Effectiveness of AI-Based E-Waste Management	Efficiency, adoption rate, environmental impact reduction, cost-effectiveness
Independent	Legal Framework	National legislation; Enforcement mechanisms; Institutional roles; Incentives & legal support; International alignment; Implementation mechanisms; Institutional & technological readiness

Table 2. Doctrinal legal analysis outcomes.

Legal / Policy Instrument	Key Strengths	Identified Gaps or Weaknesses	Recommended Legal or Policy Action
Waste Management Law (2021)	Establishes general framework for waste classification, licensing, and compliance; supports Vision 2030 sustainability goals.	Does not explicitly define e-waste as a separate category; lacks reference to AI-based waste monitoring or automated systems.	Amend law to include a dedicated E-Waste Chapter with clear definitions, classification criteria, and technological provisions (AI, IoT, sensors).
Executive Regulations of Environmental Protection	Provides environmental standards for pollution control and waste management activities.	Limited coverage of digital systems, data sharing, and AI applications in environmental enforcement.	Introduce clauses on digital traceability, AI-based compliance monitoring, and data interoperability across institutions.
National Center for Waste Management (MWAN) Circular Economy Strategy	Promotes recycling, waste valorization, and resource efficiency.	Absence of binding provisions for integrating AI or robotics in waste processing; weak enforcement mechanisms.	Issue implementing regulations linking circular economy targets with AI-driven recycling technologies and performance KPIs.
Saudi Data & AI Authority (SDAIA) - National Strategy for Data and AI (NSDAI 2020)	Establishes national AI vision, governance principles, and ethical guidelines; promotes digital transformation.	Not legally binding; lacks sector-specific mandates or accountability mechanisms for AI misuse in environmental applications.	Enact a National AI Governance Law clarifying liability, data protection, and certification standards for AI tools used in environmental management.
Communications, Space & Technology Commission (CST) - Digital Sustainability Program (2023)	Encourages adoption of smart technologies, sensors, and drones for sustainability; strong alignment with Vision 2030.	Early-stage program; lacks harmonisation with waste management regulations or inter-agency coordination framework.	Develop a Cross-Sectoral AI-Environment Task Force to ensure coordination between CST, MWAN, MEWA, and SDAIA.
Saudi Vision 2030 Framework (2016)	Provides high-level commitment to sustainability, innovation, and circular economy principles.	Non-legislative in nature; strategic but lacks operational enforcement tools or measurable environmental AI indicators.	Translate Vision 2030 environmental goals into legally enforceable regulatory measures and AI-specific implementation policies.

Legal / Policy Instrument	Key Strengths	Identified Gaps or Weaknesses	Recommended Legal or Policy Action
Basel Convention (1989) (International Benchmark)	Global framework for hazardous waste control and transboundary movement.	Does not directly regulate AI or data-driven technologies.	Use Basel guidelines as a baseline for cross-border data and e-waste traceability requirements in national legislation.
EU WEEE Directive (2012) (International Benchmark)	Provides a model for Extended Producer Responsibility (EPR), digital traceability, and reporting obligations.	Contextual adaptation is required for the Saudi legal and institutional setting.	Localize the EPR model, mandate producer responsibility, smart labeling, and digital monitoring of e-waste flows.
OECD EPR Guidelines (2001) (International Benchmark)	Outlines best practices for waste producer accountability and sustainability.	Voluntary framework; not fully adopted nationally.	Adopt OECD principles into Saudi environmental law to enhance accountability and resource recovery.

Table 3. Measurement model and construct statistics.

Construct	AIWM	Cronbach's alpha	Composite reliability (rho_a)	Average variance extracted (AVE)	R-square	HTMT
Awareness of AI and e-waste Management (AIWM)		0.797	0.807	0.622	0.445	
National Legislation on e-waste and AI	0.325	0.76	0.793	0.589	0.445	0.737
Regulatory Enforcement Mechanisms	0.272	0.679	0.74	0.525	0.445	0.787
Institutional Responsibilities	-0.145	0.824	0.827	0.663	0.445	0.598
Legal Incentives and Support for AI Adoption	-0.01	0.828	0.835	0.664	0.445	0.591
Compliance with International Standards	0.302	0.854	0.865	0.697	0.445	0.677

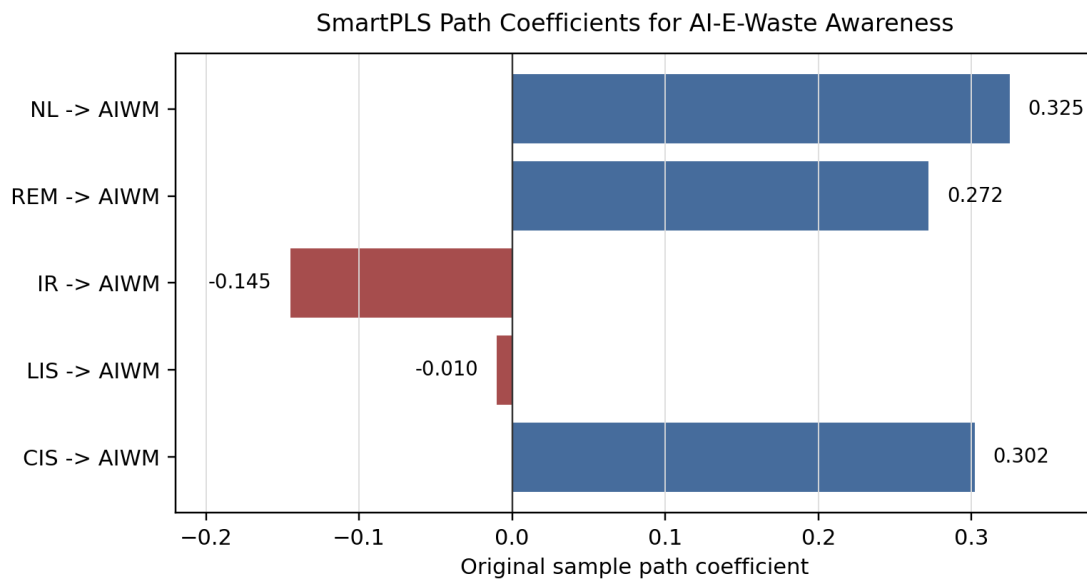
Table 4. SmartPLS bootstrapping results.

Relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
NL -> AIWM	0.325	0.315	0.149	2.185	0.029

Relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
REM -> AIWM	0.272	0.308	0.151	1.801	0.072
IR -> AIWM	-0.145	-0.177	0.198	0.732	0.464
LI -> AIWM	-0.01	0.039	0.178	0.055	0.956
CwIS -> AIWM	0.302	0.273	0.145	2.086	0.037

Figures

Figure 1. SmartPLS path coefficients for legal and institutional predictors of AI-e-waste awareness.



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Data statement

The study is based on legal, policy and perception-based research data. The datasets analysed during the study are available from the corresponding author upon reasonable request, subject to ethical and confidentiality restrictions.

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