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Towards Sustainable Hazardous Waste Management:

**A Multi-Criteria Decision-Making Approach for
Hazardous Waste Site Selection: Integrating AHP and
Monte Carlo Simulation in the Malaysian Context**

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Thesis submitted to the University of Nottingham
for the Master of Philosophy
April 2025

Abstract

This research presents a decision-support framework for hazardous waste treatment site selection by integrating the Analytic Hierarchy Process (AHP) with Monte Carlo Simulation. Malaysia serves as the case study, with findings intended to inform both national and global applications in developing countries facing similar challenges. A ten-criterion Hazardous Waste Management (HWM) index was developed to reflect the multidimensional aspects of site suitability—spanning environmental, social, economic, regulatory, and technical factors. Stakeholder input was gathered through structured pairwise comparisons with three groups: industry players, broader industrial stakeholders, and academic researchers. AHP was used to derive priority weights for each criterion, while Monte Carlo Simulation tested the robustness of the results under uncertainty. The findings reveal a strong emphasis on industry output, economic viability, and regulatory compliance across groups, with variations in the importance of environmental and social factors. Monte Carlo results validated the stability of top-ranked criteria and highlighted sensitivity in lower-ranked ones. This study contributes a replicable, adaptable framework that supports transparent, data-informed infrastructure planning. It enhances decision-making in hazardous waste management and aligns with broader goals of circular economy and sustainable development.

List of Publications:

1. **Mei Kuen Wang**, Hon Loong Lam, Towards Sustainable Hazardous Waste Management : A Circular Economy Approach : 4th Swinburne Sarawak Postgraduate Research Conference 2023 (SSPRC2023) Conferences – 3rd to 4th August 2023 , Swinburne Sarawak Campus, Malaysia, Paper no. 178.
2. **Mei Kuen Wang**, Juin Yao Lim, Yi Jing Chan, Hon Loong Lam, Sustainable Hazardous Waste Management: Smart and Innovative Solutions for Malaysia's Resilient Future: Journal of Hazardous Material [submitted].
3. **Mei Kuen Wang** , Hon Loong Lam , Hazardous Waste Site Selection by HWM Index using Analytic Hierarchy Process (AHP) Method : PRES'2024 , 25th – 28th August 2024, Xian, China, Paper no.0276.
4. **Mei Kuen Wang**, Juin Yao Lim, Yi Jing Chan, Hon Loong Lam, A Decision Support Model for Hazardous Waste Site Selection : AHP-Monte Carlo Hybrid Approach Sustainable Production and Consumption [submitted].

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Abbreviation

CAGR – Compound annual growth rate

DOSM – Department of Statistics Malaysia

MIDA – Malaysia Investment Development Authority

GDP – Gross domestic product

EPA – Environmental Protection Agency

US – United States

DOE – Department of environmental

EQA – Environmental quality act

HW – Hazardous waste

ECN – Electronic Consignment Note

GWMO – global waste management outlook

PoPs – Persistent Organic Pollutants

NGO – Non-Governmental Organization

MENGO – Malaysia Environmental Non-Governmental Organization

ESWIS – Electronic Scheduled Waste Information System

CE – Circular Economy

NCP – National Cleanliness Policy

WGs – Waste Generator

QC – Quality Control

WAC – Waste Acceptance Criteria

GHGs – Greenhouse gases

UNECE – United Nation Environment Program

GWMO – Global Waste Management outlook

SDGs – Sustainable Development Goals

DoOSH – Department of Occupational Safety and Health

OHSA – Occupational Health Safety Administration

NEPA – National Environmental Policy

CERCLA – Comprehensive environmental response, compensation, and liability act

PPA – pollution prevention Act

HCCO – Hazardous chemicals control ordinance

SWOT – Strengths Weakness opportunities Threats

WEEE – Waste Electrical and Electronic Equipment

EU – European union

Mt – Metric Tonnes

SW – Scheduled Waste

HW2W – Hazardous Waste to Wealth

IWTF – Integrated Waste Treatment Facilities

WtE – Waste to Energy

Chapter 1

Introduction

1.1 Introduction

Hazardous waste comprises materials that pose significant risks to human health or the environment due to toxic, corrosive, flammable, reactive, or infectious properties. Internationally, definitions and transboundary controls are guided by the BASEL CONVENTION and related UN frameworks (UNEP, 2021) . In Malaysia, such wastes are regulated as *scheduled wastes* under the ENVIRONMENTAL QUALITY ACT 1974 and the ENVIRONMENTAL QUALITY (SCHEDULED WASTES) REGULATIONS 2005, which prescribe classification, handling, transport, treatment, and disposal requirements supported by licensing and enforcement mechanisms (DOE, 1974) .Globally, hazardous waste generation is substantial yet uneven across regions, reflecting industrial structure, regulatory maturity, and reporting practices. Industrialised economies generate tens of millions of tonnes annually—for example, Germany reported 22.3 million tonnes in 2007, while China recorded 14.3 million tonnes in 2009 (UNEP, 2021). Developing economies, including Malaysia, also contribute significantly; Malaysia reported 1.7 million tonnes in 2009, compared with around 1.8 million tonnes in Thailand and 0.49 million tonnes in Singapore during the same period (UN, 2025). Hazardous sub streams such as e-waste are rising rapidly with digitalisation, adding toxic metals and persistent organics to the global burden and complicating end-of-life management (EEA, 2003; Ismail and Hanafiah, 2019) . The societal costs of

mismanaged waste are mounting. Global assessments estimate direct waste management expenditures at USD 252 billion in 2020, with broader environmental, health, and climate damages increasing total costs to USD 361 billion (UNEP, 2024) . Without intervention, costs may rise to USD 640 billion annually by 2050, whereas circular economy strategies could generate net benefits of USD 108 billion (World Bank, 2022). Methane emissions from dumpsites further link waste management to climate change, underscoring the urgency of circular solutions (Bogner, 2007).

Malaysia's hazardous (scheduled) waste profile reflects accelerated industrialisation, supply chain integration, and expanding healthcare services. In 2020, industries generated 7.18 million tonnes of scheduled waste—a 79% increase from 4.01 million tonnes in 2019 (DOSM, 2022). Clinical waste also rose from 33.8 to 39.9 thousand tonnes in the same period, with Selangor contributing nearly 25% of the total (DoSM, 2022). These shifts reflect both structural industrial drivers and episodic shocks, including COVID-19, that intensified clinical waste streams (FDES, 2021).

Malaysia's governance framework is comprehensive compared to regional peers. The Environmental Quality Act 1974 and the Scheduled Wastes Regulations 2005 establish cradle-to-grave controls, including generator responsibilities, transporter registration, prescribed premises licensing, and import/export restrictions aligned with Basel Convention obligations (DOE, 2005). Additional guidance supports co-processing, contaminated land

management, and automotive treatment facilities. Classification systems are harmonised with the Globally Harmonised System (GHS), ensuring consistent hazard communication (FDES, 2021; Fikri et al., 2015). Manufacturing is the principal contributor to scheduled waste, followed by healthcare, agriculture, and households. Increasing product complexity (e.g., electronics, chemicals) raises hazardous constituents across streams. Constraints common in developing contexts—such as infrastructure gaps and uneven enforcement—heighten risks if not addressed through capacity building and investment (MIDA, 2021a). The Kim Kim River pollution incident in Johor in 2019 illustrates the health and reputational consequences of inadequate hazardous waste controls, where chemical dumping exposed thousands to toxic fumes (DOSM, 2021; Jessie Yeung, 2020a). Malaysia’s hazardous waste generation is comparable to Thailand and exceeds Singapore, though below larger industrial economies such as China and India (UN, 2025). This suggests opportunities for Malaysia to adapt best practices from both advanced systems and regional peers, particularly in data harmonisation, treatment infrastructure, and cross-border stewardship (MIDA, 2021b; Schilling, 2017).

The convergence of rising hazardous waste volumes, escalating societal costs, and heightened health and climate risks makes this research urgent. Strengthening upstream prevention, monitoring, and end-of-life pathways—embedded within circular economy strategies—can reduce risk while unlocking economic value (UNEP, 2024; World Bank, 2022). By situating Malaysia’s challenges within global and regional trajectories, this study aims to generate actionable insights that support regulatory refinement, infrastructure planning,

and industry adoption of circular practices, directly contributing to the Sustainable Development Goals (SDG 3, SDG 12, SDG 13) (Ministry of Economy, 2021).

1.2 Problem statement

Hazardous waste management presents a complex policy and planning challenge across both developed and developing nations. The uneven distribution of treatment infrastructure, coupled with rapid industrial expansion, has made it increasingly difficult for many countries to manage growing volumes of hazardous waste effectively (UNEP, 2024). Transportation risks, environmental degradation, and strong public resistance to facility siting further complicate planning effort.

In Malaysia, scheduled waste rose sharply to 7.2 million tonnes in 2020, a 79% increase from 2019 (DOSM, 2022; eSWIS, 2024). While the regulatory framework under the Environmental Quality Act 1974 and Scheduled Wastes Regulations 2005 is comprehensive, implementation continues to face challenges, including enforcement gaps, uneven facility distribution, and reliance on costly long-distance waste transport (Hamzah et al., 2022).

Despite the recognized need for new infrastructure, the process of selecting appropriate sites is often hindered by a lack of structured and transparent

decision-making tools. Existing approaches in Malaysia and elsewhere rely heavily on expert intuition or fragmented assessments that fail to capture the full spectrum of environmental, social, and economic considerations (MIDA, 2023; MoE, 2021).

There is therefore a need for an integrated, multi-criteria framework that not only captures the complexity of site selection but also incorporates uncertainty analysis. Such a framework should be adaptable across national contexts, enabling informed and defensible decisions for hazardous waste facility planning that align with sustainability objectives and the Sustainable Development Goals (SDGs 3, 12, and 13)(UNEP, 2024; World Bank, 2023) .

1.3 Research objective and scope

The primary objective of this research is to develop structured and adaptable decision-making framework for hazardous waste treatment site selection that integrates both the Analytic Hierarchy Process (AHP) and Monte Carlo Simulation. This framework is designed to be globally applicable, offering a replicable model that can be tailored to different national or regional contexts.

A central component of the study is the development of a ten-criteria Hazardous Waste (HWM) index, which reflects environmental, social, technical, and regulatory priority in facility siting. While Malaysia serves as the empirical

focus of this research, the methodology itself is not context-bound. It is intended to offer a generalizable tool that supports evidence-based decision-making in any country facing similar hazardous waste infrastructure challenges.

1.4 Research question and contribution of research

To guide the direction of this study and ensure a clear research purpose, the investigation is structured around two central questions:

What are the most relevant and context-sensitive criteria for evaluating hazardous waste treatment plant sites within a structured and scalable decision-support framework?

How can the integration of the Analytic Hierarchy Process (AHP) and Monte Carlo Simulation improve the robustness and reliability of site selection decisions under conditions of uncertainty and expert subjectivity?

In addressing these questions, this research makes both methodological and practical contributions to the field of environmental infrastructure planning and hazardous waste management. It introduces a comprehensive Hazardous Waste Management (HWM) Index composed of ten evaluation criteria spanning environmental, social, economic, regulatory, and operational dimensions. This index provides a flexible and adaptable foundation for site evaluation, capable of being tailored to diverse national priorities and regional contexts.

Methodologically, the study presents a novel integration of AHP and Monte Carlo Simulation, two complementary tools that together offer a rigorous yet practical means of incorporating expert judgment while addressing uncertainty a persistent challenge in environmental decision-making. The AHP is employed to derive stakeholder-informed weights for the HWM criteria, while Monte Carlo Simulation is used to assess the stability of these weights and the sensitivity of resulting site rankings. This combination enhances the defensibility and transparency of infrastructure decisions, especially in data-limited contexts. Practically, the study contributes a transferable decision-support framework that can inform infrastructure planning not only in Malaysia, but also in other developing or transitional economies.

Chapter 4 expands on Malaysia's hazardous waste landscape through in-depth analysis, including national projections, policy gaps, SWOT assessment, and innovation strategies. Chapter 5 applies the HWM Index in combination with AHP and stakeholder-specific analysis to prioritize criteria for treatment plant siting. Chapter 6 concludes the study with strategic insights and outlines a future research agenda focused on GIS integration, stakeholder inclusion, and circular economy advancement.

By bridging methodological rigor with practical applicability, this research offers a replicable model for transparent and sustainable hazardous waste site selection. It supports global efforts in environmental protection, circular economy implementation, and responsible industrial development, while

contributing to the discourse on evidence-based environmental planning in emerging economies.

1.5 Structure of the thesis

This thesis is organized into five chapters. Chapter One introduces the research context, outlines the problem, presents the research questions, and highlights the structure of the study. Chapter Two reviews the existing literature on hazardous waste management, site selection methodologies, and multi-criteria decision-making techniques, with an emphasis on AHP and Monte Carlo Simulation. Chapter Three describes the methodology used in the study, including the development of the HWM index and the integration of AHP and Monte Carlo methods. Chapter Four presents and interprets the results of the case study conducted in Malaysia. Chapter Five concludes the thesis with a summary of key findings, implications, limitation, and recommendation for future research and policy development.

Chapter 2

Literature Review

2.1 Literature review

This chapter provide a comprehensive review of the existing literature in the field, offering insights into the scope of the industry and identifying areas with research gaps. By delving into prior research, this review aims to establish a profound understanding of the current state of knowledge while pinpointing areas that require further exploration. This not only ensures that the study is well-informed but also positions it to make a significant contribution to the field. Additionally, the literature review sets the research context and establishes a framework for interpreting the study's results.

2.2 Historical background on circular economy

The Circular Economy (CE) concept has been around for many years and has evolved over time (Adami and Schiavon, 2021) . The most recent version of CE was formalised in 2013, and it comprises four key elements: switching from the “end-of-life” concept to the “restoration” concept, pursuing the use of renewable energy sources, forgoing the use of toxic compounds, and striving to reduce waste by rearranging the production and supply processes (Winans et al., 2017). At its core, CE seeks to maximise material flow recycling while

balancing economic growth with sustainable resource utilisation (Zhu et al., 2010). The CE strategy revolve around the 3R principles :reduce, reuse, and recycle.

One of CE's notable advantages is its potential to break the connection between environmental vulnerability and financial constraint (Cheng et al., 2019). As the global population continues to grow, waste management poses increasing challenges for both developed and developing countries. However, developing nations , often constrained by limited resources , face even greater difficulties (Asase et al., 2009).

2.3 Overview of hazardous waste management

Hazardous waste management has emerged as a critical concern in both developed and developing countries due to the increasing complexity and volume of industrial, medical, and chemical waste (Kumar et al., 2023). Globally, the growth of manufacturing, energy production, and urban expansion has intensified the demand for systems capable of managing of managing toxic and hazardous substances (Qian et al., 2022a). Ineffective handling of such waste poses serious threats to environmental integrity, human health, and long-term economic resilience. As international bodies such as the United nations Environment Programme (UNEP, 2015) and the World Health Organization (WHO, 2018) emphasize, the need for comprehensive regulatory frameworks and treatment infrastructure is becoming increasingly urgent.

Countries with mature regulatory systems have adopted integrated approaches that emphasize waste minimization, strict licensing, and the use of advanced technologies for treatment and disposal (Trevisan et al., 2021). For instance, the European Union (EU, 2025) operates under the Basel Convention (Basel, 2011) and the Waste Frame Directive (European, 2023), which together promote the reduction of hazardous waste substances at the source, safe transboundary movement, and lifecycle-based management (BRS, 2025). In contrast, many developing countries still face challenges in enforcement , infrastructure availability, and institutional coordination, leading to faps between policy design and on-the-ground implementation (Schilling, 2017).

Malaysia, as an upper-middle-income and rapidly industrializing country, is facing rising pressure to strengthen its hazardous waste management framework (MIDA, 2021b). The country's primary regulation, the Environmental Quality (Scheduled Waste) Regulation 2005 (DOE, 2005), classifies and governs hazardous waste under the broader Environment Quality Act 1974 (DOE, 1974). According to the Department of Environment (NRES, 2025), Malaysia generated over 5.9 million metric tons of Scheduled Waste in recent years, primarily from the manufacturing, petrochemical, and electronic sectors (DOSM, 2022). This trend reflects not only industrial growth but also the increasing complexity of waste streams requiring specialized treatment (MIDA, 2021a).

The existing hazardous waste infrastructure in Malaysia includes several licensed treatment and disposal facilities, which the first and most prominent being Kualiti Alam in Negeri Sembilan (KA, 2018). However, the distribution and capacity of such facilities remain uneven. This has resulted in logistical inefficiencies and reliance on long-distance transportation which introduces additional risks and costs (Anwar, 2020). Moreover, enforcement challenges and occasional instances of illegal dumping suggest that regulatory oversight, while present, still faces implementation hurdles (Jessie Yeung, 2020a).

Efforts to enhance hazardous waste management in Malaysia are underway, which initiative focusing on improving data collection, tightening enforcement, and encouraging public-private partnerships. Additionally, the Twelfth Malaysia Plan (2021-2025) outlines the importance of sustainability and environment resilience, including measures to strengthen waste-related infrastructure (MoE, 2021). However, there remains a gap in strategic planning tools that can guide infrastructure expansion and site selection based on a transparent, evidence-based approach.

This study situates itself within the gap, aiming to support national planning efforts by proposing a structured, adaptable framework for evaluating hazardous waste treatment site suitability. Although tailored to Malaysia's conditions, the framework is designed with flexibility in mind, allowing it to be applied in broader contexts where similar environmental, logistical, and policy challenges exist.

2.4 Hazardous waste management issue in global

2.4.1 Available Acts and initiatives

Hazardous waste management is a global challenges that requires necessitates international cooperation and adherence to various acts and initiatives. The Global Waste management outlook (GWMO), a collaboration between the International Waste Management Association and United Nations Environment Programme, promotes a comprehensive approach to waste management, highlighting its role in sustainable development and climate change mitigation (Wilson and Velis, 2015) . Similarly, the Global Chemicals and Waste Indicator Review Document enhances nations' ability to monitor progress towards Sustainable Development Goals (SDGs) indicators related to chemicals and hazardous waste (United Nations Environment Programme, 2021).

Numerous global acts and initiatives address hazardous waste management , such as Global Waste Management Outlook, a joint initiative that serves a global assessment of waste management and a call to action. It emphasises a holistic approach to waste management , recognising its significance in sustainable development and climate change mitigation (Wilson and Velis, 2015).

In Malaysia, hazardous waste management aligns with international standards but is primarily governed by local legislation rooted in the Environmental Quality Act of 1974. This act has undergone revisions to address contemporary

challenges in hazardous waste management. The Hazardous Waste Rules of 2016 offer detailed protocols for handling such wastes, including classification, packaging, storage, transportation, treatment , and disposal procedures (DOE, 2014).

Additional regulations complement there rules by providing specific guidance on various aspects of hazardous waste management. For instance, the Environmental Quality (Prescribed Premises)(Scheduled Waste Treatment and Disposal Facilities) Order of 1989 identifies premises requiring a license to operate hazardous waste treatment and disposal facilities. The Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order of 2015 mandates environmental impact assessment for specific hazardous waste-related activities.

The Occupational Safety and Health Act of 1994 prioritises the safety and health of workers exposed to hazardous waste or associated risks (DoOSH, 1994). Malaysia also engages in international cooperation by adhering to the Basel Convention (Basel, 2011). **Table 1** provides an overview of the legislation and conventions related to hazardous waste management in Malaysia and other regions.. While the current legal framework is robust and dynamic, there exist opportunities for further improvement, such as raising public awareness, reinforcing enforcement mechanisms, and promoting sustainable practices.

Table 1 – relevant act for hazardous waste management in term of legislation and conventions between Malaysia and others

Act / convention	Country / region	Year	Scope and focus	References
Clean air act	United States	1963	Air pollution control and prevention	(OAR US EPA, 2015)
National Environmental Policy Act (NEPA)	United States	1970	Environmental impact assessment	(OP US EPA, 2013a)
Occupational Safety and Health Administration (OSHA)	United States	1970	Occupational health and safety, including hazardous waste management	(OP US EPA, 2013b)
UNEP	Global	1972	Coordination of environment programs	(UNEP, 2018)
Environmental Quality Act	Malaysia	1974	Environment protection and management	(DOE, 2001)
Resources Conservation and Recovery Act	United States	1976	Management of hazardous waste and solid waste	(OLEM US EPA, 2015b)
Comprehensive environmental response, compensation, and liability Act (CERCLA)	United States	1980	Clean-up of hazardous waste sites and liability for pollution	(OECA US EPA, 2013)
Montreal protocol	Global	1987	Ozone-Depleting Substances (ODS)	(UNEP, 2018)
Basel convention	Global	1989	Transboundary movement and disposal of hazardous wastes	(“Basel Convention,” 2011)
Pollution Prevention Act (PPA)	United States	1990	Pollution prevention and reduction	(OCSPP US EPA, 2013)
Hazardous chemicals control ordinance (HCCO)	Hong Kong	1992	Control of import, export, and use of hazardous chemical	(EPD, 1992)
Hazardous substance act	Thailand	1992	Control and management of hazardous substance	(MOI, 1992)

Table 1 (Continue) – relevant act for hazardous waste management in term of legislation and conventions between Malaysia and others

Act / convention	Country / region	Year	Scope and focus	References
Occupational Safety and Health Act *	Malaysia	1994	Occupational health and safety	(DoOSH, 1994)
Stockholm convention	Global	2001	Persistent Organic Pollutants (POPs)	(UNIDO, 2001)
The waste electrical and electronic equipment (WEEE) directive	European Union	2003	Management and disposal of electronic waste	(EEA, 2003)
Rotterdam convention	Global	2004	Prior Informed Consent (PIC)	(UEP, 2004)
Environment quality (Scheduled Waste) regulation	Malaysia	2005	Management of Scheduled Waste	(DOE, 2005)
EU Waste framework directive	European Union	2008	Waste Management and Recycling	(ECHA, 2008)
The Hazardous waste rules	Malaysia	2016	Management, handling, and transboundary movement of hazardous waste	(EiMAS, 2015)

2.4.2 Methods and technologies for hazardous waste management analysis of developed and developing countries

Hazardous waste management is a global challenge that requires international cooperation and adherence to various acts and initiatives. Hazardous waste can take various forms – liquids, solids, gases, and sludges – and poses risks to both human and environmental health. Such waste required specialised handling and disposal procedures, and proper segregation is essential. Inadequate management could jeopardise both human health and the surrounding ecosystem (Mmereki et al., 2016). Therefore, the implementation of proper labelling and storage practices is crucial., as they ensure compliance with established rules and regulations for the responsible management of hazardous waste (DOE, 2014).

The methods and technologies available for hazardous waste management , depending on the type, composition ,and characteristics of the waste. **Table 2** provides an overview of some of the common methods. They include landfill with containment system, incineration for thermal treatment, waste-to-energy technology, physical-chemical treatment, biological treatment, recycling and resources recovery, on-site treatment by industries, and advanced technology development (El-Saadony et al., 2023). These methods and technologies differ in terms of their description, practicality , recovery rates , initial investment costs, suitable hazardous waste types, potential improvements, and references.

Hazardous waste is characterised by its potential harm to human health or the environment, and encompasses materials that are flammable, corrosive, reactive, or toxic (EPA, 2020). Classification schemes for hazardous waste are provided by international standards and regulations, such as the European Waste Catalogue (EEA, 2023).

Various sources generate hazardous waste, including industrial processes , healthcare, agriculture, and households. Mismanagement of hazardous waste can lead to several environmental and health risks (Farrokhi-Asl et al., 2020). For instance , hazardous waste can contaminate water resources, damaging aquatic life, while exposure to hazardous waste can lead to serious health conditions (CELITRON, 2022a).

Management strategies for hazardous waste range from traditional methods like landfilling and incineration to modern approaches like recycling and recovery (Qian et al., 2022a). Each method presents its own set of advantages and limitation. Regulations governing hazardous waste management aim to mitigate its environmental and health impacts (EPA, 2020). Effective management of hazardous waste is impeded by several challenges, ranging from technological limitations to societal issues and policy gaps (MIDA, 2021b).

Analytic Hierarchy Process (AHP) has been used as a robust multi-criteria decision making method for solving decision-making problems in different sectors, such as social, government, and corporate sector (Silva López et al.,

2022). It has been applied in assessing hazardous waste management proposals to give the most sustainable design proposal of hazardous waste. AHP helps to give a sustainable hazardous waste proposal that can be used for the improvement of hazardous waste management (Zarin et al., 2021).

Table 2 Analysis of hazardous waste treatment technologies: descriptions, practicality, efficacy, economic investment, applicability to waste types, and prospects for technological improvement.

Method / Technology	Description	Practicality	Recovery Rate	Initial Investment Cost	Suitable Hazardous Waste Types	Potential Improvements	References
Landfill with containment system	Engineered barriers isolate hazardous waste from the environment using physical, chemical, and biological barriers	Widely used; limited processing required.	Variable depending on containment efficiency and waste type.	Moderate, primarily for containment infrastructure.	Non-reactive and stable waste; non-recyclable materials	Enhance liner and leachate management; implement advanced monitoring system.	(Cherubini et al., 2009; Donevska et al., 2021; El-Saadony et al., 2023)
Incineration for Thermal Treatment	High-temperature combustion destroys hazardous properties and reduce waste volume.	Widely used; effective for certain waste types.	Depends on combustion efficiency and waste composition.	High, due to incinerator equipment and emission control.	Organic and combustible waste; medical and pharmaceutical waste.	Improve energy recovery; optimize emissions control for reduced environmental impact.	(Abd Kadir et al., 2013; Oppelt, 1987)
Waste-to-Energy (WtE) Technologies	Pyrolysis, gasification, anaerobic digestion converts hazardous waste into energy	Varier based on technology; energy recovery potential.	Variable depending on technology and waste composition.	Moderate to high, depending on technology complexity.	Organic and combustible waste; biomass	Enhance energy recover efficiency; explore co-generation possibilities.	(Alao et al., 2022; Amirul, 2022; Asian Development Bank, 2020)

Table 2(Continue) analysis of hazardous waste treatment technologies: descriptions, practicality, efficacy, economic investment, applicability to waste types, and prospects for technological improvement.

Method / Technology	Description	Practicality	Recovery Rate	Initial Investment Cost	Suitable Hazardous Waste Types	Potential Improvements	References
Physical-chemical treatment	Chemical processes neutralize or remove hazardous properties	Widely applicable; effective for specific pollutants	Depends on treatment efficiency and waste characteristics	Moderate, for chemicals and sand equipment	Hazardous liquid; heavy metal - contaminated waste.	Develop specialized processes for targeted pollutants; optimize chemical dosages.	(Adetunji and Olaniran, 2021; Yusuf et al., 2023)
Biological treatment	Microorganisms break down hazardous substances into less harmful forms	Effective for organic waste; slower treatment	Depends on waste biodegradability and treatment conditions	Low to moderate, for equipment and process control	Biodegradable organic waste; wastewater sludge.	Optimize treatment conditions for faster degradation; explore microbial enhancement.	(Yusuf et al., 2023)
Recycling and resources recovery	Recover valuable components from hazardous waste.	Variable depending on waste type and recovery technology	Varies based on recycling processes and waste composition	Variable depending on recycling infrastructure	E-waste; precious metal bearing waste.	Improve sorting and recycling technologies; enhance material recovery rates	(Adetunji and Olaniran, 2021, 2021; Jerry A, 2023; Mohammed et al., 2013; “Waste treatment and recovery,” 2016; “Waste treatment and recovery,” 2016)

The 4R concept- Reduce, Reuse, Recycle , and Recovery – is a cornerstone for sustainable waste management, as it facilitates the transition toward a circular economy and adherences to the waste management hierarchy (Abhay, 2021). The 4R concept aims to minimize the generation of hazardous waste from various sources and mitigate the associated risks to human health and the environment (UNECE, 2022). It also maximised the resources utilisation across all phases of hazardous waste management, thus harmonising with the core tenets of both circular economy and the waste management hierarchy (Biakhmetov et al., 2022). To achieve better environment outcomes and align with global sustainability goal, significant challenges must become overcome in transitioning to more environmental friendly hazardous waste management practices objectives (MIDA, 2021a). A representation covering the approach in shown in **Figure 1**.

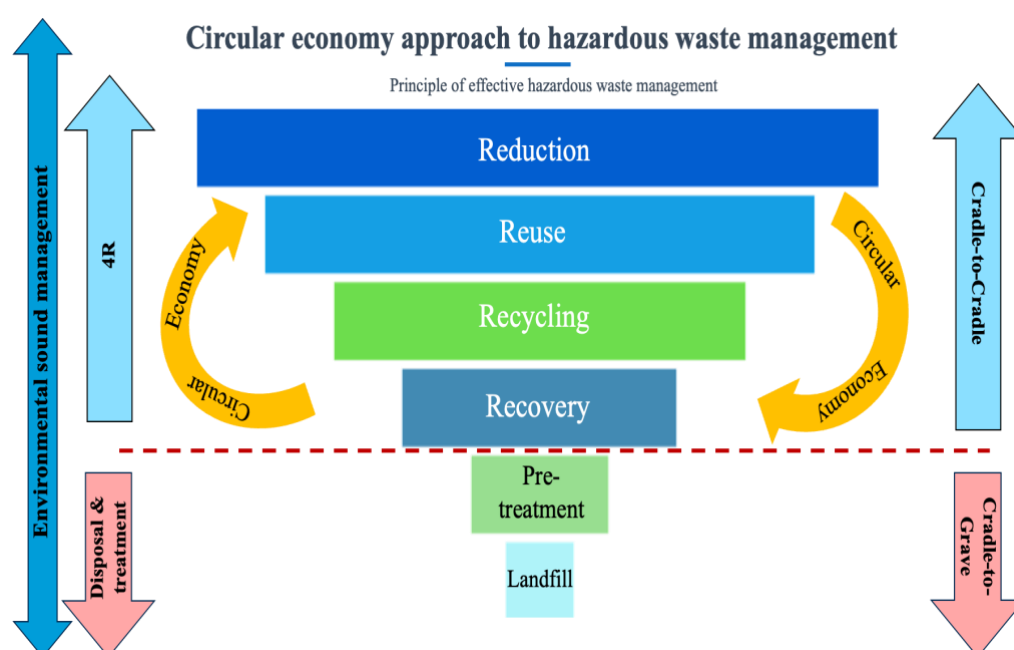


Figure 1 Hierarch of hazardous waste management with respective *solution* at each stage covering the 4Rs with pre-treatment and landfill

Methods and technologies available for hazardous waste treatment are linkage to the circular economy. The circular economy is a concept that aims to minimise waste and maximise resource efficiency by designing products and systems that can be reused, repaired, recycle , or recovered. Some of the methods that align with this concept are recovery, refinement, separation, and biological methods, as they transform hazardous waste into valuable products or by-products (UNECE, 2022). These methods also reduce the environmental impact of hazardous waste disposal and save energy an cost.

However, these methods also have some challenges, such as high initial investment , energy consumption, technical complicity and potential secondary pollution. Therefore, it is important to consider the type, quality and quantity of waste oil, as well as the local conditions, needs, and capacities, when choosing the most suitable method for hazardous waste treatment. **Table 3** summarises some of the methods and their characteristics , benefits, challenges, and circular economy link.

Table 3. Summaries some of the methods and their characteristics, benefits, challenges, and circular economy link.

Methods	Description	Benefits	Challenges	Circular Link	Economy	References
Physical methods	Techniques exploiting differences in density or charge between oil and water.	Cost-efficient; low operational costs	Potential for large sludge volumes ; 60-90% efficiency	Efficient use of resources but requires further processing	of sludge	(Osman et al., 2018)
Advanced methods	Use of membranes, catalysts, oxidants, or electric currents to separate or break down oil.	High removal efficiency (>90%); degrades complex compounds	High costs; energy needs ; potential for equipment fouling.	Highly suitable for high-concentration waste oil	efficient, waste	(Adetunji Olaniran, 2021)
Recovery methods	Methods to retrieved oil from solid waste, e.g., sludge	Waste volume reduction ; new product potential.	High costs; potential for secondary pollutants	Transforms waste into valuable products, emphasising waste reduction.	into products, waste	(Mohammed et al., 2013)
Biological Methods	Natural degradation of waste oil through organisms	Eco-friendly; produces benign by-products.	Slower; might require treatment.	Emphasise natural degradation, converting waste to beneficial by products	natural	(Singh and Singh, 2019)
Refinement	Refinement to recover base oil	Prolongs oil lifecycle ; reuse potential.	Energy-intensive; potential emissions.	Directly recycles waste oil, exemplifying waste – to -value principle	recycles oil, waste	(Lam et al., 2016)
Separation	Centrifugation for oil separation	Efficient recovery; minimal waste	Equipment and energy needs	Highlights reutilisation of resources, minimising waste generation	Highlights reutilisation of resources, minimising waste generation	(Sathasivam et al., 2016)

Table 3 (Continue) summaries some of the methods and their characteristic, benefits, challenges, and circular economy link.

Methods	Description	Benefits	Challenges	Circular Link	Economy	References
Flocculation	Chemical method that uses flocculants to neutralise and clump oil droplets for separation	Simple and effective ; energy consumption	Requires optimal dosage and pH; generates sludge	Efficient use of resources but requires further processing	use of sludge	(Mostefa and 2004) Tir,
Membrane bioreactor	Biological method that combines a biological reactor and a membrane for oil degradation and filtration	Eco-friendly; high removal efficiency (>90%); produces reusable water	High membrane fouling; requires treatment	Emphasises degradation, converting waste to beneficial by products	natural waste to products	(Scholz and 2000) Fuchs,

Developed countries have access to more advanced and diverse technologies for hazardous waste management , such as incineration , gasification, pyrolysis, chemical treatment, biological treatment, and landfill gas recovery. These technologies can effectively reduce the volume, toxicity and environmental impact of hazardous waste, as well as recover energy and materials from waste (Liu et al., 2018). However, they also required high capital , operational , and maintenance costs, as well as skilled personnel and strict emission control. Developing countries, on the other hand ,rely mostly on low-cost and low-tech options, such as dumping ,landfilling, composting and recycling. These options are more accessible and affordable, but they also have limitation, such as low efficiency, high environmental pollution, low resource recovery ,and potential health hazardous (Cheng et al., 2019). Therefore, there is a need for technology transfer and innovation to enable developing countries to adopt more sustainable and appropriate technologies for hazardous waste management, taking into account their local conditions, needs an capacities.

2.4.3 Hazardous waste to wealth (HW2W)

The concept of hazardous waste to wealth (HW2W) concept advocates for the transformation of waste into valuable resources, aligning perfectly with the Circular Economy (CE) framework. The CE aims to extend the lifespan of materials, which resonates with Malaysia's efforts to improve waste separation, recycling facilities, and overall waste-to-wealth programs (MIDA, 2021b).

These initiatives are also align with the objectives set forth in the National Cleanliness Policy (NCP) 2019 (PMO, 2019).

Adequate financial resources are critical for the effective management of hazardous waste. Insufficient funding is a significant barrier, particularly in economically disadvantaged countries with limited capital for waste management infrastructure (Diaz, 2017). This shortfall extends to infrastructure and technology, hindering the efficient handling, disposal, and comprehensive management of hazardous waste.

The success of waste management practices is closely tied to the geographical location of hazardous waste generation and treatment. The lack of appropriate waste treatment and disposal facilities in densely populated areas often leads to elevated transportation costs, logistical issues, and potential hazards to both the community and the environment, largely due to poor siting practices (EPA, 2020).

Transporting hazardous waste becomes complex due to inadequate logistic arrangements, leading to challenges in meeting regulatory requirements, potential environmental contamination, and compromised oversight (Salihoglu, 2010; Zhao and Ke, 2019). Significant logistical obstacles emerge in the transportation, monitoring, and tracking of hazardous waste due to infrastructural and resource constraints.

Inefficient collection methods lead to the containment of hazardous waste issues at its source, leading to improper disposal, illegal dumping, and poor segregation (Jessie Yeung, 2020b; Otwong et al., 2021a; White and Heckenberg, 2011). Particularly in informal and rural areas, effective hazardous waste management is crucial and relies heavily on efficient waste collection. Inadequacies in these areas give rise to potential health risks, environmental pollution, and instances of noncompliance instances.

Limited awareness among stakeholders, including waste generators (WGs) and communities, further complicates responsible waste management (Hamzah et al., 2022). This affects individuals' willingness to engage in hazardous waste reduction , reuse, recycling ,and recovery efforts, as well as how hazardous waste is perceived. Transforming it from a burden into a valuable resource requires addressing these challenges comprehensively.

The challenges hindering successful HW2W efforts are summarised in **Table 4**, offering unique opportunities for improvement and the promotion of sustainable hazardous waste management practices.

Table 4: Bridging current gaps to a sustainable hazardous waste management.

AREA	CURRENT GAP	POSSIBLE SOLUTION	EXAMPLES
CAPITAL	Inadequate financial resources for management	Increase funding from government and private sector; explore cost-effective solution prioritizing environmental protection	Government grants, green financing, waste reduction
LOCATION	Unsuitable sites for treatment and disposal	Develop location-specific strategies prioritizing community engagement, community engagement, environmental protection, and social equity	Community-based waste management programs
LOGISTICS	Poor infrastructure for transportation	Develop sustainable transportation solution prioritizing safety and efficiency	Hazardous waste collection centers, recycling programs
AWARENESS	Low awareness and knowledge about hazards	Implement effective awareness strategies prioritizing community engagement and participation	Environmental education programs, public awareness
COMPLIANCE	Lack of enforcement and monitoring	Strengthen regulation, penalties for non-compliance, improve inspection systems	Monitoring and inspection system, penalties for non-compliance

2.5 Impact of hazardous waste on environmental and human health

The disposal of hazardous waste in developing countries has extensive and far-reaching impacts on both the environmental and human health. Sustainable hazardous waste management practices are being introduced to mitigate environmental damage, including the release of climate-altering pollutant gases such as greenhouse gases (GHGs) and ammonia emission. The management of medical waste is particularly risky (IRCR, 2011). Hazardous material originating from industrial processes pose potential risks to human health.

Contaminants like heavy metals, which enter the food chain due to improper hazardous waste disposal and the release of metal-laden industrial effluents into drainage systems or open dumping sites, present a host of challenges (Abdullah, 1995; Jessie Yeung, 2020b; Vesilind et al., 2013). These challenges encompass chemical poisoning through inhalation, stormwater blockage leading to flooding, adverse impacts on birth weight, increased incidence of cancer, congenital deformities, neurological disorders, and symptoms such as nausea and vomiting. Additional risks involve mercury toxicity from fish consumption, plastic ingestion by wildlife, accelerated algal growth in aquatic ecosystems, and degradation of water and soil quality (Gill and Mix, 2020; Järup, 2003; Manay, 2023; Walker et al., 2013).

An overview on the source of contamination due to waste mismanagement with the concept of circular mitigation strategies is shown in **Figure 2**. These strategies aim to transform the linear process of waste generation and disposal

into a circular model (with example shown with used tires and electrical equipment), where waste is minimized, and any waste that is produced is reused, recycled, or recovered. The transition towards a circular economy not only mitigates the environmental and health impacts of hazardous waste but also contributes to sustainable development by promoting resource efficiency and reducing reliance on virgin materials. Essentially, the figure underscores the importance of transitioning from traditional waste management practices towards a circular economy approach to mitigate the impacts of hazardous waste on the environment and human health.

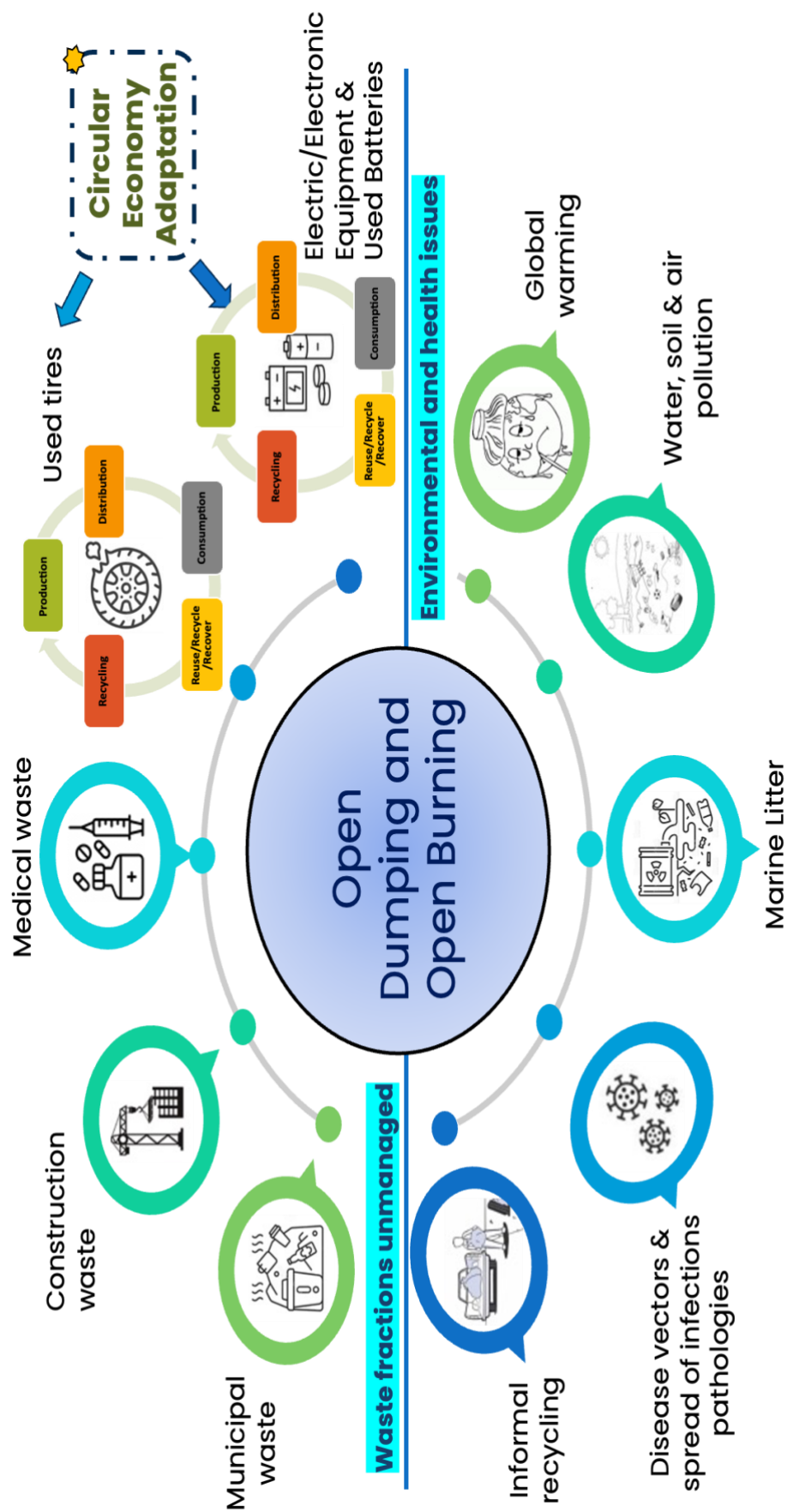


Figure 2 Sources of contamination that let to ineffective hazardous waste mismanagement and potential upgrade with circular economy.

2.6 Overview of hazardous waste in Malaysia

Hazardous waste management is a critical and pressing issue in Malaysia, which is experiencing rapid economic growth and industrialisation. As the nation's economy expands, various industries emerge and flourish, leading to increased waste production, posing significant environmental and health challenges. Consequently, developing and implementing effective waste management strategies to address these concerns is imperative. In this context, Malaysia's scheduled waste management sector assumes great importance. It plays a vital role in regulating and overseeing the proper handling, storage, transportation, and disposal of hazardous waste. The economic environment of Malaysia, driven by industrial growth and technological advancements, has contributed to the rising waste generation. As such, robust waste management practices are crucial to safeguard the environment and public health.

To effectively manage hazardous waste, Malaysia has established national legislation and regulations. These legal frameworks provide guidelines and standards for waste management activities, ensuring industry compliance and accountability. By adhering to these laws, Malaysia aims to mitigate the adverse impacts of waste on the environment and human well-being. Balancing economic progress with sustainable waste management practices is essential for Malaysia's continued development. It requires a collaborative effort between industries, government bodies, and society to promote responsible waste management practices, raise awareness, and foster a culture of environmental stewardship. However, this economic growth has contributed to increased waste

production, requiring robust waste management practices to safeguard the environment and public health.

Hazardous waste management in Malaysia is governed by the Environmental Quality Act 1974 and the Environment Quality (Scheduled Waste) Regulation 2005. Over the past three decades, Malaysia has addressed waste management challenges by enacting legislation, adopting new technologies, and developing infrastructure networks. Despite these regulations, managing hazardous waste still faces obstacles such as inadequate infrastructure, limited technical expertise, and a lack of public awareness.

To comprehensively address scheduled waste management in Malaysia, a holistic approach is necessary (Jamin and Mahmood, 2015). The hazardous waste to Wealth (HW2W) framework offer a solution by promoting a sustainable and circular economy (CE). This framework emphasises reducing the environmental impact of scheduled waste and unlocking economic opportunities through resource recovery. Note that the implementation of the CE principles requires transformative changes in business activities, including strategic choices, business models, and processes.

Malaysia's diversified and robust economy plays a significant role in Southeast Asia, with a strong industrial base, particularly in electronics, automotive, and petroleum products. However, rapid economic development has led to

environmental degradation and increased scheduled waste generation. The harmful effects on human health and the environment must be reduced by effective and sustainable scheduled waste management (Aja et al., 2016a). To facilitate the circular business approach, CE principles are crucial (Uvarova et al., 2023).

Malaysia's commitment to environmental sustainability is evident through the development of the Strategic Plan 2020-2030: Environmental Sustainability (Ministry of Economy, 2021). This plan set clear goals and targets for achieving environmental sustainability, encompassing areas like climate change and mitigation, sustainable consumption and production, biodiversity conservation, and sustainable waste management. Furthermore, collaboration among stakeholders is essential to realise the objectives outlined in the plan and ensure the preservation of Malaysia's environment.

With the country experiencing rapid economic growth and industrialisation, effective waste management strategies are crucial to tackle the environmental and health challenges posed by increasing waste production. By examining the background and developments of the scheduled waste management industry in Malaysia, exploring the regulatory framework, and analysing the current state of waste management practices, this study aims to clarify the current difficulties and prospects.

Any waste product that poses a significant risk to the environment, human health or both is referred to as hazardous waste. It contains substances that are toxic, flammable, corrosive, reactive, or otherwise harmful (Jamin and Mahmood, 2015). Note that hazardous waste can come from various sources, including industrial activities, manufacturing processes, commercial establishments, healthcare facilities, and households (Aja et al., 2016a).

Classification of hazardous waste is typically based on regulatory frameworks of the Environment Quality Act and Environment Quality (Scheduled Waste) Regulation in Malaysia. These regulations provide criteria for identifying and categorising hazardous waste based on its properties, such as toxicity, flammability, and persistence.

Hazardous waste exhibits specific characteristics that require specialised management (Lee et al., 2022a). These characteristics include toxicity, ignitable, corrosive, and reactive, containing substances that can cause harm to living organisms and the environment. Moreover, ignitable waste is flammable and can easily catch fire. Corrosive waste has high acidity or alkalinity and can corrode or damage materials. Reactive waste is chemically unstable and can potentially explode or release toxic gasses when exposed to other substances.

Hazardous waste can originate from various sources, including industrial processes such as chemical manufacturing, metal plating, and pharmaceutical

production. It can also result from commercial activities such as automotive maintenance, painting, and electronic waste disposal. Other than that, healthcare facilities generate hazardous waste through medical procedures, laboratory testing, and the use of hazardous chemicals. Even households contribute to hazardous waste by improperly disposing of household chemicals, batteries, and electronic devices.

The inappropriate management of hazardous waste can affect the environment and human health. When hazardous waste is not managed, stored, or disposed of properly, it can contaminate soil, water bodies, and air. This contamination can lead to the degradation of the ecosystem, the loss of biodiversity, and the pollution of drinking water sources. Furthermore, exposure to hazardous waste may severely harm human health. By understanding the definition, classification, characteristics, sources, and environmental and health impacts of hazardous waste is crucial for developing effective management strategies. Hence, by comprehensively assessing their aspects, policymakers, waste management authorities, and other stakeholders can implement measures to mitigate the adverse effects of hazardous waste and promote sustainable waste management practices.

2.6.1 Regulatory framework of hazardous waste management in Malaysia

In response to increasing industrial pollution in the 1960s, Malaysia enacted the Environmental Quality Act 1974 (Act 127), which was gazette on 14 March and came into force on 15 April 1974. This legislation marked a significant milestone in the country's environmental governance, providing a legal foundation for the prevention, control, and abatement of pollution, as well as for broader environmental protection and enhancement initiatives.

Subsequently, in 1975, a dedicated federal enforcement agency known as the Environment Division was established under the Ministry of Housing and Local Government. This agency was tasked with implementing environmental legislation and overseeing pollution control across the country. In 1976, the Environment Division was restructured under the Ministry of Science, Technology and the Environment, and in 1983, it was formally renamed the Department of Environment (DoE). Today, the DoE operates under the Ministry of Natural Resources, Environment and Climate Change, and remains the principal authority for environmental regulation and enforcement in Malaysia.

In the mid-1980s, as environmental concerns intensified—particularly regarding the handling of industrial and hazardous wastes—the government introduced more specific legal instruments to regulate the management of scheduled (hazardous) waste. These efforts culminated in 1989 with the promulgation of several key regulations and orders under the Environmental Quality Act. These include:

- Environmental Quality (Scheduled Wastes) Regulations 1989
- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Regulations 1989
- Environmental Quality (Prescribed Premises) (Scheduled Wastes Treatment and Disposal Facilities) Order 1989

Together, these legal instruments provide a regulatory framework for the generation, storage, transportation, treatment, and disposal of hazardous (scheduled) wastes in Malaysia. They also establish licensing requirements for prescribed premises, set technical standards for waste handling, and define the responsibilities of waste generators and facility operators. The development and enforcement of these regulations represent a significant evolution in Malaysia's hazardous waste management system, aligning national policy with international environmental norms and promoting safer and more sustainable industrial practices.

2.6.2 Involvement in an International Agreement

The international treaty known as the Basel Convention aims to reduce the hazards of handling hazardous waste and ensure that it is handled and disposed of in an environmentally conscious way. Note that the Transboundary Movement of Hazardous Wastes between Developing Countries is governed by the Convention. The agreement was established in reaction to the 1980s rise in

the price of disposing of toxic waste and the subsequent rise in the export of waste from developed to developing nations.

Malaysia acceded to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal on 8 October 1993, and the Convention entered into force domestically on 6 January 1994. The Department of Environment (DOE) is designated as the competent authority responsible for the enforcement of the Convention's provisions in Malaysia. To ensure compliance, the government amended both the Customs (Prohibition of Import) Order 1988 and the Customs (Prohibition of Export) Order 1988, under the Customs Act 1967, to incorporate the list of controlled wastes outlined by the Basel Convention.

As part of the national implementation strategy, Malaysia established a policy framework to regulate the transboundary movement of scheduled wastes. This framework includes several key provisions. Firstly, the importation of scheduled wastes for the purpose of recovery or final disposal is strictly prohibited. Secondly, scheduled waste importation is permitted only for direct reuse or as an alternative raw material, and only when such waste is not locally available. Thirdly, scheduled waste exportation is allowed under specific conditions, including: (a) if the receiving country possesses superior recovery technology; (b) if a higher recovery rate can be achieved abroad compared to local facilities; or (c) if no technical capacity exists domestically to treat or recover the waste in question.

In line with the Basel Convention's Ban Amendment, Malaysia has also prohibited the importation of scheduled wastes from all parties that are members of the Organization for Economic Cooperation and Development (OECD), the European Commission (EC), and Liechtenstein. This reflects the country's commitment to uphold the principles of environmental responsibility and to minimize risks associated with the cross-border movement of hazardous materials.

2.6.3 Birth of the first hazardous waste management facility in Malaysia

The birth of the first centralised scheduled waste management facility in Port Dickson, Negeri Sembilan, Malaysia, was a significant step in developing the country's waste management infrastructure. Kualiti Alam Sdn. Bhd (KASB), a consortium of Malaysian and Danish Companies, was awarded the exclusive right to implement and operate the facility for 15 years by the government.

The facility, completed in June 1998, was the first of its kind in the region and was designed to collect, transport and dispose of (Incineration and Landfilled) scheduled waste in a Cradle-to-Grave (C2G) manner. Note that the facility excluded the management of explosives, radioactive, and clinical wastes.

Establishing this facility was a critical step towards achieving sustainable waste management in Malaysia, and it helped to address the increasing amount of waste generated by industries.

2.6.4 Classification and identification of hazardous waste

The categorization of hazardous waste based on distinct physical properties serves as a cornerstone for managing its inherent complexities (Jerry A, 2023). Multiple discernible parameters are involved in classifying hazardous waste. For instance, the United States Environmental Protection Agency (US EPA) identifies four fundamental characteristics : ignitability, corrosivity, reactivity, and toxicity (US EPA, 2015). Similarly, Malaysia's Department of Environment has provided exhaustive guidelines that cover a broad range of categories including corrosive, explosive, infectious , flammable liquids, flammable solids, organic peroxides, oxidising substances, solids that are spontaneously combustible, solids that are dangerous when wet, toxic substances, and amalgamation of varied has hazardous components (DOE, 2014) . A list of the classification of hazardous waste are shown in Supplementary Material: **Table 5**.

Central to this discourse is the regulatory backbone for the hazardous waste classification in Malaysia (known as scheduled waste) principally embodied in the Environmental Quality Act and Environmental Quality (Scheduled Waste) Regulation. These legal instruments not only set forth the overarching guidelines but also articulate comprehensive criteria set for identifying and categorizing hazardous waste based on inherent attributes like toxicity, flammability, and persistence (Lee et al., 2022b). Within this framework, specific attributes such as toxicity, ignitability, corrosivity, and reactivity serve as defining factors. Each of these traits presents unique challenges and

consequences, such as the potential for toxic wastes to harm ecosystems, the capacity for corrosive wastes to deteriorate materials, and the inherent instability of reactive wastes that could result in explosive or noxious emissions upon interaction with other substances (CELITRON, 2022b).

Hazardous waste can emanate from a myriad of activities and sources, including but not limited to industrial processes such as chemical manufacturing, metal refining, metal finishing and coating, cement production, petroleum refining, and the electrical and electronics industries (Che Jamin and Mahmood, 2015). Furthermore, commercial activities like auto maintenance involving the use of solvents, oils, and paints generate hazardous waste. Medical procedures, laboratory activities, the utilization of dangerous chemicals, and the improper disposal of items like household chemicals, batteries, and electronic gadgets also add to the hazardous waste burden (Adetunji and Olaniran, 2021).

However, the ramifications of hazardous waste spill over beyond the source into both environmental and human health contexts. Improper management, storage, or disposal can lead to soil, water, and air contamination, resulting in ecological degradation, loss of biodiversity, and pollution of vital water sources (Qian et al., 2022b). Moreover, exposure to hazardous waste can have severe health implications, including but not limited to cancer, respiratory issues, skin conditions, and reproductive disorders. Therefore, this paper accentuates the necessity for effective hazardous waste management strategies. It highlights the imperative for policymakers, waste management authorities, and stakeholders

to collaborate in mitigating these adverse effects. The discussion underscores the critical importance of adopting waste management practices that are environmentally sound, socially responsible, and economically sustainable while addressing the specific challenges posed by hazardous waste on both environmental and human health fronts.

Table 5 Hazardous waste classification and characteristics in Malaysia as proposed by DOE (2014)

Hazardous Waste Characteristic	Pictogram hazard	Definition	Example
Corrosive substances		Waste that can corrode or dissolve metals or other materials	Acidic waste (e.g., battery acid), alkaline waste (e.g., drain cleaners)
Explosive substances		Waste that can cause an explosion	Explosives, pyrotechnic waste
Infectious substances		Waste containing microorganisms or their toxins that can cause disease in humans or animals	Biological waste, contaminated sharps
Inflammable liquids		Waste that can easily catch fire or support combustion	Flammable liquids (e.g., gasoline, paint thinners)
Inflammable solids		Waste that can easily catch fire or support combustion	Flammable solids (e.g., matches, fireworks)
Oxidizing substances		Waste that provides oxygen and can cause or enhance the combustion of other materials	Oxidizing agent (e.g., hydrogen peroxide, nitric acid)
Organic peroxides		Waste that contains organic compounds with an oxygen-oxygen bond	Organic peroxides used in chemical processes
Solid: spontaneously combustible		Solid waste that can ignite and burn spontaneously	Self-heating substances (e.g., oily rags)
Solid: dangerous when wet		Solid waste that can emit flammable gases when in contact with water	Water-reactive substances (e.g., sodium, potassium)
Toxic substances		Waste that contains substances or compounds that can be harmful to human health or the environment	Hazardous chemicals (e.g., pesticides, heavy metals), radioactive waste, biological waste
A mixture of miscellaneous dangerous substances		Waste that is a combination of different hazardous substances	A mixture of various hazardous chemicals and waste with multiple hazards.

and permitting of hazardous waste management facilities, which are governed by the Department of Environment (DOE) under the Environmental Quality Act 1974 and its related regulations. These facilities play a crucial role in ensuring the safe handling, treatment, recovery, and disposal of hazardous waste in accordance with national standards and international best practices (Aja et al., 2016a). The country's hazardous waste infrastructure includes a variety of facility types, each serving distinct but complementary functions. One of the core facilities is the Special Waste Management Facility, which offers integrated treatment services for both hazardous and general waste. These facilities are designed to provide comprehensive end-to-end waste management solutions, including collection, treatment, and final disposal, thereby minimizing environmental impact.

On-site waste storage facilities, typically located within industrial premises, enable companies to temporarily store and, in some cases, pre-treat hazardous waste before it is transported to off-site facilities. These facilities are particularly important for managing small volumes of hazardous waste or waste generated continuously during production processes. In parallel, off-site storage facilities are licensed to manage hazardous waste from multiple sources and ensure safe containment until sufficient capacity or processing schedules are available. Both types of storage facilities are vital in preventing environmental contamination and ensuring traceability throughout the waste handling chain.

Local off-site recovery facilities are also part of the licensed ecosystem. These facilities focus on material recovery, converting waste into reusable materials or by-products. Their operation supports the implementation of Cradle-to-Cradle (C2C) design principles and reinforces Malaysia's transition towards a Circular Economy-Life Cycle Assessment (CE-LCA) approach. By prioritizing recovery over disposal, these facilities contribute to waste minimization, resource efficiency, and long-term environmental sustainability.

Specialized treatment infrastructure is also in place for clinical waste, which includes items such as contaminated medical tools, expired pharmaceuticals, and clinical chemicals. Licensed clinical waste treatment facilities handle this category of waste in accordance with strict safety and hygiene protocols to protect human health and the environment. These facilities are crucial for healthcare institutions and other entities generating biohazardous waste streams.

Two major operators—Kualiti Alam Sdn. Bhd. and Trienekens (Sarawak) Sdn. Bhd.—serve as national benchmarks for integrated hazardous waste management. Kualiti Alam operates a centralized incineration and landfill facility in Peninsular Malaysia, offering comprehensive waste treatment services across multiple categories. Trienekens, based in Sarawak, plays a similar role in East Malaysia, ensuring the safe, environmentally sound treatment and final disposal of hazardous waste in the region. These licensed operators are essential in providing the technological capacity and logistical infrastructure necessary for national-level hazardous waste governance. Overall,

the licensing and permitting of hazardous waste facilities in Malaysia not only ensure regulatory compliance but also underpin the country's commitment to sustainable development and environmental stewardship. By supporting the ethical and efficient management of hazardous materials, these facilities form a vital part of Malaysia's long-term environmental protection strategy.

The summary for all the scheduled waste licenses issued in Malaysia is as given in **Table 6** below:

Table 6 Type of facilities used to treat hazardous waste (scheduled waste) from Malaysia

No	Type of Facilities Used to Treat Malaysia's Scheduled Waste	Function of Facility	References
I	Special Waste Management Facility	The facility where scheduled waste can be managed together with general waste.	(DOE, 2005)
II	On-Site Treatment Facility	Facility owned by the company that generates the waste.	(DoE, 2015)
III	Local Off-site Recovery Facility	Facility where waste is recovered into items that can be reused or sold.	
IV	On-site Storage Facility	The facility where waste is stored for the time being until there is capacity to process it.	
V	Off-site Clinical Waste Facility	A facility that manages clinical waste only, which includes waste like medicine, medical tools, clinical chemicals and more.	
VII	Foreign Facility (Export)	Malaysian waste is exported overseas for processing.	
VIII	Kualiti Alam Sdn. Bhd	Incinerator and Landfill Site.	(Cenviro, 2023)
VIII	Trienekens (Sarawak) Sdn. Bhd	Incinerator and Landfill Site.	(Trienekens, 2024)

Overall, in the year 2022, there were approximately 300 registered hazardous waste management companies with the Department of Environment (Eswis, 2019), primarily holding licenses for operating off-site hazardous waste management facilities (Prescribed Premises) and clinical waste disposal facilities. Malaysia classifies hazardous waste into 77 categories under the Environmental Quality Act (DoE, 2019). Additionally, transportation of hazardous waste requires a separate license (Aja et al., 2016b).

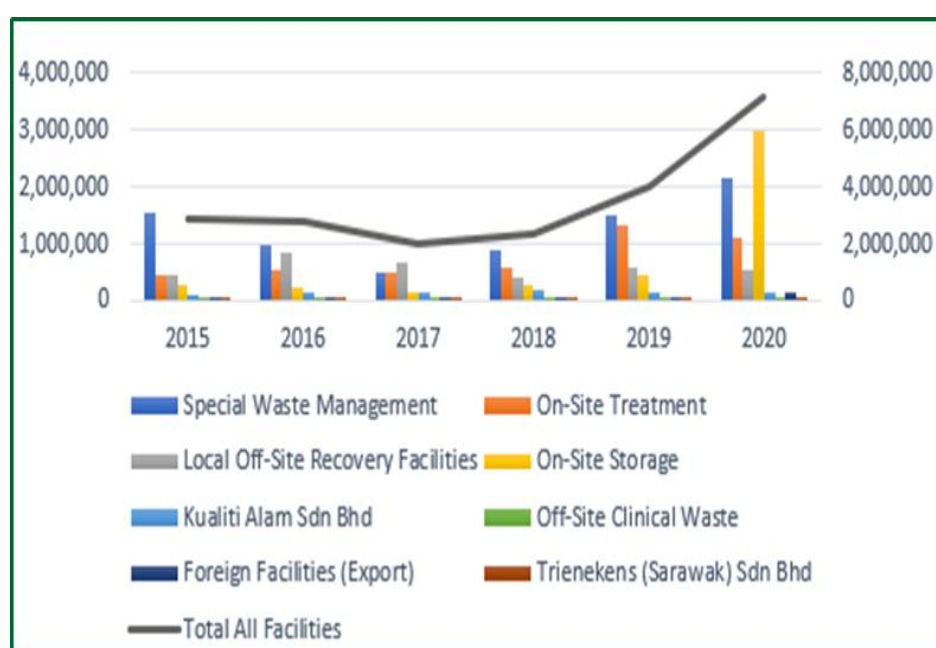


Figure 3 Breakdown of Malaysia's scheduled waste management and distribution according to facility types.

Figure 3 The breakdown of Malaysia hazardous waste management and distribution according to facility types is depicted above. Among the 300 companies, only 20 consider major players in the industry as they can process over 10 hazardous waste code, which most can process only one waste code per company (Eswis, 2019).

According to data from the Department of Statistics Malaysia (DoSM, 2022), there has been a growing awareness of hazardous waste management in Malaysia from 2015 to 2020. This awareness is reflected in the increased volume of waste being treated on-site and recovered in local recovery facilities. However, the existing facilities face challenges in managing the rising volume of waste generated in Malaysia, leading local companies to resort to less environmentally friendly waste management practices.

The volume of waste being stored, exported overseas for processing, and sent to local landfills as general waste has increased. On-site waste storage has also surged significantly but intended for temporary use, as hazardous waste needs to be processed within a specific timeframe to minimise risk. Failure to increase the number of recovery and treatment facilities to match the increasing waste volume could lead to potential environment and health hazards (Jessie Yeung, 2020b). Hazardous waste is increasingly sent to landfills and treated as general waste, and if this trend continues, it may result in fires, leaks, and environmental pollution, among other issues. and sent to local landfills as general waste has increased. In 2020, various facilities collectively managed a substantial 7,185,228 Mt of hazardous waste in Malaysia. The data reveal that 45.1% of hazardous waste management is allocated to on-site storage, indicating room for improvement in treatment, recovery, and disposal practices. Specialised waste management and on-site treatment account for a combined 45.6% of all managed waste, highlighting the significance of decentralised management approaches. Additionally, approximately 23% is managed through on-site

treatment and local off-site recovery facilities, emphasising the need for waste reduction and resource recovery strategies.

The notable increase in hazardous waste management in 2020, with a 79.05% surge compared to the previous year, underscores the growing imperative for more effective waste management measures to mitigate potential environmental and health risks. In **Figure 4**, the percentage distribution of hazardous waste management facilities among major industrial player in Malaysia is depicted.

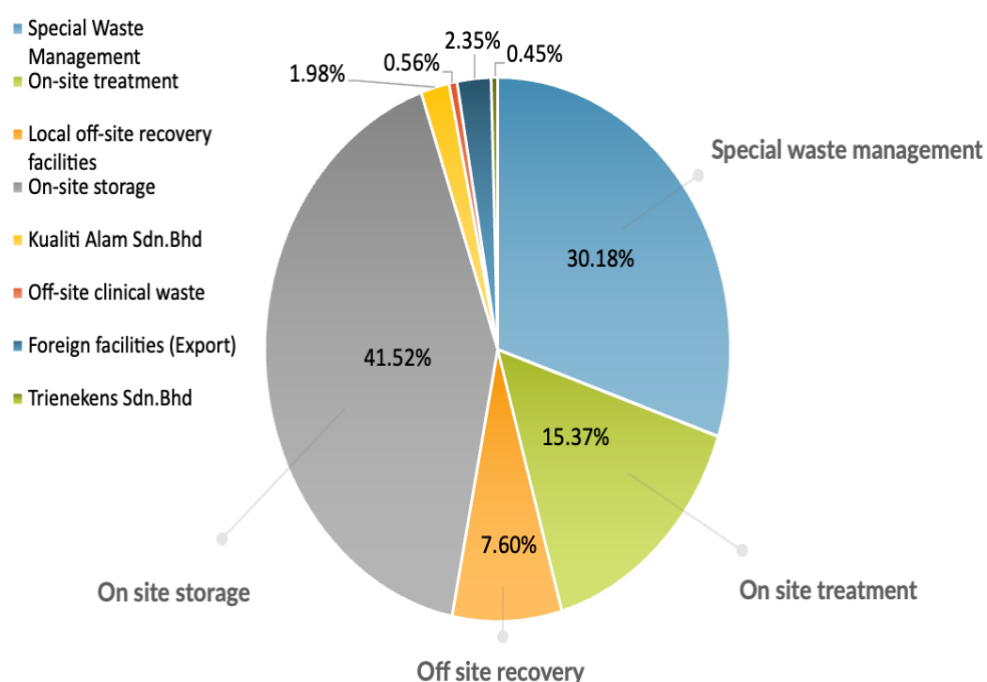


Figure 4 Percentage distribution of hazardous waste management by facility type in Malaysia.

2.6.6 Projection of future hazardous waste generation

The projection of future hazardous waste generation is a critical aspect of waste management planning. This review focuses on three methods commonly used for projection : logistic increase method, arithmetic increase method, an exponential increase method.

Each of these methods offer unique insights and has its own advantages and limitations. By understanding these methods and their applications in various studies, we can better project future hazardous waste generation and contribute to more effective and sustainable waste management strategies (Abid and Mhada, 2021; Willems et al., 2022). Furthermore , the review of these methods reveals the need for more comprehensive models that can incorporate the strengths of each method and provide more accurate projection (Gawatre et al., 2016).

2.6.7 Waste minimisation and best practices

Waste minimisations refer to the strategies and actions taken to minimise hazardous waste generation at its source. It aims to minimise waste production, promote resource efficiency, and prevent or reduce hazardous waste's environmental and health impacts.

The Environmental Protection Agency (EPA) defines waste minimisation as the use of source reduction and/or environmentally sound recycling techniques before waste is used for energy, recovered, treated, or disposed of. It excludes waste treatment, which is any procedure intended to alter the physical, chemical, or biological makeup of waste streams.

Waste minimisation involves processes and practices aimed at reducing waste generation. By reducing or eliminating the production of harmful and persistent waste, waste minimisation supports efforts to create a more sustainable society. This can be achieved through product and process redesign, as well as by changing patterns of consumption and production. The most environmentally and economically efficient way to manage waste is often to prevent the problem in the first place .

According to the Environmental Agency, waste minimisation is the use of source reduction and environmentally sound recycling techniques before waste is used for energy, recovered, treated, or disposed of. Waste treatment, which alters the physical, chemical, or biological makeup of waste streams, is not included. Some strategies of waste minimisation include reducing packaging material, such as shrink wrap, by redesigning packages to use recyclable or degradable materials, reducing harmful wastewater , holding employees accountable, improving recycling programs, and processes.

2.6.8 Waste tracking and reporting

Hazardous waste tracking and reporting are crucial components of hazardous waste management in Malaysia. Furthermore, it involves the systematic monitoring and documentation of the movement and disposal of hazardous waste from its waste generator to its final treatment or disposal.

Hazardous waste is produced across a range of industries, including those in the healthcare industry, laboratories, and other industries. Thus, properly identifying and classifying waste according to regulatory guidelines is important—Malaysia’s practice of using a hard copy of the consignment note and Electronic Consignment Note (ECN). The hard copy of the consignment typically consists of six copies. Note that the first copy is kept by the WG, whereas the second copy is sent to the state DoE for record purposes. Consequently, the third copy is retained by the transporter. Meanwhile, the fourth copy is kept by the prescribed premises (the treatment or disposal facility) upon receiving the hazardous waste. Subsequently, the fifth copy is returned to the WG as proof of receipt, and finally, the sixth copy is sent to the prescribed premises’ state DoE for record purposes.

In addition to the traditional hardcopy consignment note system, the DoE in Malaysia is promoting the use of ECN for hazardous waste management. The ECN is facilitated through the government Porter Electronic Scheduled Waste

Information System (eSWIS) system (DoE, 2015), which aims to digitise and streamline the waste management process.

To generate an ECN, a WG must register in the eSWIS system. The ECN process involves two simple steps. In step 1, the WG prepares a draft ECN, which is then provided as a print copy to the transporter responsible for transporting the hazardous waste to the designated treatment or disposal facility. In step 2, the prescribed premises confirms the receipt of the hazardous waste and updates the information in the eSWIS system.

Note that the ECN system implementation brings several benefits to hazardous waste management. It helps maintain a comprehensive and easily accessible record of hazardous waste movement, ensuring transparency and traceability throughout the transportation and disposal chain. The digital nature of the ECN system also facilitates efficient data management and reliability of waste tracking.

Waste tracking and reporting involve systematic monitoring, documentation, and regulatory compliance of hazardous waste from its generation to its final treatment or disposal. Therefore, this process ensures transparency, accountability, and proper management of hazardous waste in Malaysia. **Figure 5** below illustrates the hazardous waste disposal flow in Malaysia.

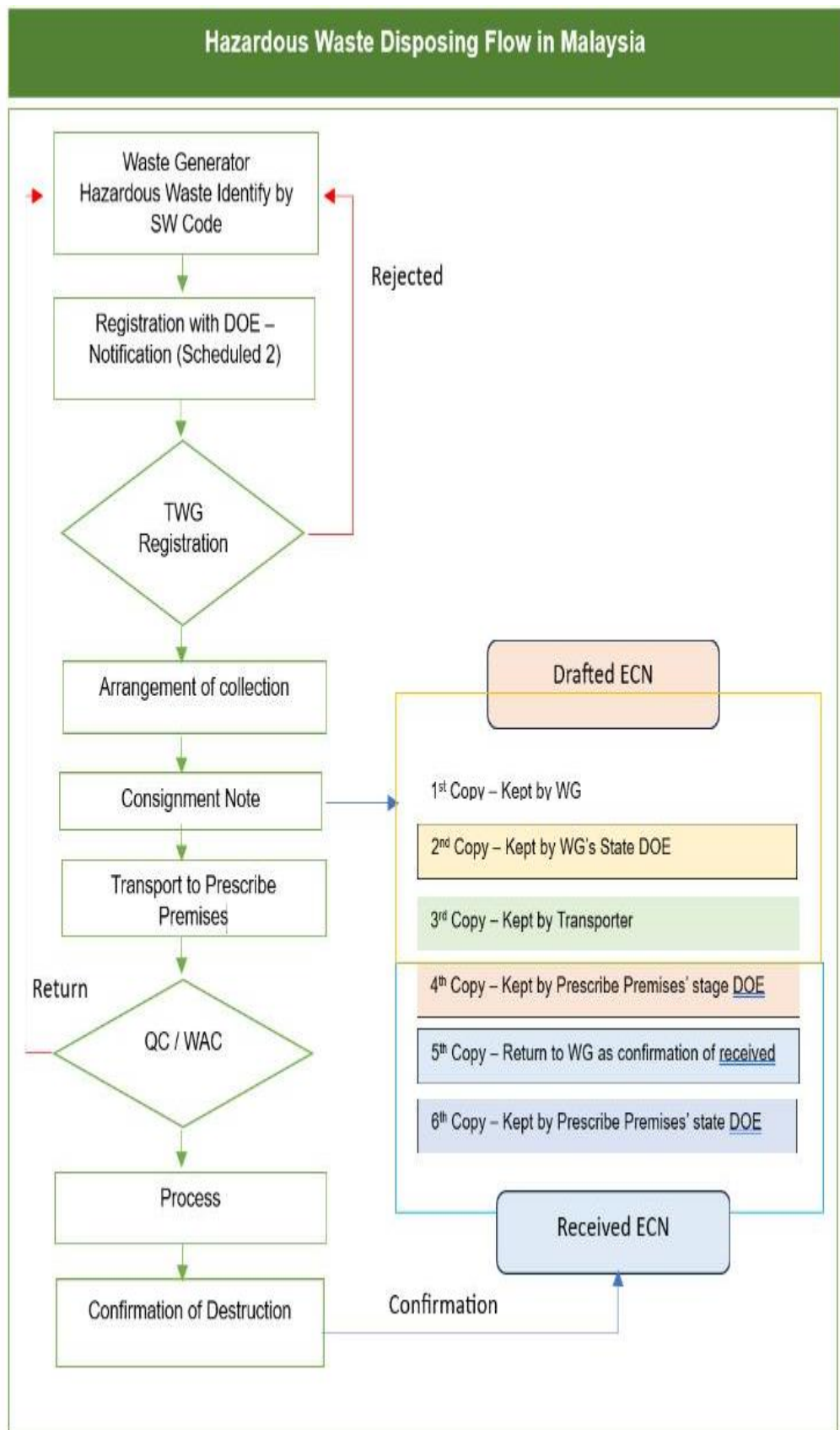


Figure 5 Hazardous waste disposing flow in Malaysia (DoE,2019)

2.7 Challenge in hazardous waste site selection

Selecting suitable locations for hazardous waste treatment facilities is widely recognized as one of the most complex tasks in environmental infrastructure planning. This complexity arises from the need to balance environmental protection, social acceptance, economic feasibility, technical viability, and legal compliance—often in the face of conflicting stakeholder interests and evolving policy landscapes (Ampofo et al., 2023a).

One of the central challenges is the high degree of public sensitivity surrounding hazardous waste facilities. Communities frequently express strong resistance to the siting of such infrastructure in their vicinity, a phenomenon commonly referred to as “Not In My Backyard” (NIMBY) (Cobos-Mora et al., 2023). This resistance is often fuelled by fears of air, water, and soil contamination, adverse health effects, and declining property values. Even when proposed sites meet environmental and technical standards, opposition from local stakeholders can delay or block implementation, leading to costly project setbacks (Meena et al., 2023).

Environmental concerns also play a major role. Hazardous waste facilities must be sited away from ecologically sensitive areas, water bodies, and zones prone to natural hazards such as floods or landslides. At the same time, these facilities must remain accessible to industrial zones that are the primary generators of hazardous waste (E. UNEP, 2021). Achieving this balance is particularly

difficult in regions with limited available land or where urban sprawl encroaches on suitable sites.

In addition, infrastructure constraints pose significant challenges. Effective hazardous waste management requires reliable transportation networks, proximity to utilities such as water and electricity, and compatibility with existing land use plans (Harinderan, 2023). Many potential sites may lack the necessary infrastructure, or their development may conflict with local zoning regulations or regional development plans.

Economic considerations further complicate site selection. The costs associated with land acquisition, construction, transportation, and long-term monitoring can vary greatly depending on the location. Sites that are optimal from an environmental or technical standpoint may prove financially unsustainable, especially in countries with constrained public budgets or where hazardous waste management is dominated by private operators (MIDA, 2023).

Legal and regulatory factors also influence site feasibility. Inconsistent enforcement, overlapping jurisdictions, or vague guidelines can hinder the siting process. In some cases, policy frameworks may lack clearly defined criteria for evaluating and approving new facilities, leaving decision-makers without the necessary tools to guide strategic planning (Otwong et al., 2021b).

Another significant challenge is the absence of a standardized methodology for evaluating and comparing potential sites. Many current approaches rely on qualitative assessments, expert judgment, or basic scoring methods that do not adequately account for the complexity and interdependence of the factors involved (Ampofo et al., 2023b). Moreover, uncertainty in data, future waste generation patterns, and stakeholder behaviour adds further ambiguity to an already intricate decision-making process.

These challenges underscore the need for integrated, transparent, and flexible site evaluation tools that can manage multiple criteria, accommodate uncertainty, and support defensible decisions. Multi-criteria decision-making (MCDM) approaches have gained increasing attention in this context for their ability to handle complex, conflicting factors in a structured manner (Hamlat et al., 2022). However, their effectiveness depends on how well the underlying criteria are selected, weighted, and tested for reliability—highlighting the importance of combining such techniques with sensitivity analysis or probabilistic modelling.

2.8 Multi-Criteria Decision-Making (MCDM) in environmental planning

Environmental planning decisions often involve numerous stakeholders, diverse priorities, and complex trade-offs. In this context, Multi-Criteria Decision-

Making (MCDM) methods have emerged as valuable tools to support structured, transparent, and balanced evaluations. MCDM enables decision-makers to assess alternatives based on multiple, often conflicting, criteria—such as cost, environmental risk, technical feasibility, and public acceptance—while accommodating both qualitative and quantitative inputs.

Traditional decision-making approaches in infrastructure planning frequently rely on single-objective optimization or unstructured expert assessments. While useful in narrow applications, these methods often fall short when applied to multifaceted problems like hazardous waste facility siting (Silva López et al., 2022). The need to reconcile economic efficiency with environmental protection, or to balance regional equity with logistical convenience, makes single-criterion approaches inadequate (Feng, 2022). In contrast, MCDM frameworks allow decision-makers to systematically capture and weigh diverse considerations, improving both the robustness and legitimacy of the final outcome (Hamlat et al., 2022).

There are two primary classes of MCDM methods: multi-attribute utility theory (MAUT) and outranking approaches. MAUT-based methods, such as the Analytic Hierarchy Process (AHP), convert preferences into numerical weights, allowing the aggregation of criteria scores into a single utility value (Silva López et al., 2022). Outranking methods, like ELECTRE or PROMETHEE,

work by comparing alternatives pairwise and identifying dominance relationships. Both families of techniques offer distinct advantages depending on the context and decision complexity.

The application of MCDM in environmental domains has been widely documented. These methods have been used for prioritizing renewable energy sites, selecting landfill locations, evaluating ecosystem services, and determining transportation corridor alignments (WHO, 2018). Their flexibility and ability to handle qualitative judgments make them particularly suitable for problems where data may be incomplete or where stakeholder preferences must be incorporated.

Hazardous waste management is a prime candidate for MCDM because it involves diverse and sometimes competing objectives. Decisions about where to locate treatment facilities, how to allocate budgets, or which technologies to adopt all require the simultaneous consideration of environmental, social, and economic criteria. MCDM not only helps to identify optimal or compromise solutions but also enhances transparency, making the process more defensible in the face of public or political scrutiny (Zarin et al., 2021).

However, the effectiveness of MCDM depends heavily on the selection and structuring of the criteria used. Poorly defined indicators, biased weight assignments, or untested assumptions can undermine the reliability of the results. For this reason, many studies recommend pairing MCDM techniques with sensitivity analysis or probabilistic modelling to better understand the impact of uncertainty on decision outcomes.

In recent years, the integration of MCDM with other tools such as Geographic Information Systems (GIS), artificial intelligence, and simulation techniques has become increasingly common (Çalış Boyacı et al., 2021). These hybrid models offer powerful capabilities for spatial analysis, scenario testing, and stakeholder engagement. Among these, the integration of MCDM with Monte Carlo Simulation has shown promise in addressing uncertainty in decision parameters, a feature especially relevant to hazardous waste site selection.

2.9 Analytic Hierarch Process (AHP) in site selection

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is a widely used multi-criteria decision-making (MCDM) that structures complex problems into a hierarchy of goal, criteria, and alternatives (Saaty, 2008). AHP enables decision-makers to compare criteria through pairwise evaluations, using a numerical scale to assign relative weights that reflect expert or

stakeholder judgments (Silva López et al., 2022). This structured approach transforms qualitative insights into quantitative data, making it particularly suitable for decisions that involve both measurable and intangible factors.

The strength of AHP lies in its systematic process. Each criterion is compared with every other criterion using Saaty's nine-point scale, and a consistency ratio (CR) is calculated to assess the logical coherence of judgments. A CR below 0.10 is generally accepted, indicating consistency in pairwise comparisons (Saaty, 2008). This consistency check is crucial in ensuring the reliability and credibility of the model outputs.

In hazardous waste facility planning, AHP has proven valuable due to the multifactorial nature of the decision-making context. Criteria such as environmental impact, proximity to sensitive areas, infrastructure availability, and public acceptance often conflict with one another, making trade-offs necessary. AHP provides a framework to balance these competing interests transparently and methodically. Researchers like Zamorano et al. (2008), Chang et al. (2008), and Vasiljević et al. (2012) have demonstrated AHP's utility in evaluating landfill and hazardous waste treatment sites by incorporating stakeholder preferences and spatial data.

AHP's adaptability also makes it suitable for settings where data are incomplete or uncertain. In these cases, expert knowledge becomes a vital input. However, this reliance on subjective input introduces potential bias. To address this, AHP

models often include sensitivity analysis or integration with probabilistic methods like Monte Carlo Simulation to assess the robustness of outcomes (Stropnik et al., 2019).

By using AHP, the research builds a transparent, evidence-based foundation for decision-making in hazardous waste management (Zarin et al., 2021). It supports policymakers and stakeholders in navigating complex environmental planning challenges, providing a replicable model that balances precision with inclusivity (Alao et al., 2022).

2.10 Monte Carlo Simulation in decision analysis

Monte Carlo Simulation (MCS) is a probabilistic modelling technique widely applied in decision-making processes where uncertainty and variability significantly influence outcomes (Zhou et al., 2022). First developed in the mid-20th century during nuclear research, the method has since become a staple across domains such as finance, engineering, and environmental planning. In contrast to deterministic models, which provide a single solution based on fixed inputs, MCS generates a distribution of outcomes by randomly sampling input values from defined probability distributions (Ma et al., 2025). This enables analysts to understand not only the most likely results, but also the full spectrum of possible scenarios and associated risks.

In decision analysis, particularly within multi-criteria decision-making (MCDM) frameworks, MCS is frequently used to address the uncertainty inherent in expert judgment and input data (Feng, 2022). When applied to models such as the Analytic Hierarchy Process (AHP), MCS introduces variability into the weightings of criteria or performance scores of alternatives (Ampofo et al., 2023a). This allows decision-makers to assess how sensitive their final rankings are to changes in input assumptions, making the evaluation process more resilient and evidence-based.

The integration of MCS into AHP-based site selection studies has grown steadily in recent years. Researchers have used this approach to model real-world uncertainty in areas where expert input is relied upon heavily, such as hazardous waste facility planning, infrastructure development, and environmental impact assessments. For instance, Yusoff et al. (2016) demonstrated how AHP–MCS integration improved the robustness of landfill site selection decisions in Malaysia by simulating thousands of variations in expert weightings. Similarly, Kabir and Sadiq (2012) applied the combined method in risk-based decision-making to evaluate waste treatment options under data uncertainty, reinforcing its value in high-stakes environmental applications.

Monte Carlo Simulation works by defining probability distributions for one or more uncertain input variables. These distributions can be based on observed data, expert estimation, or assumed ranges when data is lacking (Zhou et al., 2022). Through repeated sampling—often in the range of 1,000 to 10,000

iterations—the model generates a statistical distribution of outcomes for each alternative or decision path. The outputs typically include measures such as means, standard deviations, and confidence intervals, offering a richer interpretation than single-value outputs from deterministic approaches.

In environmental planning, the use of MCS is particularly compelling due to the inherent uncertainties surrounding regulatory changes, technological adoption, future demand patterns, and stakeholder behaviour. When applied to hazardous waste management, MCS allows planners to quantify the likelihood of different facility rankings, evaluate the robustness of the preferred site, and communicate risk more effectively to stakeholders and regulatory bodies.

Despite its advantages, MCS is not without limitations. The method depends heavily on the quality and accuracy of the input distributions. Poorly defined assumptions or unrealistic variance ranges can lead to misleading outcomes. Additionally, the interpretation of probabilistic outputs requires statistical literacy, which may pose challenges in policy environments where decision-makers are more accustomed to deterministic results (Feng, 2022).

Nonetheless, when used in conjunction with structured methods like AHP, MCS enhances the decision-making process by accounting for variability that would otherwise be ignored. This combination allows for a more nuanced understanding of how weight uncertainty affects site selection, increasing both transparency and confidence in the final recommendations.

In this study, Monte Carlo Simulation is employed to complement the AHP-based evaluation of hazardous waste site suitability. After deriving the relative weights of ten key decision criteria through expert pairwise comparisons, MCS is used to simulate a range of plausible variations in these weights. Thousands of iterations generate a probabilistic distribution of site rankings, which helps assess the sensitivity of the final decision to uncertainty in expert input. This integration not only reinforces the robustness of the proposed decision framework but also supports better-informed, risk-aware environmental planning.

2.11 Integration of Analytic Hierarchy Process (AHP) and Monte Carlo Simulation (MCS) in literature

The combination of the AHP with MCS has become increasingly popular in decision-making research, particularly in domains where both complexity and uncertainty are central concerns. While AHP is well established for its ability to organize and prioritize criteria based on expert judgment, it remains sensitive to inconsistencies and subjective biases. MCS, when integrated with AHP, serves to validate the reliability of those judgments by introducing controlled variability into the analysis (Ampofo et al., 2023b; Stropnik et al., 2019). The result is a more robust, risk-aware, and defensible decision-making framework.

This hybrid approach has been successfully applied in various sectors, including waste management, transportation, energy planning, and environmental risk

assessment. For example, Mendoza and Martins (2006) applied the AHP–MCS combination in forest management to examine stakeholder preferences under uncertainty, while Yusoff et al. (2016) used it for landfill site selection in Malaysia, demonstrating how the approach could identify stable site rankings even when weights fluctuated. Similarly, Kabir and Sadiq (2012) employed the model in evaluating hazardous waste treatment technologies, highlighting how probabilistic modelling improved stakeholder trust and decision reliability.

The integration typically begins by using AHP to generate a set of deterministic weights through pairwise comparisons, reflecting stakeholder priorities. MCS is then applied by assigning probability distributions to these weights—often normal, triangular, or uniform distributions depending on the data—and performing thousands of simulations to model how ranking results vary across a range of plausible conditions. The outputs provide insights into the likelihood of each alternative being ranked first, the sensitivity of each criterion, and the range of possible decision outcomes.

In the context of hazardous waste facility planning, this integrated method is particularly relevant. Site selection involves a combination of hard-to-measure environmental and social factors, and decisions are often made in the presence of incomplete or uncertain information (Feng, 2022). The AHP–MCS framework accommodates expert-driven priorities while recognizing the variability inherent in real-world decision-making.

2.12 Research gap and conceptual framework

Although considerable research has been conducted on hazardous waste management and facility siting, several important gaps remain unaddressed—particularly in the development of nationally adaptable, uncertainty-aware frameworks. Many studies rely on deterministic MCDM models that produce static rankings, often overlooking the inherent variability in expert assessments and real-world conditions (Hamlat et al., 2022). As a result, the robustness of these decisions is rarely tested, potentially reducing confidence in their long-term applicability.

Another limitation in the existing literature is the lack of a standardized, multidimensional index tailored to hazardous waste infrastructure planning (Silva López et al., 2022). While various criteria have been used across studies, there is no universally accepted framework that integrates environmental, social, economic, logistical, and regulatory dimensions in a structured and replicable way. Furthermore, existing models often focus on specific regions or municipalities and are rarely tested at a national scale.

This study addresses these gaps through the development of a ten-criteria Hazardous Waste Management (HWM) index and its application within an AHP–Monte Carlo decision-making framework. The criteria—derived from both international literature and national policy relevance—are weighted through expert input using AHP and tested for sensitivity using MCS. This dual-

method approach enhances the transparency, adaptability, and credibility of the framework.

Malaysia serves as the primary case study due to its rapid industrialization, uneven hazardous waste treatment capacity, and active policy efforts toward circular economy and sustainability (Amirul, 2021). However, the proposed framework is not Malaysia-specific. Its modular structure allows for replication and customization in other countries or contexts with similar waste management challenges.

Chapter 3

Methodology

3.1 Research design and structure

This research adopts a structured, multi-phase approach to support the evaluation and planning of hazardous waste treatment infrastructure in Malaysia. It integrates both qualitative and quantitative methods to construct a scalable, evidence-based decision-support framework. A foundational literature review was conducted using databases such as Scopus, ScienceDirect, and Google Scholar. Keywords including hazardous waste, recycling technology, circular economy, and life cycle assessment guided the search and enabled the identification of global best practices, decision-making methodologies, and knowledge gaps relevant to the Malaysian context.

The structural flow of the thesis is illustrated in **Figure 6**, which outlines the relationship between chapters. Chapter 1 introduces the study's background, research problem, objectives, and scope. Chapter 2 provides a comprehensive review of academic and policy literature, including theoretical frameworks and multi-criteria evaluation approaches. Chapter 3 presents the research design, including the construction of the Hazardous Waste Management (HWM) Index, the stakeholder engagement process, and the integration of Analytic Hierarchy

Process (AHP) with Monte Carlo Simulation. Chapter 4 presents the findings, including the national-level analysis of hazardous waste trends, stakeholder-weighted criteria, and robustness validation through simulation. Chapter 5 discusses the site selection results and outlines implications for policy and infrastructure planning, while Chapter 6 concludes the study and proposes directions for future research.

To support empirical analysis, the study drew upon secondary data from multiple authoritative sources. These include regulatory and technical documentation from the Department of Environment (DOE), such as the Environmental Quality Act 1974 and Scheduled Waste Regulations. Hazardous waste classification and identification systems, including pictograms and waste codes, were obtained from DOE technical guidelines. Facility licensing data and treatment infrastructure information were retrieved from national facility listings, while waste tracking and movement records were accessed via the Electronic Scheduled Waste Information System (eSWIS). Statistical data on hazardous waste generation from 2015 to 2020, disaggregated by sector and facility type, were obtained from the Department of Statistics Malaysia (DoSM). Supplementary insights on international waste transfers were acquired from Basel Convention national reporting archives.

This dataset provided the foundation for constructing the HWM Index, which was operationalized through AHP to capture stakeholder priorities and validated

through Monte Carlo Simulation. The integrated decision-support model is further detailed in the subsequent sections of this chapter.

Table 7: Summary data and information collected

No	Types of Data	Description	Sources
I	Regulatory	Malaysia Environmental Act	Ministry of Natural Resources, Environment and Climate Change – Department of Environmental
II	Classification and identification of Hazardous Waste	Hazardous waste characteristic and pictogram	Ministry of Natural Resources, Environment and Climate Change – Department of Environmental: Scheduled Waste guidelines
III	Scheduled Waste Licencing and permitting	Scheduled Waste licenses issued in Malaysia	Ministry of Natural Resources, Environment and Climate Change – Department of Environmental: Facility list
IV	Waste tracking and reporting	Scheduled Waste tracking and reporting procedure	Ministry of Natural Resources, Environment and Climate Change – Department of Environmental: Scheduled Waste guideline, eSWIS (Electronic Scheduled Waste Information System)
V	Hazardous Waste Generation	Hazardous waste generation by sector from the year 2015 to 2020	Department of Statistics Malaysia - Scheduled Waste compendium report from the year 2015 to 2020
		Scheduled waste volume from the year 2015 to 2020 by facility types	
		Scheduled waste exported from the year 2016 to 2020 from Malaysia to processing facilities overseas	Department of Statistic Malaysia / Basel – countries / national reporting

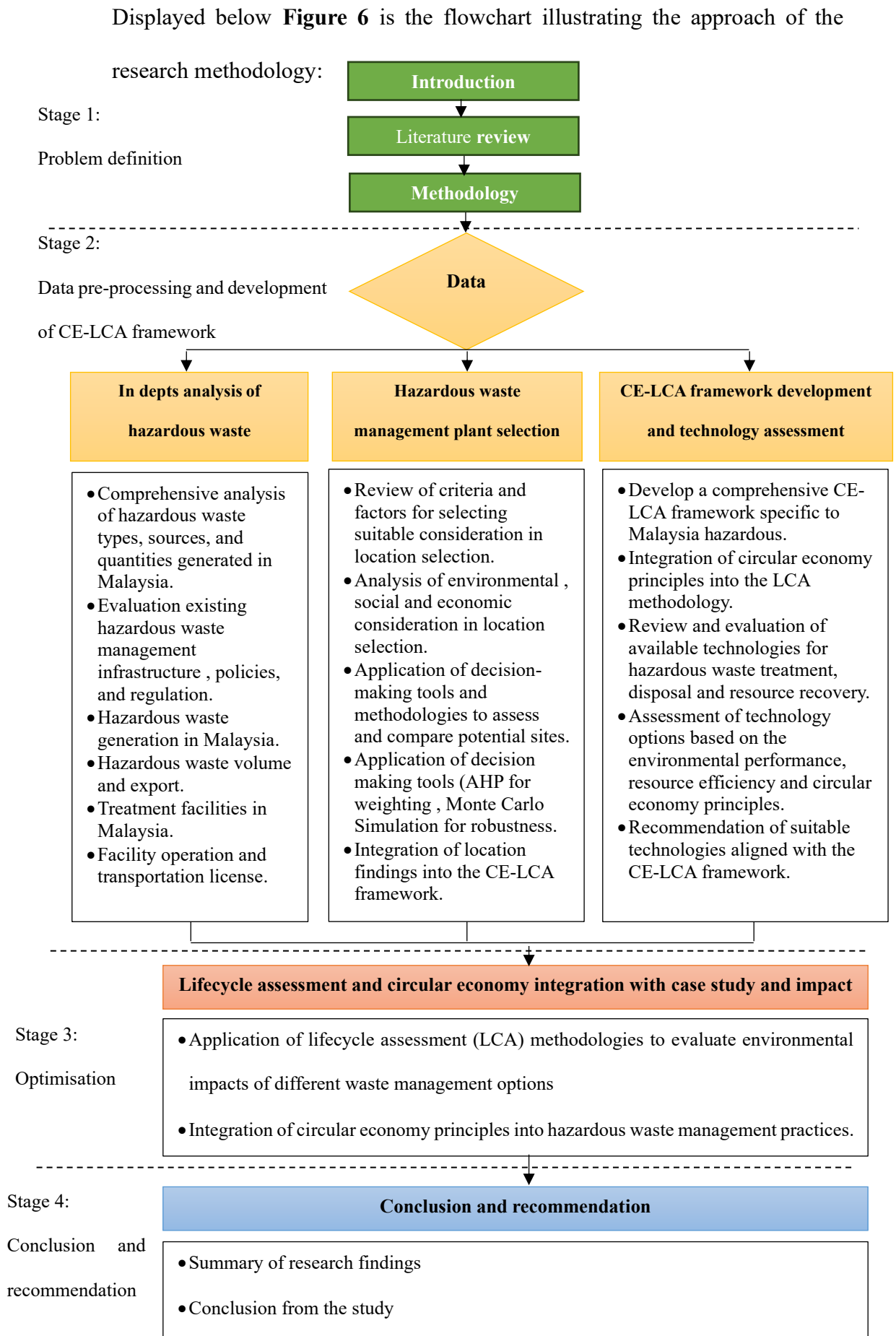


Figure 6 Flow chart of research methodology

3.2 Contextual review and data sources

This study is grounded in a national-level contextual review that informs the construction of the Hazardous Waste Management (HWM) Index, and the analytical framework employed for site selection. The review synthesizes Malaysia's legislative, operational, and statistical landscape related to hazardous waste management, ensuring the relevance and applicability of the decision-support model.

Key legal instruments such as the Environmental Quality Act 1974 and the Scheduled Waste Regulations 2005 form the regulatory foundation for scheduled waste control in Malaysia. These were analyzed alongside technical documents from the Department of Environment (DOE), including scheduled waste guidelines, classification protocols, and facility licensing requirements. In addition, data on waste movement and treatment activities were obtained through Malaysia's electronic tracking platform, the eSWIS system. This provided insights into the volume and routing of hazardous waste across different regions.

Quantitative data from the Department of Statistics Malaysia (DoSM), covering the period from 2015 to 2020, served as the basis for understanding sectoral contributions to hazardous waste generation. This included data disaggregated by facility type and industry, as well as records of international waste transfers reported under the Basel Convention. Together, these data sources enabled a

comprehensive understanding of both current and historical waste management performance.

To project future hazardous waste generation, three forecasting approaches were adopted: arithmetic, exponential, and logistic growth models. These methods reflect varying assumptions about industrial expansion, policy limitations, and ecological carrying capacity, thereby providing a nuanced view of potential waste accumulation scenarios over time. These projections were particularly useful in identifying the urgency of infrastructure development and planning requirements.

Complementing this projection effort, a strategic evaluation of the hazardous waste system was conducted through a SWOT analysis. The review identified regulatory structure and institutional awareness as key strengths, while limited treatment capacity and inter-agency coordination were among the major weaknesses. Opportunities were recognized in emerging technologies and public awareness trends, while threats included environmental risks, weak enforcement in some regions, and uncertainty in global trade regulations.

A broader academic perspective was also introduced through a research trend analysis using VOS viewer. This bibliometric tool helped to visualize evolving priorities in the hazardous waste literature, revealing increasing attention toward circular economy integration, e-waste management, and technology-driven

solutions. These insights helped validate the selection of criteria used in the HWM Index and align the research with international discourse.

3.3 Develop of hazardous waste management index (HWM Index)

The Hazardous Waste Management (HWM) Index developed in this research provides a structured and comprehensive framework for assessing and ranking the suitability of potential sites for hazardous waste treatment plants. Designed specifically for the Malaysian context but adaptable to other developing countries, the index integrates a broad spectrum of environmental, technical, regulatory, and socio-economic considerations into a unified decision-support system. Its development is informed by an extensive review of literature, policy documents, and stakeholder consultations, as well as by empirical data collection and expert judgment.

To operationalise the HWM Index, a clear definition of its components was necessary. An indicator is defined as an observable and measurable variable that reflects the performance or impact of hazardous waste systems. Data collection items are the empirical means used to quantify these indicators, such as national statistics, licensing records, stakeholder surveys, or expert assessments. Indicators and data inputs are organised under ten key domains: Environmental, Social, Economic, Existing Waste Structure, Industry Output, Petrochemical Hubs Proximity, Technical, Regulatory, Risk, and Innovation. These domains together capture the multi-dimensional nature of hazardous waste planning.

The Environmental Domain evaluates ecological effects, including land use efficiency, biodiversity impacts, and resource conservation. The Social Domain focuses on community health, public engagement, and equity, ensuring that waste facilities do not disproportionately burden vulnerable populations. The Economic Domain considers capital costs, operational efficiency, and regional economic contribution, assessing the financial sustainability of the facility. The Existing Waste Structure Domain examines the current distribution and capacity of treatment infrastructure, prioritising regions with unmet demand or logistical bottlenecks.

The Industry Output Domain evaluates the concentration and intensity of industrial activity in a given region, especially as it relates to hazardous waste generation. The Proximity to Petrochemical Hubs domain captures logistical and risk-reduction advantages of siting facilities near high-volume waste generators. The Technical Domain includes geotechnical stability, utility access, and transport connectivity—factors that directly affect construction feasibility and operational safety. The Regulatory Domain ensures alignment with licensing requirements, enforcement capacity, and institutional readiness, minimising legal and compliance risks. The Risk Domain assesses the probability and severity of environmental or health incidents, including spill potential, fire hazards, and natural disaster vulnerability. Finally, the Innovation Domain evaluates the potential for technological advancement, adaptive capacity, and compatibility with future waste-to-resource conversion processes.

Each of these domains was selected through a rigorous process involving academic literature review, technical guideline analysis, and multiple rounds of stakeholder feedback. Their inclusion reflects not only current best practices in hazardous waste management but also Malaysia's national development goals and circular economy aspirations. Data for each domain were sourced from the Department of Environment (DOE), Department of Statistics Malaysia (DoSM), the Electronic Scheduled Waste Information System (eSWIS), and Basel Convention national reports, among others.

Table 8 provides a consolidated overview of the HWM Index domains, corresponding indicators, and data collection items used in the study. This structure allows for systematic evaluation of treatment site alternatives and ensures that both quantitative and qualitative considerations are embedded in the selection process.

Overall, the HWM Index forms the core analytical foundation for this research. By translating complex planning priorities into structured, comparable criteria, it enables more informed, transparent, and adaptive decision-making in hazardous waste infrastructure planning. The application of this index in combination with AHP and Monte Carlo Simulation is further detailed in the subsequent sections of this chapter.

Table 8 Indicators and data collection items for hazardous waste management HWM index.

DOMAIN	INDICATORS	DATA COLLECTION ITEMS	
ENVIRONMENTAL	Land use efficiency,	Ration of the land area occupied by the waste management facilities to the total land area available.	
	Waste resource protection	The percentage of water resources that are not contaminated or depleted by the waste management activities.	
	Biodiversity conservation	The number and status of endangered species or habitats affected by the waste management activities.	
	Air quality improvement	The reduction of greenhouse gas emissions and air pollutant from the waste management activities.	
	Climate change adaptation	The resilience and adaptation measures of the waste management system to cope with extreme weather events and natural disasters.	
	Social impact	The net effect of the waste management system on the well-being and the quality-of-life on the affected communities.	
SOCIAL	Health awareness	The level of knowledge and awareness of the potential health impacts of the waste management system among the stakeholders.	
	Public participation	The degree and quality of involvement and empowerment of the stakeholders in the decision-making and implementation of waste management system.	
	Cultural preservation	The respect and protection of the cultural and historical of the areas affected by the waste management system.	
	Cost- benefit analysis	The total cost and benefit of waste management system. Including the direct and indirect costs, and benefit.	
ECONOMY	Revenue generation	The amount of revenue generated from waste management activities.	
	Employment creation	The number and type of jobs created by waste management system.	
	Industrial development	The amount and percentage of industrial output related to waste management.	

Table 8 (Continue) Indicators and data collection items for hazardous waste management HWM index

DOMAIN	INDICATORS	DATA COLLECTION ITEMS
EXISTING WASTE STRUCTURE	Waste collection coverage	The percentage of population served by waste collection.
	Waste collection frequency	The number of waste collection trips.
	Waste collection efficiency	The amount of waste collected per trip.
	Waste collection quality	The percentage of waste collected without spillage or leakage.
INDUSTRY OUTPUT	Waste intensity	The ratio of waste generated to industrial output.
	Waste composition	The percentage of different type of waste.
	Waste reduction potential	The amount of waste that can be avoided or minimized by implementing waste prevention or reduction measures.
	Waste reuse potential	The amount of waste can be reused for same or different purposes without further processing.
	Waste recycling potential	The amount of waste that can be recycle into new products or materials.
PETROCHEMICAL HUBS PROXIMITY	Waste transport distance	The average distance from waste generation sites to petrochemical hubs.
	Waste transport cost	The average cost of waste transport per ton
	Waste transport time	The average time of waste transport per trip
	Waste transport reliability	The percentage of waste transport trips without delay or disruption.

Table 8 (Continue) Indicators and data collection items for hazardous waste management HWM index

DOMAIN	INDICATORS	DATA COLLECTION ITEMS
TECHNICAL	Site accessibility	The road network condition and capacity for waste management facilities.
	Utility availability	The power supply availability and reliability for waste management facilities.
	Site suitability	The site size and configuration for waste management facilities.
	Geotechnical stability	The soil type and condition for waste management facilities.
REGULATOR	Infrastructure integration	The existing infrastructure type and condition for waste management facilities.
	Regulatory compliance	The adherence of the waste management system to the local and national regulations for waste management.
	Permitting process	The duration and cost of the permitting process for the waste management system.
	Regulatory enforcement	The standard and penalties of the regulatory enforcement for the waste management system.
RISK	Residential distance	The distance from residential areas to waste management facilities.
	Accident probability	The likelihood of occurrence of accidents or spills related to the waste management system.
	Accident severity	The magnitude and extent of the damage or harm caused by the accidents or spills related to the waste management system.
	Accident uncertainty	The degree of unpredictability or variability of the accidents or spills related to the waste management system.
	Emergency response	The plan and capacity of the waste management system to respond to and mitigate the accidents or spills.
	Security	The plan and capacity of the waste management system to prevent and protect against unauthorized or malicious access or interference.

Table 8 (Continue) Indicators and data collection items for hazardous waste management HWM index

DOMAIN	INDICATORS	DATA COLLECTION ITEMS
INNOVATION	Technology development	The number and type of patents, publications, or projects related to waste management.
	Technology adoption	The percentage of waste management facilities using new or improved technologies.
	Technology diffusion	The number and type of stakeholders involved in the dissemination and application of the new or improved technologies,
	Technology transfer	The number and type of agreements or partnerships related to the exchange and sharing of the new or improved technologies.

3.4 AHP development and criteria weighting

The Analytic Hierarchy Process (AHP) was adopted in this study as the core multi-criteria decision-making tool to evaluate and prioritise potential sites for hazardous waste treatment facilities. Informed by the contextual review and criteria established through the Hazardous Waste Management (HWM) Index, the AHP structure reflects both national planning priorities and broader environmental and technical considerations. The process ensures that the decision model is methodologically robust, grounded in stakeholder engagement, and structured for transparency and reproducibility.

The decision hierarchy begins with the goal of selecting the most suitable hazardous waste treatment site, followed by ten key criteria derived from the HWM Index. These criteria were organised in a hierarchical structure and assessed using structured stakeholder feedback. **Figure 7** illustrates the AHP hierarchical model applied in this study.

Methodological Flowchart Support Model for Hazardous Waste Site Selection

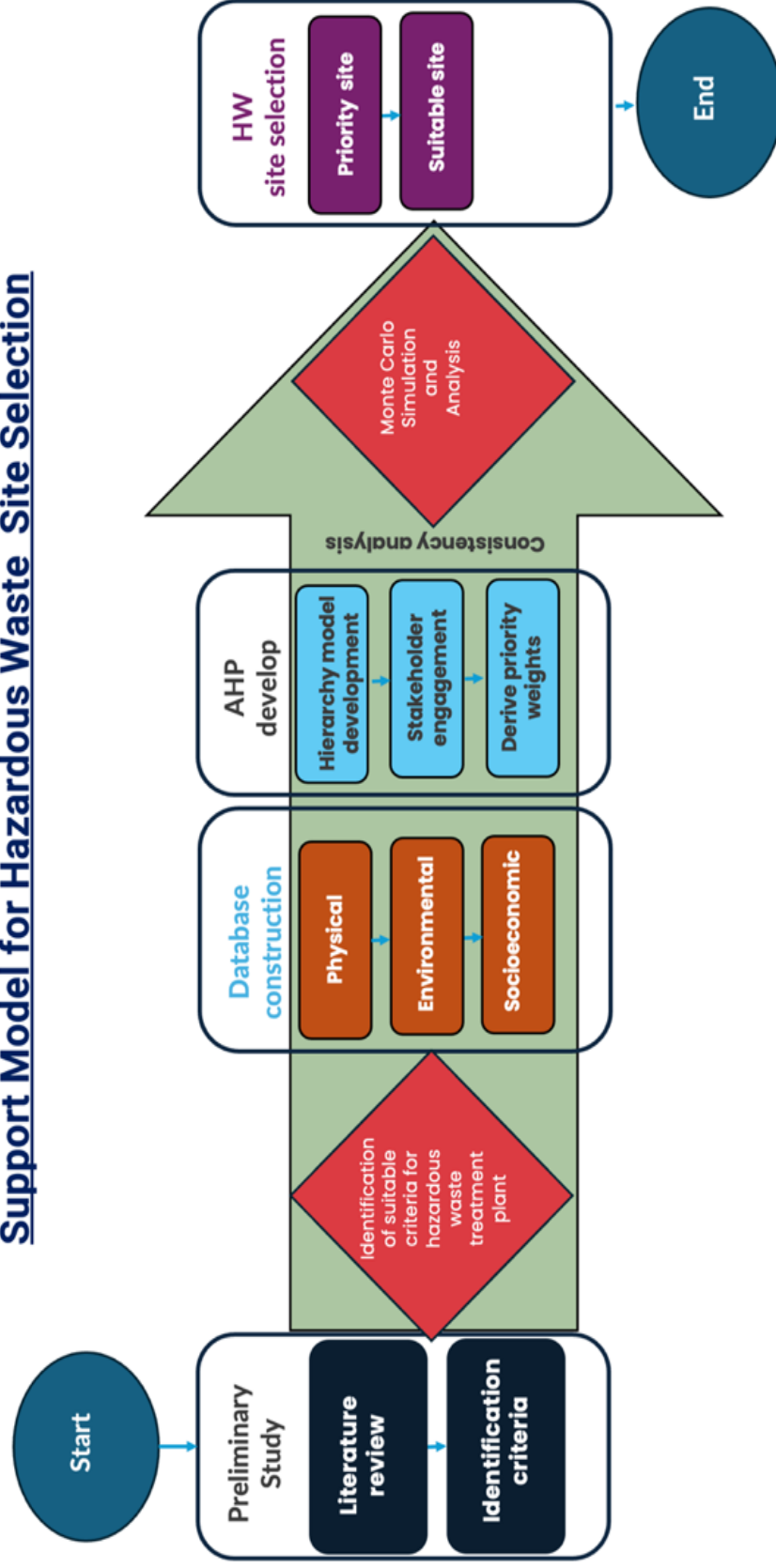


Figure 7 Methodology flow chart : Support model for HWM site selection

The decision hierarchy used in AHP begins with the overarching goal—selecting the most suitable site for a hazardous waste treatment facility. This is followed by the ten criteria defined in the HWM Index, including environmental, social, economic, technical, regulatory, and innovation-related dimensions. These criteria are structured to capture a comprehensive range of site considerations and to reflect both stakeholder priorities and planning constraints.

A crucial step in AHP is the pairwise comparison judgment, where stakeholders are asked to evaluate the relative importance of each criterion against all others. This evaluation follows Saaty's 9-point fundamental scale (Table 9), which ranges from 1 (equal importance) to 9 (extreme importance of one criterion over another). Intermediate values (2, 4, 6, 8) are used when finer distinctions are needed. This systematic approach enables the conversion of subjective expert opinions into quantifiable weights.

Table 9 : Pairwise comparison judgement

Comparing the criteria in pair, based on the dominance relationship

<i>Environment</i>	9	7	5	3	1	3	5	7	9	Social
<i>Social</i>	9	7	5	3	1	3	5	7	9	Economy
<i>Economy</i>	9	7	5	3	1	3	5	7	9	Existing waste structure
<i>Existing waste structure</i>	9	7	5	3	1	3	5	7	9	Industry output

<i>Industry output</i>	9	7	5	3	1	3	5	7	9	Petrochemical hub proximity
<i>Petrochemical hub proximity</i>	9	7	5	3	1	3	5	7	9	Technical
<i>Technical</i>	9	7	5	3	1	3	5	7	9	Regulator
<i>Regulator</i>	9	7	5	3	1	3	5	7	9	Risk
<i>Risk</i>	9	7	5	3	1	3	5	7	9	Innovation
<i>Innovation</i>	9	7	5	3	1	3	5	7	9	Environment

Using these judgments , a comparison matrix was generated, and weights were calculated by deriving the principal eigenvector. These weights were then normalised to sum to one, forming the basis for evaluating and ranking site alternatives.

Stakeholder engagement played a critical role in developing the AHP framework. Participants were selected from government agencies, hazardous waste facility operators, academic experts, and environmental consultants. Structured interviews and questionnaires were administered to collect expert judgement on the relative importance of each criterion.

This input was used to construct a pairwise comparison matrix, which served as the foundation for the weighting process. The pairwise comparison method **Table 9** allows experts to express their preferences for one criterion over another using a structured 9-point scale developed by Saaty (2008). The scale

ranges from 1 (equal importance) to 9 (extreme importance of one criterion over another), with intermediate values used for more nuanced distinctions.

Table 10 Pairwise comparison judgements

Scale	Description
1	Equal importance of two elements.
3	Moderate importance of one over another.
5	Strong or essential importance.
7	Very strong or demonstrated importance.
9	Extreme importance or dominance of one over another.
2,4,6,8	Intermediate value to capture nuances between the primary judgements.

Once the comparison matrix was populated, criteria weights were derived by calculating the principal eigenvector of the matrix. These weights quantify the relative importance of each domain and are essential for aggregating site evaluation scores. The transparency of this process transforms qualitative expert opinion into structured, quantitative data, enhancing the reproducibility and credibility of the final site rankings.

To ensure the internal consistency of stakeholder judgments, a consistency ratio (CR) was calculated for each matrix. The consistency index (CI) was first computed using the formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{Equation 1}$$

Where:

λ_{max} is the largest or principal eigenvalue of the pairwise comparison matrix.

n is the number of criteria being compared.

where λ_{max} is the principal eigenvalue of the comparison matrix and n is the number of criteria. The consistency ratio was then obtained by comparing the CI to a random index (RI), based on matrix size:

$$CR = \frac{CI}{RI} \quad \text{Equation 2}$$

A CR value of 0.10 or less was accepted as an indication of logically consistent responses. If the CR exceeded this threshold, the participant was asked to revisit and refine their comparisons. This validation step is essential to ensuring the methodological rigor and trustworthiness of the AHP outputs. It also serves to improve stakeholder understanding of trade-offs and promotes transparency in decision-making.

The application of AHP in this research offers several methodological benefits. First, it provides a structured and replicable framework for managing complex, multi-criteria decisions. Second, it facilitates stakeholder inclusivity by integrating expert perspectives into a formalised model. Third, it produces quantifiable and consistent outputs, enabling systematic comparison across site options. Finally, the inclusion of consistency checks strengthens the reliability of the model and safeguards against biased or inconsistent input.

3.5 Monte Carlo Simulation for Robustness Testing

To enhance the reliability and robustness of the results obtained from the Analytic Hierarchy Process (AHP), this study incorporates Monte Carlo Simulation (MCS) as a complementary validation technique. While AHP effectively captures stakeholder judgments and translates them into quantifiable priority weights, the method is deterministic and inherently sensitive to subjectivity in expert inputs. By applying MCS, the study introduces a probabilistic layer to examine how uncertainty in these inputs might influence the final site rankings and overall decision model stability.

Monte Carlo Simulation involves the generation of many random scenarios, each based on plausible variations in input data. In this study, the simulation is applied to the AHP-derived criteria weights, which were obtained through pairwise comparisons and stakeholder aggregation. Recognizing that these weights are subject to judgmental variability, probability distributions were

assigned to each of the ten criteria in the Hazardous Waste Management (HWM) Index. These distributions were constructed based on the observed ranges and standard deviations of stakeholder responses. Each simulation run generates a new set of weight values by randomly sampling from the predefined distributions, subject to the constraint that the total weight must sum to one. This set of weights is then applied to the site evaluation matrix, and the resulting composite scores are used to determine the ranking of alternative sites. This process was repeated over 1,000 iterations to ensure the statistical reliability of the results and to generate a distribution of possible outcomes for each site.

The simulation enables an analysis of ranking stability and sensitivity. Sites that consistently appear in the top positions across many iterations are deemed robust, while those that fluctuate significantly indicate greater sensitivity to changes in input assumptions. This information provides a deeper understanding of which criteria most influence the overall ranking and whether the initial AHP-derived decision is resilient under varying conditions. Moreover, Monte Carlo outputs include confidence intervals, mean rankings, and standard deviations for each site, offering an additional layer of transparency and precision in the decision-making process. These outputs can support policymakers in making informed decisions by highlighting areas of uncertainty and identifying criteria that may warrant further scrutiny or data collection.

The integration of Monte Carlo Simulation into the AHP framework exemplifies a methodologically rigorous approach to decision support. It reflects best practices in environmental systems planning by combining expert judgment with stochastic modelling, ensuring that the resulting site selection model is not

only grounded in stakeholder input but also capable of withstanding the inherent uncertainties of real-world applications. This probabilistic validation is particularly valuable in the context of hazardous waste management, where decisions have long-term environmental and public health implications. As such, the MCS-AHP hybrid approach adopted in this study represents a transparent, reliable, and adaptable methodology for evaluating infrastructure alternatives in data-limited and high-stakes contexts.

3.6 Individual Contributions of AHP and Monte Carlo Simulation

The integration of Analytic Hierarchy Process (AHP) and Monte Carlo Simulation (MCS) in this study provides complementary strengths, but it is important to clarify their individual roles. AHP serves as the deterministic core of the framework. It translates expert judgment into structured, quantifiable weights across the ten criteria of the Hazardous Waste Management (HWM) Index. By applying pairwise comparisons and consistency checks, AHP produces a transparent ranking of priorities and ensures that complex trade-offs are expressed in a reproducible form (Saaty, 2008). This step directly reflects stakeholder preferences and generates the baseline results for site selection. Monte Carlo Simulation, by contrast, provides the probabilistic layer of validation. While AHP produces a single set of rankings, MCS introduces random variation into the AHP-derived weights, running thousands of iterations to test the sensitivity and stability of outcomes. This stochastic approach accounts for the uncertainty inherent in expert judgment and highlights criteria

that exert the strongest influence on ranking shifts (Saltelli et al., 2004). The outputs — such as distributions, rank transitions, and confidence intervals — reveal whether the baseline AHP results are robust or fragile under different assumptions.

Individually, AHP establishes the structured decision framework, while Monte Carlo Simulation strengthens its credibility by testing resilience under uncertainty. Together, they form a hybrid model that combines deterministic transparency with probabilistic robustness, ensuring that the final recommendations are both methodologically rigorous and policy relevant.

3.7 Stakeholder Engagement , Data collection ,and Ethical Considerations

The development of the Hazardous Waste Management (HWM) Index within the Analytic Hierarchy Process (AHP) framework required rigorous and inclusive stakeholder engagement. Given the complexity and sensitivity of hazardous waste treatment site selection, the study sought to incorporate a broad spectrum of expert opinions to ensure the resulting model reflected the realities, priorities, and constraints of national environmental planning.

Stakeholders were carefully selected to represent three key groups. The first group comprised industry practitioners directly involved in hazardous waste management operations, including facility operators, logistics coordinators, and

environmental compliance officers. Their contributions offered operational and technical insights into the feasibility and practicality of siting decisions. The second group consisted of indirect industry stakeholders, including representatives from industries that generate hazardous waste but do not manage it directly. These participants contributed broader economic and strategic perspectives. The third group involved academic researchers and domain experts, who offered analytical depth and methodological input to ensure the scientific robustness of the index and weighting processes.

Data collection was conducted using structured surveys and guided interviews. Participants were introduced to the HWM Index framework and asked to perform pairwise comparisons of the ten site selection criteria based on Saaty's 9-point scale. These judgments formed the basis for the AHP pairwise comparison matrices, which were subsequently used to derive criteria weights. The structured nature of this process allowed for the transformation of subjective expert input into objective, quantifiable weights, forming the analytical backbone of the study's evaluation framework.

To maintain methodological integrity, the stakeholder engagement process was designed with clear ethical guidelines. All participants were briefed in advance about the purpose of the research, the nature of the AHP method, and how their inputs would be used. Participation was voluntary, and all responses were anonymized to reduce bias and encourage open, honest contributions. Feedback

was collected independently, without group influence, and moderated impartially to ensure balanced representation across all stakeholder groups.

Ethical considerations were further reinforced by ensuring transparency, confidentiality, and respect for participant input. Data were recorded and stored securely, and findings were reported in aggregate form without attribution. This approach not only upheld the ethical standards expected of academic research but also enhanced the legitimacy and acceptability of the final model among stakeholders.

Chapter 4

In-depts analysis of hazardous waste management in Malaysia : Smart and innovative solution for Malaysia's resilient future

4.1 Hazardous waste in-depth analysis in Malaysia

Malaysia generated approximately 7.5 million tonnes (Mt) of hazardous waste in 2021, representing a 4.5% increase compared to 7.2 Mt in 2020. Notably, clinical waste increased sharply by 43.9%, from 0.39 Mt in 2020 to 0.57 Mt in 2021. According to the Department of Statistics Malaysia (DOSM, 2022), hazardous waste generation is projected to reach 20.8 Mt by 2030, reflecting a compound annual growth rate (CAGR) that aligns with increasing urbanisation, industrialisation, and population growth. This upward trend has significant environmental and public health implications, particularly in light of unscientific waste disposal practices and the limited reach of advanced treatment technologies. The growing volume of hazardous waste is further exacerbated by inadequate infrastructure for proper collection, treatment, and disposal. Much of the waste is currently stored on-site or managed through basic containment systems, with only 26.41% being treated or recovered through environmentally sound methods (DOSM, 2022). The persistence of outdated

practices and infrastructure deficiencies highlights a critical need for modernisation and regulatory reinforcement in hazardous waste management. Despite advancements in environmental awareness and regulatory frameworks, Malaysia's overall approach to hazardous waste remains largely reactive and fragmented. There is a pressing need for integrated, scientifically driven strategies that prioritise long-term sustainability and public health. Existing technologies are often insufficient to address the scale and complexity of contemporary hazardous waste streams, resulting in negative consequences for environmental quality, ecosystem integrity, and national economic performance (Artika H et al., 2019).

An overview of national waste generation and macroeconomic data is presented in Table 4.1, which summarises Malaysia's Gross Domestic Product (GDP), solid waste growth rates, and population dynamics between 2015 and 2021. While population growth has remained relatively stable at around 1.2% to 1.5% annually, GDP growth has fluctuated significantly—from a contraction of -5.53% in 2020 due to the COVID-19 pandemic to a rebound of 5.81% in 2017. Likewise, solid waste generation varied widely, ranging from a decrease of -27.06% in 2017 to a sharp increase of 79.03% in 2020. These trends underscore the complexity of hazardous waste generation, which is influenced by multiple, interrelated drivers.

Several factors have been identified as key contributors to hazardous waste trends in Malaysia. First, rapid industrial expansion and shifts in consumption patterns have led to increased demand for resource-intensive goods and services,

thereby elevating hazardous waste outputs. Economic growth in sectors such as petrochemicals, agriculture, and healthcare has resulted in higher volumes of scheduled waste, including industrial sludges, solvent residues, and biomedical materials.

Second, limitations in waste management infrastructure continue to hinder effective handling. Many facilities lack the capacity, technology, or geographic coverage to manage increasingly diverse and hazardous waste streams. This inadequacy often results in improper storage, illegal dumping, or over-reliance on outdated treatment methods, further compounding environmental risks.

Third, inconsistencies in regulatory enforcement present additional challenges. While Malaysia has established legislation for hazardous waste control including the Environmental Quality Act 1974 and its associated regulations implementation remains uneven. Varying degrees of compliance, limited monitoring capacity, and overlapping institutional responsibilities undermine the effectiveness of these frameworks (Jessie Yeung, 2020a).

Finally, the COVID-19 pandemic introduced significant disruption. In 2020, the country experienced negative GDP growth alongside a surge in hazardous waste generation. Changes in production, consumption, and healthcare activities during the pandemic altered waste generation profiles and stressed existing treatment capacities. These disruptions illustrate the vulnerability of Malaysia's

waste management system to external shocks and reinforce the need for resilient, forward-looking policies.

This section sets the foundation for subsequent analyses by highlighting the urgent need for coordinated policy reform, strategic infrastructure development, and robust decision-support tools. The integration of multi-criteria decision-making methods, as detailed in the following sections, seeks to address these gaps and enhance Malaysia's capacity for sustainable hazardous waste planning.

Table 11: Hazardous waste generated, grow rate, population and GDP grow rate.

Year	SW Generated (t)	SW grow rate (%)	Population grow rate (%)	GDP grow rate (%)
2015	2,918,478	N/A	1.51	5.09
2016	2,766,614	-5.21	1.47	4.45
2017	2,017,280	-27.06	1.43	5.81
2018	2,355,085	16.75	1.32	4.84
2019	4,013,188	70.42	1.25	4.41
2020	7,185,230	79.03	1.21	-5.53
2021	7,505,200	4.46	N/A	3.09

4.2 Gap analysis and challenges in Malaysia's of hazardous waste management

A thorough evaluation of hazardous waste management in Malaysia, in relation to national regulations, operational capacity, and environmental policies, reveals several significant gaps that undermine the country's ability to ensure sustainable and effective waste governance. This section presents an analysis of current system limitations and the barriers impeding Malaysia's progress toward a resilient hazardous waste infrastructure. The analysis draws upon the regulatory framework under the Environmental Quality Act (EQA) and Scheduled Waste Regulations, alongside stakeholder observations and performance data. A schematic overview of the analytical framework is presented in **Figure 8**.

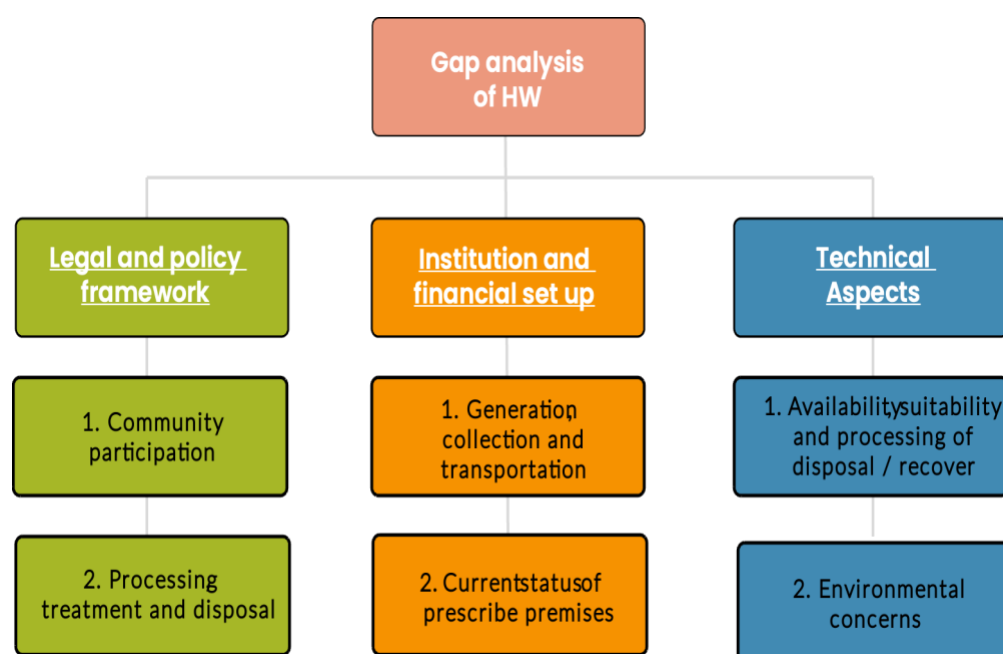


Figure 8 Assessment of current situation or status and gap analysis in the country.

Despite the existence of formal waste control legislation, service coverage and performance vary substantially across regions. The baseline study highlights discrepancies between regulatory requirements and actual implementation, especially in remote or underdeveloped areas. Local demographic and geographic conditions, as well as differing levels of environmental governance, further exacerbate regional inequalities in waste service provision.

Stakeholder engagement studies such as that by Shanmugaraj (2018) have emphasised the importance of multi-sectoral collaboration in shaping effective waste management. Civil society organisations like the Malaysian Environmental NGOs Coalition (MENGO) play a critical advocacy and monitoring role. However, collaboration between governmental, private, and community actors remains inconsistent and often fragmented. Malaysia's hazardous waste sector faces a range of persistent and interrelated challenges. Technical and infrastructural barriers include the limited number of centralised treatment facilities, insufficient waste collection points, outdated waste transportation mechanisms, and the absence of robust technologies for segregating and treating complex hazardous streams (Chin and Yong, 2019). Organisational challenges are compounded by institutional silos and weak inter-agency coordination. The lack of clearly defined roles and data sharing protocols impairs overall system responsiveness and planning.

Socio-cultural barriers also inhibit progress. Public awareness of hazardous waste risks remains low, contributing to poor waste separation at source and

limited participation in recovery and recycling programmes. Financial constraints further limit the establishment of modern facilities, as the high capital and operational costs often deter investment. Political and legal challenges, including regulatory gaps, inconsistent enforcement, and changing policy priorities, also contribute to long-term uncertainty and underperformance (NEHAP, 2020). **Table 12** summarises the key challenges identified across technical, financial, institutional, and social domains, which collectively inform the strategic directions discussed in the next section.

Table 12. Key challenges of hazardous waste management in Malaysia covering

Factor	Trends	Challenges	Opportunities	References
Economic development	Malaysia's economy rebounds post-Covid-19, projecting 6.5% (2021) and 6% (2022) GDP growth rates	Economic resurgence might augment goods and service demand, potentially escalating hazardous waste generation	Economic recovery engenders resources and incentives for waste management, spanning infrastructure, technology, and innovation.	(BNM, 2022; MoE, 2022; World Bank, 2022)
Government policies and regulation	Malaysia enforces diverse policies, e.g., Environmental quality Act 1974, for hazardous waste governance	Inconsistent enforcement and compliance due to capacity and coordination gaps challenge policy efficacy	Enhanced policies and regulation heighten waste management standards, fortifying monitoring, evaluation, and accountability.	(DOE, 2001) ,(GSSB, 2020; NEHAP, 2020)
Population growth	Malaysia population moderately grown at 0.8% annually (2020-2025)	Population surge may elevate goods and services consumption, correlating with increased hazardous waste production	Growth prompts heightened awareness nurturing waste management initiatives through education, participation, and collaboration.	(DOSM, 2021; World Bank, 2022)
Stakeholder involvement	Malaysia stakeholders – NGSs researchers, service providers support waste management endeavors.	Fragmented involvement stemming from communication and cooperation deficits constrains stakeholder impact	Stakeholder integration enhances collaboration, facilitates dialogue, and empowers diverse industry and consumer engagement.	(TS Shanmugaraj, 2018), (Vlerë Hyseni, 2023)

4.3 Strategic Approaches to Strengthen Hazardous Waste Management in Malaysia

In response to the challenges identified in the preceding analysis, a range of strategic interventions is proposed to strengthen Malaysia's hazardous waste management framework. As outlined in **Figure 9**, the proposed strategy includes both short-term corrective actions and long-term systemic reforms, designed to align the country's hazardous waste policies with sustainability objectives and international best practices.

Central to this strategy is the development of a comprehensive National Hazardous Waste Management Master Plan, coordinated across federal, state, and local levels. The plan should establish clear targets, implementation mechanisms, and performance indicators. Priority actions include expanding infrastructure coverage, particularly in under-served regions, and upgrading treatment technologies to support compliance with evolving environmental standards (MIDA, 2021a).

Malaysia's hazardous waste management framework



Figure 9 Malaysia's hazardous waste management framework covering different spectrum

Improving the national data infrastructure is equally essential. Malaysia's hazardous waste tracking systems, such as the Electronic Scheduled Waste Information System (eSWIS), must be strengthened to ensure accurate, real-time monitoring of waste flows and treatment outcomes. Enhanced data transparency will support better risk assessment, facility planning, and regulatory enforcement (eSWIS, 2019).

Promoting cleaner production and sustainable waste minimisation is another critical pillar. Initiatives such as industrial symbiosis, circular design, and green technology incentives can reduce waste generation at source (Adami and Schiavon, 2021b; Asian Development Bank, 2020). Strengthening the capacity

of existing facilities and introducing decentralised, modular treatment systems can also increase resilience and reduce logistic inefficiencies.

Raising public awareness and fostering environmental education are key to promoting behavioural change. Public campaigns should communicate the risks of improper hazardous waste disposal, while also highlighting opportunities for recovery and resource reuse (Debrah et al., 2021; Hamzah et al., 2022). Equally important is improving stakeholder coordination through structured engagement platforms that link government regulators, industry actors, and civil society organisations (Song et al., 2021; Vasconcelos et al., 2022).

In sum, Malaysia's hazardous waste strategy must move from a reactive, compliance-based model to a proactive, integrated framework that leverages data, technology, and cross-sector collaboration. These interventions will not only enhance national environmental performance but also position Malaysia as a regional leader in sustainable hazardous waste governance.

4.4 Hazardous waste quantification , environmental impact assessment & Effective tracking and reporting of hazardous waste

A comprehensive understanding of hazardous waste generation and its impacts requires a dual focus on quantification and environmental impact assessment, supported by robust tracking and reporting mechanisms. In Malaysia, the Department of Statistics Malaysia (DOSM) and the Department of Environment (DOE) play critical roles in facilitating the collection, classification, and evaluation of hazardous waste data. According to DOSM (2021), hazardous waste production is quantified primarily through records obtained from the Electronic Consignment Note (ECN) system, administered via the Electronic Scheduled Waste Information System (eSWIS). This system mandates licensed facilities to report waste generation, handling, transportation, and disposal data in a consistent and traceable manner.

The quantification process, supported by ECN data, provides granular insights into the volume, source, and type of hazardous waste generated across various sectors, including industrial, agricultural, and healthcare domains. This data forms the basis for assessing the environmental burden of hazardous waste, particularly in terms of risks to air, water, and soil quality. Inadequate treatment or improper disposal of such waste can lead to soil contamination, groundwater pollution, and long-term ecological degradation. These risks reinforce the importance of accurate waste data collection, as well as the integration of environmental impact assessments into waste policy and facility planning.

Figure 10 presents an overview of the hazardous waste management workflow in Malaysia, incorporating proposed enhancements to the ECN tracking mechanism. This includes streamlined procedures for data collection, automated input and verification systems, and integrated reporting protocols. These modifications aim to improve the traceability and responsiveness of the system, enabling real-time monitoring and data-driven environmental oversight.

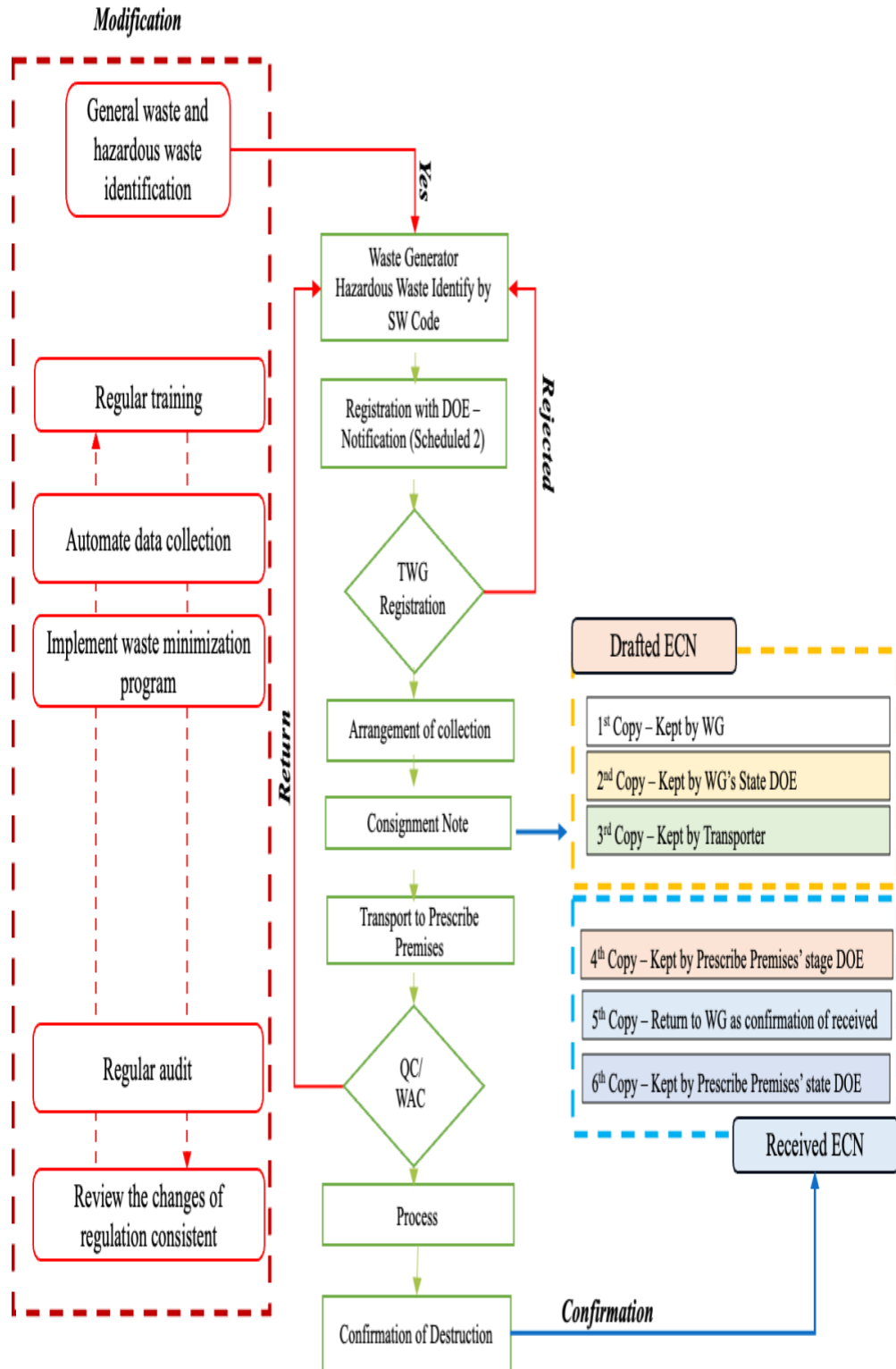


Figure 10 Overview of hazardous waste disposal procedure in Malaysia with proposed modification of such framework.

In developing economies such as Malaysia, hazardous waste generation is intrinsically linked to the pace and structure of industrial growth. The unique profiles of industries—ranging from electronics and petrochemicals to pharmaceuticals—significantly influence both the quantity and toxicity of waste streams. As such, recognizing industrial expansion patterns is essential for anticipating future waste challenges and planning appropriate interventions.

To support environmentally sound management, this study proposes an optimization strategy encompassing key measures: improved waste identification and classification, regular training of facility staff, automation of data capture, minimization at source, periodic regulatory audits, and systematic review of relevant legislation. These actions collectively enhance operational efficiency, ensure compliance with environmental regulations, and build capacity for proactive waste governance.

Effective waste tracking and reporting systems are indispensable for regulatory enforcement and strategic planning. Under Malaysia's existing framework, both physical and electronic consignment notes are employed to document hazardous waste movements from generation to final treatment or disposal. However, operational inefficiencies, data delays, and limited inter-agency integration remain persistent challenges. The full adoption and continuous enhancement of electronic tracking systems such as eSWIS can significantly mitigate these issues. By offering real-time data access, automated reporting, and standardized

protocols, such systems support transparent oversight, strengthen institutional accountability, and improve environmental outcomes.

The environmental consequences of deficiencies in hazardous waste tracking are substantial. As noted by Misra and Pandey (2005), mismanagement can lead to widespread contamination of ecosystems and pose significant public health risks. Hence, rigorous monitoring, combined with effective legislation and cross-sectoral collaboration, is vital to ensure that hazardous waste is managed responsibly and in alignment with sustainability goals.

4.5 SWOT analysis for sustainable hazardous waste management

In the evolving landscape of hazardous waste management, strategic planning grounded in a structured assessment framework is essential. A SWOT analysis—evaluating Strengths, Weaknesses, Opportunities, and Threats—provides a foundational tool for diagnosing system performance and identifying targeted interventions. This section applies a stakeholder-informed SWOT framework to Malaysia’s hazardous waste management system, incorporating perspectives from public agencies, private sector operators, and civil society organizations. A synthesis of the findings is illustrated in **Figure 11**.

SWOT Analysis Infographics

Private, public, community sector for sustainable hazardous waste management

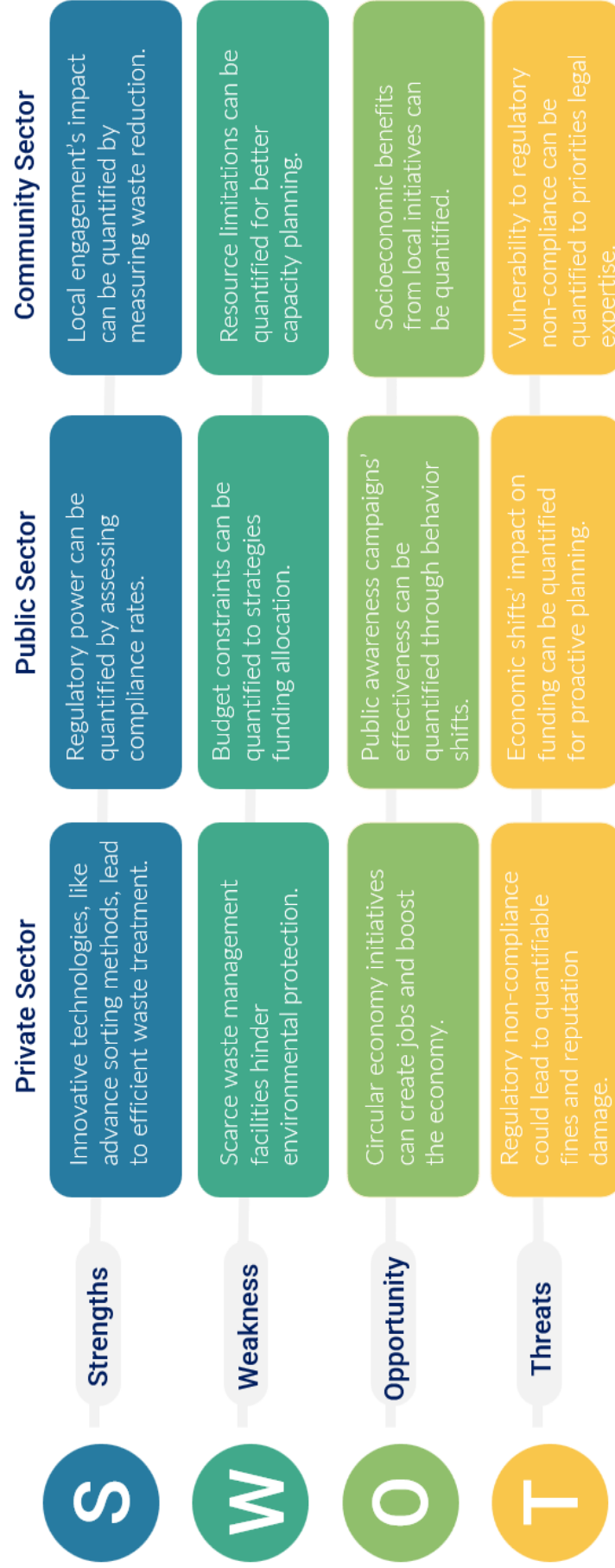


Figure 11 SWOT analysis for sustainable hazardous waste management -details of SWOT in different spectrum.

Malaysia's hazardous waste sector is underpinned by several intrinsic strengths. Chief among these is the existence of a robust regulatory foundation, exemplified by the Environmental Quality Act of 1974 and its supporting regulations, which collectively demonstrate the government's longstanding commitment to environmental protection (DOE, 2001). Emerging technological capabilities such as cradle-to-cradle (C2C) principles and pilot-scale waste-to-resource programmes also offer a progressive foundation for system innovation. In addition, established networks of technical and regulatory expertise across agencies and academic institutions provide Malaysia with a strong base for collaborative problem-solving and adaptive capacity building.

However, critical weaknesses persist that limit the effectiveness of the system. Foremost are the shortage and uneven distribution of hazardous waste treatment infrastructure, particularly in East Malaysia and rural industrial zones. This limitation impedes efficiency and increases logistical costs. Further challenges arise from underinvestment in new technologies, limited private sector participation, and the overregulation of certain processes, which stifles innovation. Quantifying these gaps—particularly in terms of treatment capacity shortfall and regional service disparities—is crucial for informed planning and resource allocation.

Within this context, numerous opportunities can be harnessed. The alignment of Malaysia's national policies with international environmental standards (e.g., Basel Convention compliance and SDG frameworks) presents avenues for

regulatory harmonization, green investment, and technology transfer. The development of a circular economy model in hazardous waste—through initiatives such as resource recovery, industrial symbiosis, and localized recycling—could generate economic and employment benefits, especially for small and medium-sized enterprises. Additionally, awareness campaigns and capacity-building programmes offer opportunities to improve public engagement and expand participation in sustainable waste practices.

Conversely, several external threats may compromise progress. The COVID-19 pandemic has diverted public funding and attention away from long-term environmental investments, delaying key infrastructure projects. Climate-related disasters, such as floods or landslides, also pose growing risks to waste storage and treatment facilities. The continued presence of ambiguous classification standards increases the likelihood of illegal dumping, while fluctuating policy priorities and limited institutional coordination weaken enforcement mechanisms. Quantitative risk assessments and scenario planning are urgently needed to build resilience against these threats.

By combining these internal and external factors, this stakeholder-informed SWOT analysis supports the design of targeted, evidence-based strategies for system reform. A quantified and participatory approach enables prioritization of interventions, efficient allocation of resources, and systematic monitoring of progress over time. Furthermore, by incorporating the perspectives of key actors—government agencies, industries, and local communities—this

assessment framework ensures that planning is both inclusive and contextually grounded.

Overall, the SWOT analysis functions not merely as a diagnostic tool but as a strategic compass for advancing Malaysia's hazardous waste management towards a more sustainable, decentralized, and resilient system. As demonstrated in **Figure 12**, the findings directly inform the development of policy roadmaps and operational strategies, linking systemic gaps to actionable reforms. This approach is consistent with international best practices and mirrors the participatory model highlighted by Palika et al. (2017), which advocates for stakeholder-led policy innovation in environmental governance.

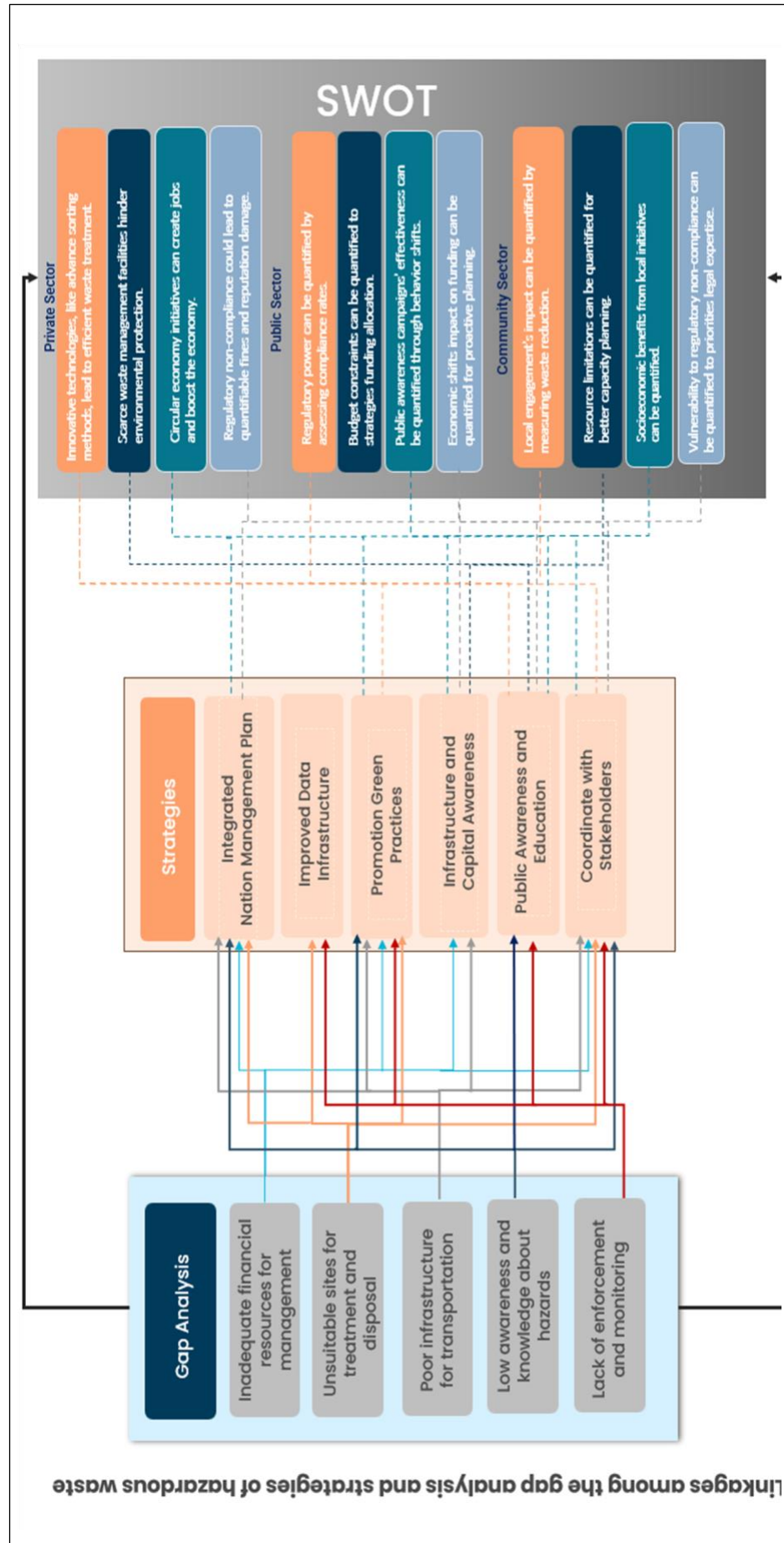


Figure 12 SWOT analysis for sustainable hazardous waste management - the linkage between the gap identified with substantial strategies steered by SWOT components.

4.6 Trends and future outlook

Apart from highlighting the current hazardous waste management practices in Malaysia as being discussed in previous sections, this section provides explicit insights on the research trends aligning with the theme of sustainable hazardous waste management. A total of 648 published journal article was identified from the Web of Science database, and the pool of published work is translated into a visualization of research hotspot with VOS Viewer as shown in **Figure 13**. Different clusters of hotspots were identified that would provide the trends and probable research direction devoted to this specific field. The hotspot identified are macroscopic projections, public health, e-waste, treatment efficiency, and industrial sector; in which a substantial discussion is made by following the sequence mentioned.

The emergence of macroscopic projections is serving as a pivotal area of focus, reflecting on the assorted strategies and practices deployed by different countries globally. A profound exploration of individual nations' models, substantiated by meticulous case studies, unveils a diverse array of methodologies, each delineating a distinct balance between industrial growth and ecological sustainability. Countries are epitomizing the incorporation of environmental considerations within industrial development, establishing benchmarks in innovative waste management strategies. Meanwhile, the emerging economies are endeavouring to calibrate the delicate balance between fostering industrial growth and integrating sustainable waste management

practices, augmenting the breadth of research to evolve universally applicable and eco-conscious waste management frameworks.

In parallel, the interaction between public health and sustainable development is becoming a focal area of study, underlining the essential linkage between environmental conditions and human well-being. A significant aspect of this intersectional research is the management of e-waste, which, due to its rapidly increasing volumes and intricate composition of hazardous materials, is emerging as a central concern. The in-depth analysis and development of sustainable strategies for e-waste management are crucial for mitigating environmental degradation and its consequent impacts on public health. The necessity for robust recycling, recovery, and disposal strategies is underscored by the potential health risks associated with mismanaged e-waste, pushing the research boundaries to develop comprehensive and sustainable solutions. This synergistic approach is acting as a catalyst for extensive research, paving the way for holistic and multi-dimensional strategies, emphasizing harmonized solutions that encompass environmental, social, and health dimensions concurrently.

Intricately woven into this research spectrum are in-depth analyses focusing on the optimization of waste treatment methodologies, encompassing the heterogeneous waste produced by diverse industrial sectors like construction and oil refineries. The comprehensive evaluation of these varied treatment modalities is integral to refining waste management strategies, focusing on the pivotal aspects of environmental conservation, waste reduction, and resource recovery. The amalgamation of evaluative methodologies with breakthrough technologies is elevating the paradigms of industrial waste management, aligning industrial operations with ecological conservation aspirations. This synergistic fusion of innovative technologies with analytical insights is pivotal in addressing the multifaceted challenges presented by disparate industrial wastes, ensuring the seamless coexistence of industrial advancement with ecological sustainability.

Given the extensive and multifaceted nature of these research domains, it is essential to emphasize the significance of international collaboration and cohesive policy frameworks to address the transboundary movement of hazardous waste. The dynamic realm of international trade and globalization mandates a unified approach to regulating hazardous waste movements globally, reinforcing adherence to environmental conservation and sustainability norms. The collaborative development and rigorous implementation of international policies and agreements are crucial in fostering mutual accountability and cooperation among nations, promoting responsible hazardous waste management and adherence to sustainability principles.

4.7 Smart and innovative incorporation

The evolution of hazardous waste management is pivotal in today's rapidly industrializing world, where the amalgamation of innovative and intelligent solutions is becoming increasingly essential to manoeuvring the environmental challenges of waste in a sustainable manner. Advanced sensor technologies are central to this transformative journey, providing a new dimension of monitoring waste storage conditions in real-time. This real-time monitoring enables the detection and mitigation of potential hazards and contaminations, subsequently enhancing environmental safety and resilience. The capability to monitor waste storage conditions continuously is foundational for embedding Artificial Intelligence (AI) in waste management systems. For instance, study by Shi et al., (2023) developed a prediction model which analysed the hazardous waste generation in Shanghai. AI, leveraging predictive analytics, serves to optimize waste collection routes and schedules meticulously. The optimized processes not only streamline operational efficiency but also significantly reduce emissions and fuel consumption, thereby minimizing the overall environmental footprint of waste collection endeavours. A detailed review by Fang et al., (2023) has described the incorporation of AI for an efficient waste management in smart cities. Apart from that, it is possible to adapt the framework proposed by Ya et al., (2023) with the aid of AI which identify the lifespan of landfill for hazardous waste with various model discussed in the study.

In this technological renaissance of waste management, blockchain technology emerges as a revolutionary force, instilling unparalleled levels of traceability

and accountability in waste disposal and recycling processes. Blockchain's intrinsic secure and immutable characteristics ensure the integrity and legality of waste management data, creating a formidable barrier against illegal dumping and unscrupulous waste disposal practices. A study by Hrouga et al., (2022) has layout the potential of incorporating blockchain in the hazardous waste management (specifically asbestos) with the logic of reverse logistics. Then, a comprehensive framework (Song et al., 2022) of hazardous waste transport management system is then discussed on covering different factors including infrastructure, blockchain services, related functions, and end-users. This development is monumental in establishing responsible and transparent waste management practices globally. The amalgamation of real-time sensor data, predictive analytics, and blockchain's secure traceability formulate a robust, innovative approach to hazardous waste management, embedding core values of transparency, efficiency, accountability, and sustainability in every facet of waste management.

However, technological innovations alone cannot encapsulate the entirety of sustainable waste management; they must intertwine with economic and ecological models that champion sustainability. Here, the principles of the circular economy serve as a beacon of transformation, transcending conventional linear economic models that are inherently unsustainable. Circular economy initiatives like zero-waste cities and cradle-to-cradle product designs emphasize resource conservation, waste reduction, and recycling, modelling a more sustainable and responsible industrial ecosystem. Ilyas et al., (2021) has demonstrated the possibility of restoration for copper and gold via microbial

with the concept of circular bioeconomy. These initiatives challenge and reconfigure the traditional ‘take, make, consume, dispose of’ model, redirecting the industrial trajectory towards a harmonious balance between progress and preservation (Calderón Márquez and Rutkowski, 2020). Commonly, the circular economy is coupled and assessed with life cycle assessment (LCA) which could be simply adapt in the scenario of hazardous waste management. Various studies have demonstrated the integration of LCA in hazardous waste management with various scenarios such as the fly ash from municipal solid waste incineration (Hossain et al., 2020), medical waste during Covid-19 (Zhao et al., 2021), polymer electrolyte membrane fuel cell (Stropnik et al., 2019), fluorescent powders (Yang et al., 2019), waste cooking oil (Hosseinzadeh-Bandbafha et al., 2022), and air pollution control residues (Maresca et al., 2022). The fusion of circular economy models with renewable energy innovations marks a significant stride in solidifying the role of sustainability in waste management.

This harmonious integration offers sustainable energy solutions while promoting holistic environmental conservation. By mitigating vulnerabilities associated with resource scarcity, these integrated models are poised to rejuvenate economic landscapes, fostering a symbiotic relationship between industrial development and ecological well-being. The amalgamation of circular models and renewable energy innovations is an embodiment of sustainable evolution, transcending the boundaries of conventional waste management and setting the stage for a future where resource efficiency and sustainability are synonymous with industrial progress.

Amidst the myriad of technological and ecological innovations, the exploration and development of advanced material recovery techniques are reshaping the waste management landscape. Hydrometallurgical processes (Sethurajan et al., 2019) and bio-based recovery methods (Upadhyay and Ramayya, 2023) are emerging as beacon technologies, unlocking new potentials for extracting valuable materials from e-waste and organic waste. These novel methodologies are critical in combatting the escalating challenges posed by resource scarcity and environmental degradation. They signify a paradigm shift in waste management practices, aligning industrial advancements with ecological imperatives and creating a balanced and sustainable intersection between the two. Hydrometallurgical processes mitigate the environmental impacts associated with conventional metal extraction methods, offering a sustainable alternative that also addresses the burgeoning global e-waste crisis. Concurrently, bio-based recovery methods harness the power of biodegradability, extracting valuable materials from organic waste and fostering ecological harmony. These innovations represent the dawn of a new era in waste management, where technological advancements and ecological preservation coalesce to form a cohesive and balanced approach to handling waste sustainably.

However, realizing the vision of fully sustainable hazardous waste management necessitates robust and coherent global policy frameworks as well as international collaborations. The intricate complexities and transboundary nature of hazardous waste movements necessitate a unified international approach, one that mitigates risks and fosters ethical and equitable waste

management practices worldwide (Loy et al., 2023). For instance, a study which aims to project an ideal solution for plastic waste management covering multiple nation was conducted. Policies focusing on regulating transboundary movements of hazardous waste and fostering green product designs are paramount. These policies play a pivotal role in driving industrial transformation, encouraging the inception of eco-friendly products, and enhancing life-cycle management as demonstrated in China (Guo et al., 2021) and Latin America (Margallo et al., 2019). The robust global policy frameworks act as the linchpins for establishing international collaborations, fostering a global culture of shared responsibility, mutual accountability, and environmental conservation. They serve as the catalysts for cultivating global environmental stewardship and driving industrial transformations towards sustainable practices. These policies, coupled with innovations in technology and circular economy models, are integral components in steering hazardous waste management towards ultimate sustainability such as demonstration by Xavier et al., (2021) on the e-waste management in Americas. They pave the way for a future where ecological balance, sustainable industrial progress, and shared global responsibility coexist seamlessly, guiding humanity towards a harmonious and resilient future.

In conclusion, the convergence of digital transformations, innovative material recovery methodologies, circular economy principles, and robust global policies and collaborations presents a multifaceted approach to hazardous waste management. This integrated approach promotes environmental conservation, economic resilience, operational efficiency, and global responsibility, aligning

the aspirations of industrial progress with the imperatives of ecological balance and sustainability. The ongoing innovations and integrations in the realm of waste management are critical in achieving long-term environmental harmony and resilience. The cumulative effect of these developments marks a significant step forward in the quest for a future where the symbiosis between industrial development and ecological sustainability is not a mere aspiration but a tangible reality.

Chapter 5

Hazardous waste management plant selection by HWM Index using AHP method

5.1 Introduction

This chapter presents the results of the Analytic Hierarchy Process (AHP) and Monte Carlo Simulation, both of which were used to evaluate and prioritize criteria for hazardous waste treatment plant site selection. The results are structured in a sequential manner to provide a comprehensive discussion, beginning with the overall findings and followed by a detailed breakdown of the stakeholder-specific perspectives from Group 1- Industry players, Group 2 - Others Industry Players, and Group 3 – Researcher. The ranking stability and sensitivity analysis further validate the reliability of the findings.

The structure of this chapter is as follows:

- i. Overall AHP results – Presents the final ranking of criteria based on the combined input from all groups.

- ii. Stakeholder specific results – Provides separate analyses for each group, highlighting their priorities.
- iii. Comparative analysis – Compares variations in ranking among different groups and discusses the implications of stakeholder differences.
- iv. Monte Carlo simulation analysis – Examines the stability of ranking through uncertainty analysis.

By following this structure, the discussion ensured that both the quantitative results and qualitative insights are clearly communicated. The next section presents the overall AHP results , which form the foundation for subsequent analyses.

5.2 Overall AHP Results

5.2.1 Final AHP Weight Rankings (All Groups Combined)

The final AHP weight rankings based on the aggregated input from all groups was presents in **Table 13**.

Table 13 : AHP weight rankings for site selection criteria (All group)

RANK	CRITERIA	WEIGHT
1	Environment	0.1198
2	Risk Management	0.1125
3	Regulatory	0.1079
4	Industry Output	0.1038
5	Economy	0.1034
6	Innovation	0.1027
7	Petrochemical Hub proximity	0.0960
8	Technical	0.0960
9	Existing Waste Structure	0.0812
10	Social	0.0763

The top three criteria Environment, Risk Management, and Regulatory emerge as the most influential factors. These priorities are aligned with stakeholder expectations: a sustainable site must first ensure environmental protection, effective risk mitigation, and strict regulatory compliance. In contrast, social consideration ranks lowest, potentially reflecting a context in which technical, economic, and regulatory factors dominate the decision-making process.

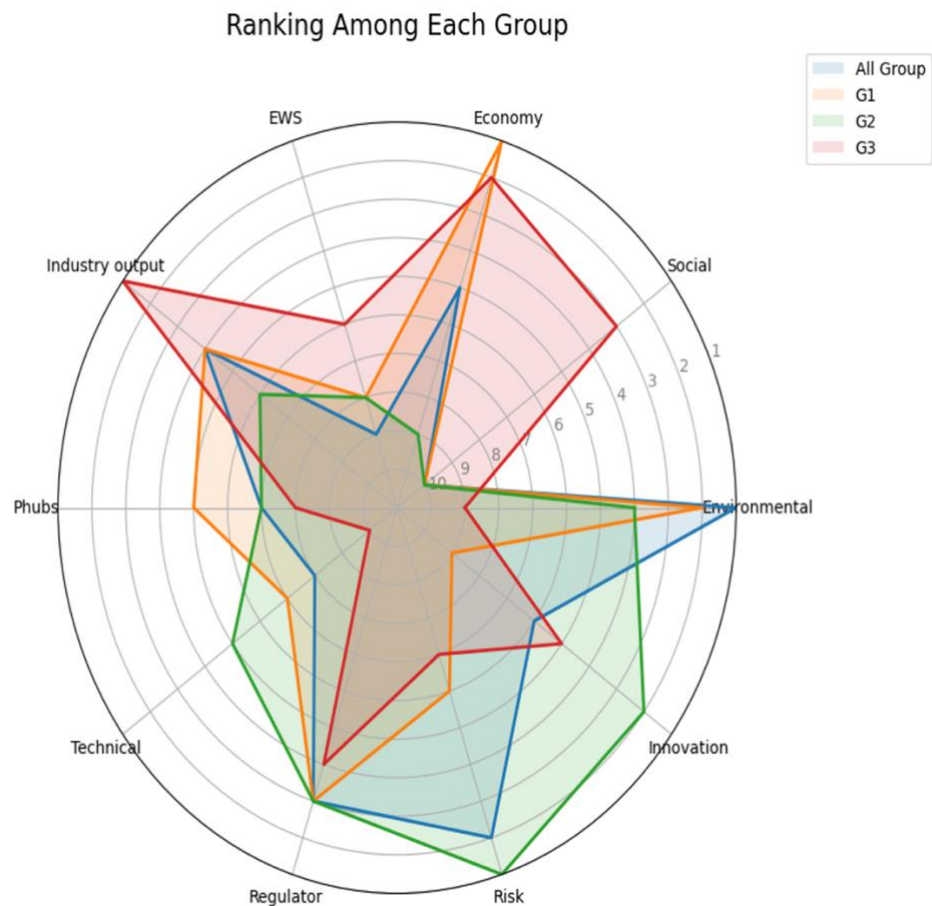


Figure 14 Ranking among each group

The **Figure 14** present the stakeholder-specific ranking preference for hazardous waste treatment site selection it Visualizes how different groups prioritize various criteria, revealing critical insights into industry decision-making. Group 1 – Industry player, Group 2- Others industry planer , Group 3- Researcher .

Environmental Index is a higher -priority factor for Group 1 and 2, while Group 3 assign it lower weight. Group 1&2 prioritize Environmental concerns due to regulatory compliance requirement and sustainability commitments. Group 3 –

Emphasize Risk and Innovation over environmental concerns, suggesting a preference for technology driven solutions.

Table 14 : Interpretation of stakeholder - specific ranking

KEY FINDING	GROUP 1 – INDUSTRY PLAYER	GROUP 2 – OTHERS INDUSTRY PLAYER	GROUP 3- RESEARCHER
ENVIRONMENTAL	High priority due to regulatory compliance and sustainability commitments.	High priority, ensuring minimal environmental damage while maintaining industrial feasibility.	Lower priority, with greater focus on risk and technological solutions.
ECONOMIC	Highest priority, driven by financial feasibility and cost-effectiveness.	Moderate priority but secondary to industrial output.	Lower priority, as long-term sustainability and regulatory compliance are emphasized.

RISK	Considered important but ranked below economic factors.	Important for operational stability but secondary to economic and industrial concerns.	Highest priority, highlighting safety and long-term hazard mitigation.
INNOVATION	Moderate importance, focused on practical and cost-effective solutions.	Considered beneficial but not a primary driver of site selection.	High priority, emphasizing advanced technologies in waste treatment.
INDUSTRY OUTPUT	Important but ranks below financial feasibility and environmental concerns.	Highest priority, ensuring high-volume waste treatment efficiency.	Lower priority, with more emphasis on long-term regulatory and environmental considerations.
REGULATOR	Critical for ensuring legal site operations.	High priority to avoid legal repercussions but with	One of the top priorities, with strict adherence to policies and

		flexibility in environmental compliance regulations. approaches.	
SOCIAL	Low priority, as economic and regulatory aspects dominate decision-making.	Low priority, reflecting the focus on operational feasibility.	Considered more than in other groups but still ranks lower than risk and innovation.
EXISTING WASTE STRUCTURE	Least prioritized, as new infrastructure development is expected.	Minimal consideration, as industrial needs take precedence.	Lower priority, with emphasis placed on new and advanced treatment facilities.

The distinct priorities across stakeholder groups suggest that hazardous waste site selection is a multidimensional decision, requiring balance consideration of environment, economic, and technological factors. These findings provide insights for policy makers and industry planners , regulatory frameworks should align with environmental sustainability while also fostering economic feasibility Industry stakeholders should be incentivized to adopt innovative

hazardous waste treatment methods. Risk assessment models should be integrated into site selection frameworks to enhance long-term sustainability.

5.2.2 Monte Carlo Simulation Results

To incorporate uncertainty and variability in stakeholder judgement, a Monte Carlo Simulation was performed with 1,000 iteration per criterion. The simulation produced the following key insights:



Figure 15 Mean weights with standard deviation

The bar chart **Figure 15** Illustrates the mean weights assigned to each factor based on the AHP analysis across all three stakeholder groups. The standard deviation bars indicate the variability of expert opinions across iterations. Decision-makers prioritize Environmental, regulatory and legal compliance rather than public perception.

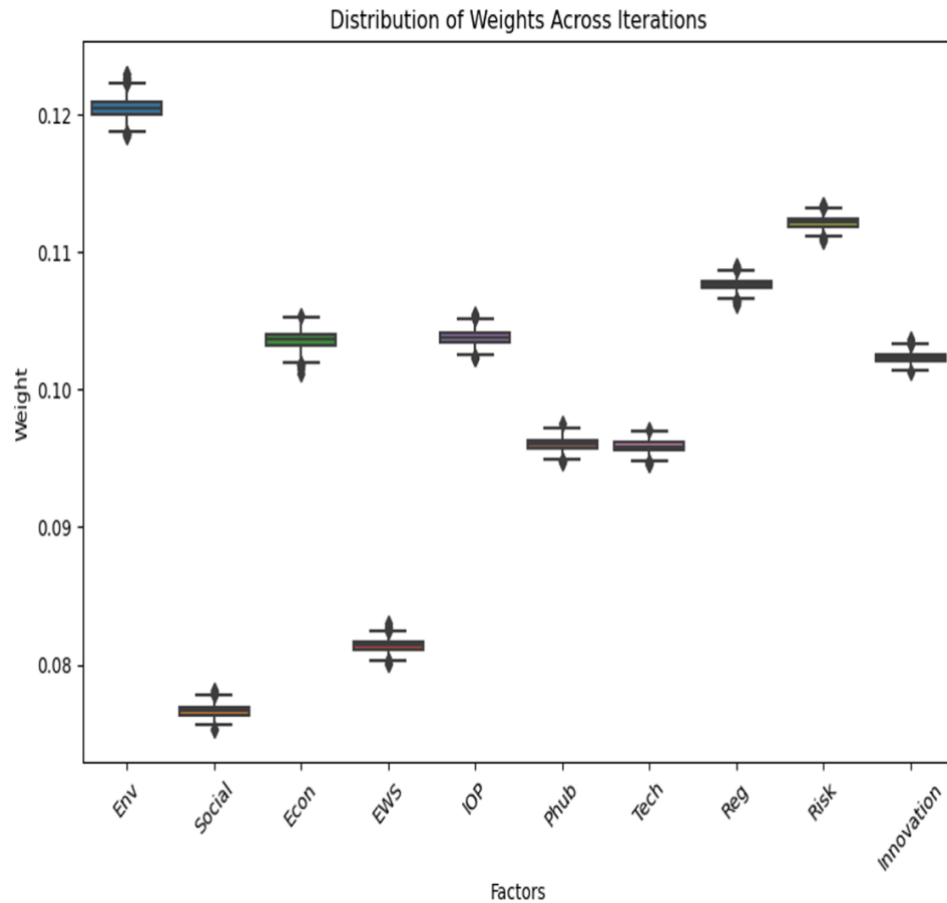


Figure 16 Boxplot of weights across iteration

The boxplot **Figure 16:** represents the distribution of weight variations across different Monte Carlo iterations, providing insight into ranking stability under uncertainty. Environment remains the most influential factor across all simulations, confirming its dominance in decision-making. Regulator and Risk exhibit moderate variability, reflecting slight differences in stakeholder

perspective but remaining amount the top priorities. Social and Existing Waste Structure consistently rank the lowest, with minimal variation, reinforcing that they are not primary decision drivers. The tight clustering of mot weighs suggest that the ranking order remains stable, reinforcing the reliability of AHP results.

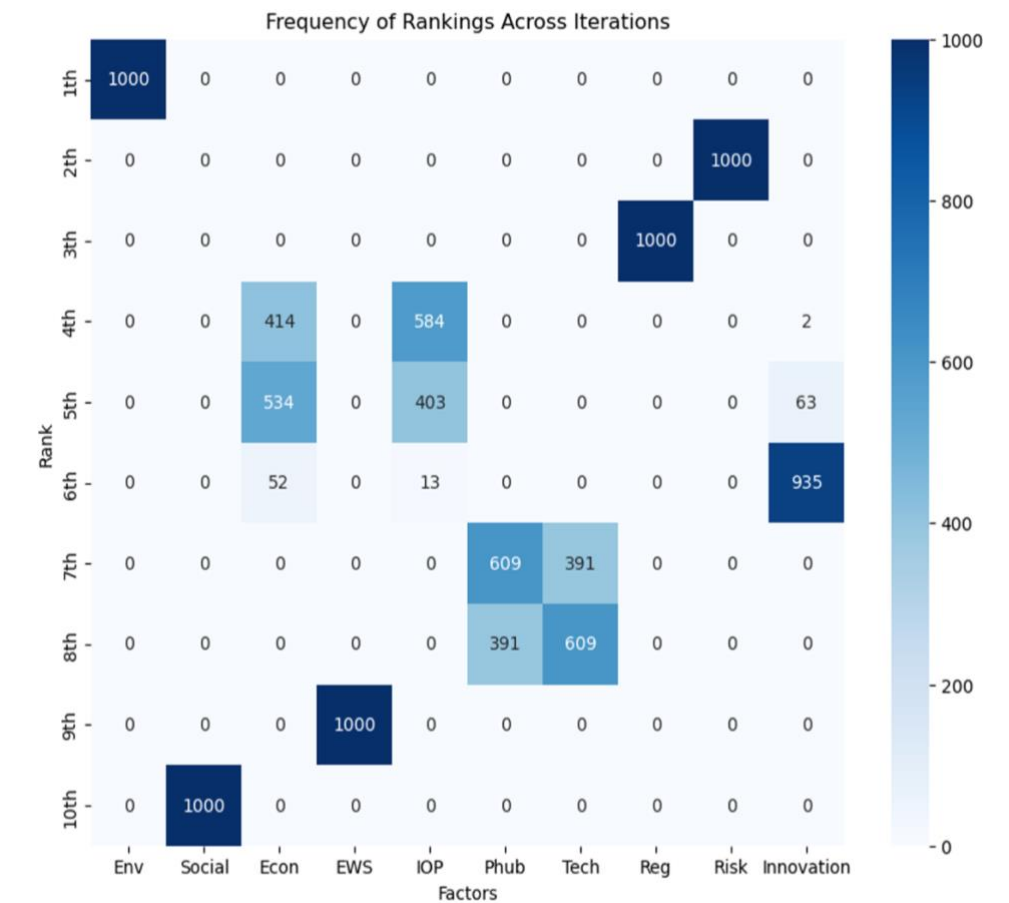


Figure 17 Frequency of rankings across iterations

The heatmap **Figure 17** illustrates how often each criterion was ranked in a specific position across 1,000 Monte Calo iterations. The frequency distribution highlights the consistency of rankings and identifies criteria with potential variability. Environmental and Risk consistently rank among the highest priorities, confirming their dominance in site selection. Social consideration

consistently ranks the lowest across all iterations reinforcing that stakeholder emphasis is places on technical, regulatory and economic factors.

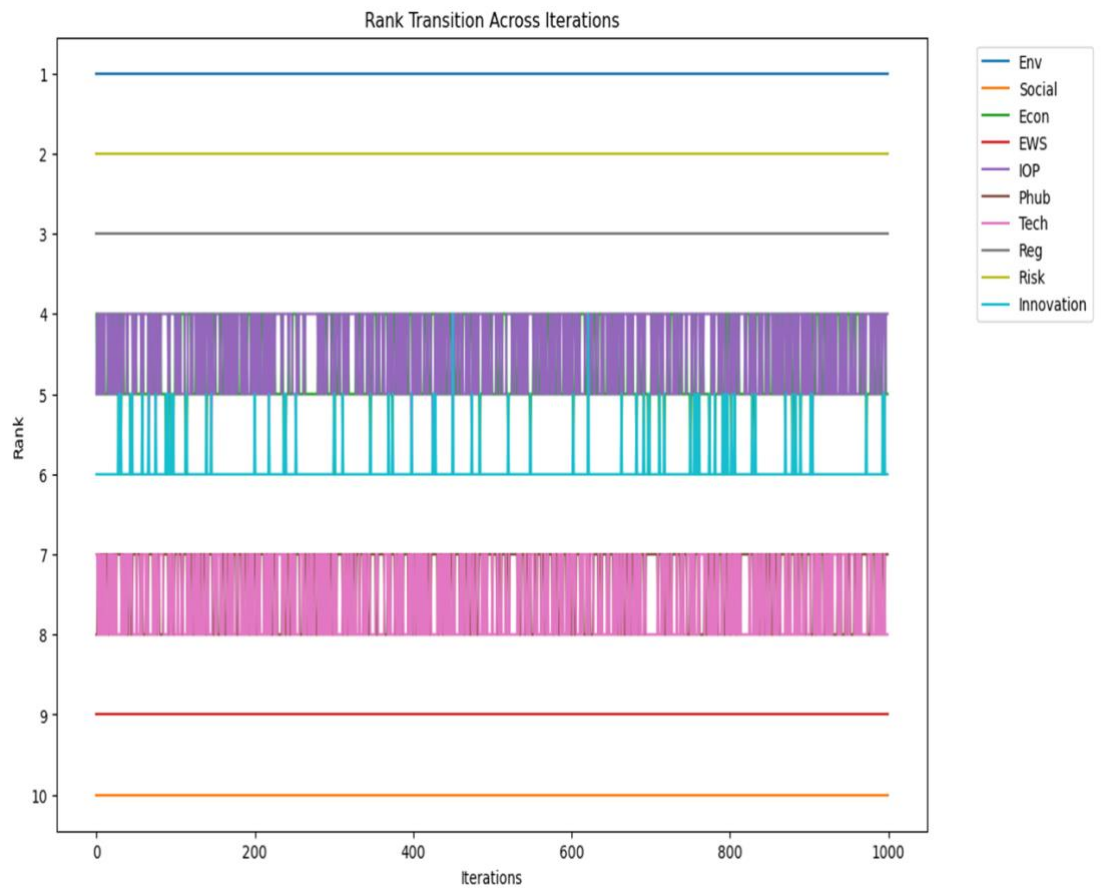


Figure 18 Rank transition across iterations

This rank transition plot **Figure 18** shows how the ranking of each criterion fluctuated over 1,000 Monte Carlo iterations. The Y axis represents the rank position (1st to 10th), while the X-axis represents the number of iterations (1 to 1,000). Each coloured line represents a different criterion. The stability of the top 3 ranking (Environment, Risk and Regulator) confirms that these criteria are universally accepted as the most important actors in site selection. Monte Carlo simulations validate the robustness of rankings, with minimal changes in top and bottom-ranked factors despite some variability in middle-tier criteria.

5.3 Stakeholder-Specific Analysis

This section examines the distinct decision-making preferences of the three stakeholder groups – Group 1- Industry Player, Group 2 – Other Industry Player, Group 3 – Researcher – in hazardous waste treatment site selection. Each group prioritizes different factors based on their operational, regulatory, and technological needs.

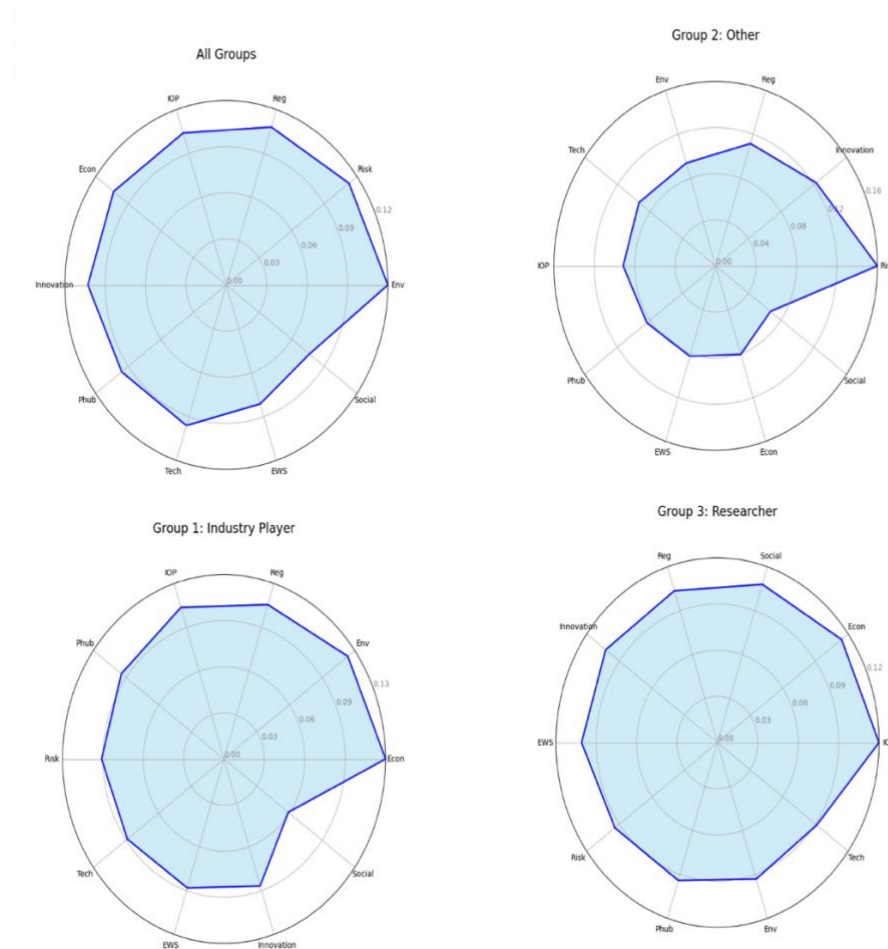


Figure 19 Weightage for each group type

The **Figure 19** present a radar chart comparison of AHP weightage for hazardous waste site selection criteria across three stakeholders' groups. Each radar chart highlights the relative importance assigned to different criteria by each stake holder groups.

5.3.1 Group 1: Industry Players

Industry players, comprising hazardous waste treatment companies and industrial generators, emphasize financial and regulatory factors in the decision-making

Table 15 :AHP weight rankings for site selection criteria (Group 1)

RANK	CRITERIA	WEIGHT
1	Economic	0.126
2	Environment	0.1195
3	Regulatory	0.1109
4	Industry Output	0.1090
5	Petrochemical Hub proximity	0.0991
6	Risk	0.0956
7	Technical	0.0933
8	Existing Waste Structure	0.0927
9	Innovation	0.0913
10	Social	0.0620

Economic viability is the top priority shown in **Table 15** because industry players (Group 1) focus on cost-effectiveness and ensuring profitability in hazardous waste management. Environment and Regulator compliance are essential to meet legal requirements and avoid fines or operational shutdowns. Innovation and Social consideration rank low, indicating a preference for established, cost-effective solutions over cutting-edge technology or community concerns.

Policy makers should create financial incentives for industries to adopt environmentally sustainable yet cost-effective waste treatment methods. Regulatory bodies must ensure enforcement of compliance while accommodating economic considerations for businesses. Site selection policies should align with industry waste generation patterns, balancing economic feasibility with sustainability.

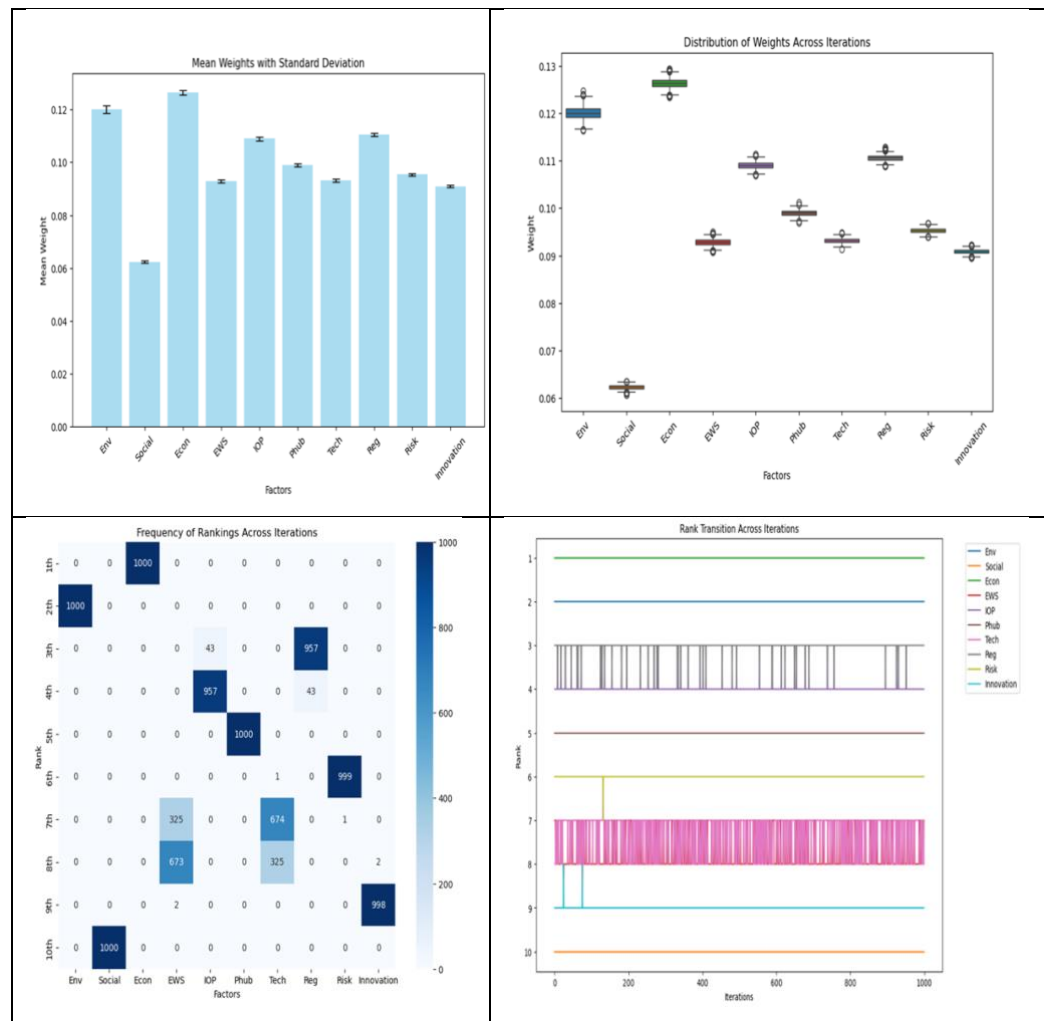


Figure 20 Monte Carlo observation for Group 1

Industry players prioritize economic viability, regulatory compliance, and environmental considerations. The Monte Carlo simulation evaluates how stable these preferences remain across multiple iterations. The simulation results provide deeper insights into how industry players prioritize economic viability, regulatory compliance, and environmental considerations for hazardous waste site selection. The four subplots in **Figure 20** illustrate different perspectives of these rankings across multiple iterations.

The bar chart in the top left corner shows the mean weightage assigned to each criterion along with standard deviation bars. Economic viability, regulatory compliance, and environmental considerations have the highest weights, reinforcing the industry's pragmatic approach to balancing financial feasibility and compliance. The low standard deviation across most factors suggests strong agreement within the industry group, indicating that their preferences are well-aligned and stable.

The boxplot in the top right corner presents the distribution of weights for each factor across Monte Carlo simulations. Narrow distributions for high-priority criteria (economic viability, regulatory compliance, environment) indicate consistency in industry preferences. Broader variations in technical and social considerations suggest these factors are less consistently prioritized among industry players. The heatmap in the bottom left represents how frequently each criterion appeared in specific ranks over 1,000 iterations. Economic viability (Econ), environmental impact (Env), and regulatory compliance (Reg) consistently occupy the top rankings, emphasizing their critical importance for industry decision-making. Lower-ranked factors such as social considerations and technical innovation appear to have more variability, suggesting industry players perceive them as less crucial.

The line plot in the bottom right tracks how the ranking of each criterion fluctuated across multiple iterations. The top three criteria remain highly stable, with minimal movement, reinforcing their dominance in industry decision-making. More fluctuations appear in technical, social, and risk-related factors,

indicating that industry players do not have a clear consensus on their relative importance.

Table 16 : Analysis and finding for Group 1

ANALYSIS ASPECT	FINDINGS
MEAN WEIGHTS WITH STANDARD DEVIATION	Economic viability and environmental impact have the highest mean weights, indicating their dominance. The standard deviation is minimal, suggesting high stakeholder agreement.
DISTRIBUTION OF WEIGHTS ACROSS	Economic and environmental factors consistently receive high weights across simulations, reinforcing their importance in industry decision-making.
FREQUENCY OF RANKINGS ACROSS ITERATIONS	Economic viability maintains the top rank in almost all iterations, whereas social considerations frequently appear in the lowest ranks.
RANK TRANSITION ACROSS ITERATIONS	Economic viability and regulatory compliance remain stable in the top three ranks, while innovation and social considerations exhibit higher volatility.

5.3.2 Group 2: Other Industry Representatives Researchers

Group 2 consisting of services provider, logistic operators, financial, prioritizes risk management and technological innovation over direct economic feasibility.

Table 17 : AHP weight ranking for Group 2

RANK	CRITERIA	WEIGHT
1	Risk	0.1620
2	Innovation	0.1243
3	Regulatory	0.1129
4	Environment	0.0949
5	Technology	0.0947
6	Industry Output	0.0926
7	Petrochemical Hub Proximity	0.0933
8	Existing Waste Structure	0.0834
9	Economic	0.0816
10	Social	0.0679

Risk management ranks highest, reflecting concerns about hazardous safety and long-term site stability. Innovation is a major factor, as other industry players seek advanced technology to improve waste treatment efficiency. Environmental is ranked lower, suggesting that while compliance is necessary, it does not drive decision-making in **Table 17**.

Investment in risk mitigation strategies should be encouraged to align with industry safety concerns. Incentivizing R&D for waste treatment technology will align with industry needs while fostering innovation. Waste facility selection should consider technological advancements ensuring new plants incorporate efficient and safer waste treatment needs.

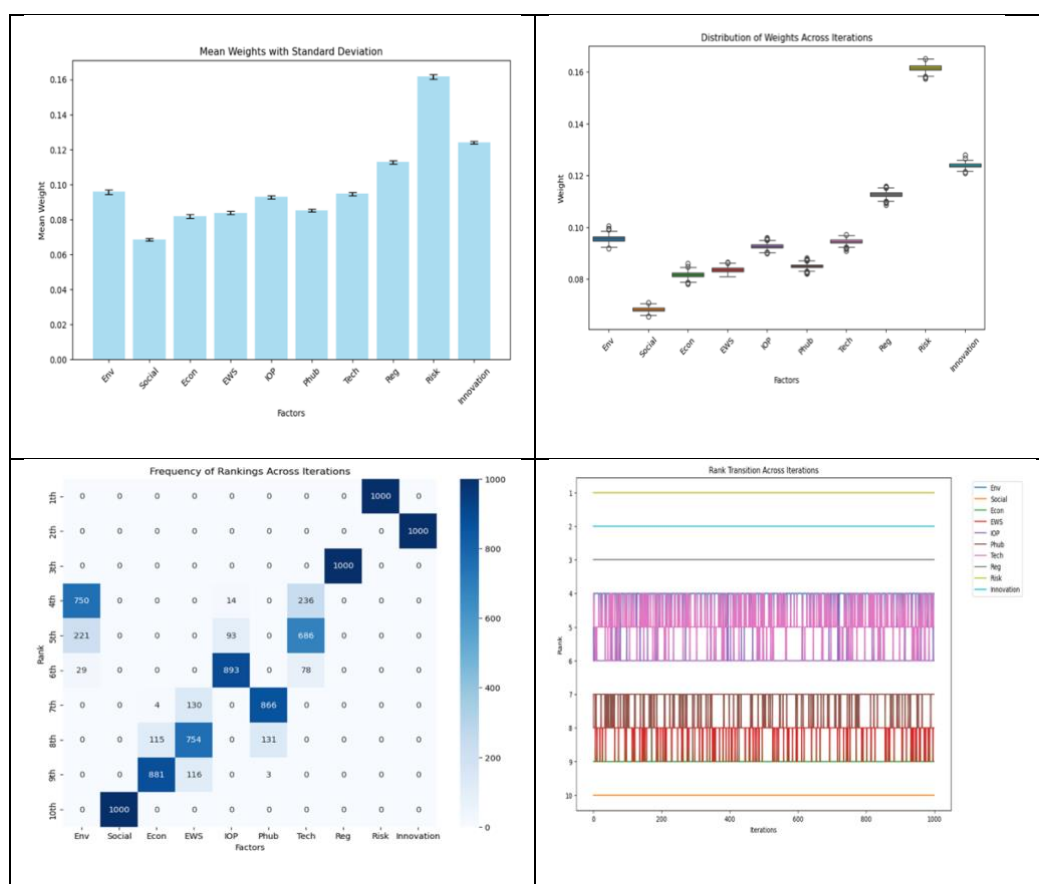


Figure 21 Monte Carlo observation for Group 2

The Monte Carlo simulation results for Group 2 – Other Industry Players provide an in-depth analysis of how this stakeholder group prioritizes different factors in hazardous waste site selection. The four visual

representations in **Figure 21** demonstrate the stability and variability of these preferences over multiple iterations.

The bar chart (top left) presents the average weightage assigned to each criterion, with error bars representing standard deviations. Risk management and innovation receive the highest weights, indicating that this group prioritizes safety, hazard mitigation, and technological advancements. The relatively high standard deviations for risk and innovation suggest some variability in expert opinions within the group, though they remain dominant factors. Environmental and economic considerations hold moderate weight, reflecting an awareness of sustainability and financial feasibility, but they are secondary to risk-related concerns. The boxplot (top right) illustrates the spread of weights across different Monte Carlo iterations. Risk management and innovation exhibit broader distributions, reinforcing that while these are high-priority factors, individual opinions vary more significantly than in Group 1 (Industry Players). Economic, environmental, and regulatory factors have narrower distributions, indicating greater consensus among stakeholders regarding their relative importance. The lower weight variability for regulatory compliance suggests that Group 2 largely agrees on its necessity but does not view it as the primary factor influencing site selection.

The heatmap (bottom left) represents how frequently each criterion appeared in specific ranks over 1,000 iterations. Risk management (Risk) and innovation (Innovation) consistently occupy the top rankings, affirming their dominant

influence on decision-making. Environmental impact (Env) and economic viability (Econ) are placed in the middle rankings, showing they are important but secondary to risk considerations. Social considerations and existing waste structure consistently rank at the bottom, indicating they have the least influence on this group's decisions. The line plot (bottom right) depicts how the rankings of different criteria fluctuate across 1,000 iterations. Risk management and innovation remain stable at the top, further validating their significance and agreement among stakeholders. Economic and environmental factors exhibit minor ranking shifts, reflecting some level of internal debate within the group. Lower-ranked factors, such as technical and social considerations, display significant fluctuations, highlighting that these aspects are not consistently prioritized.

Table 18 : Analysis and findings for Group 2

ANALYSIS ASPECT		FINDINGS
MEAN WEIGHTS WITH STANDARD DEVIATION		Risk management and innovation exhibit high mean weights, with moderate standard deviations indicating mixed opinions.
DISTRIBUTION OF WEIGHTS ACROSS	OF	Risk management consistently ranks among the top priorities, while environmental and economic considerations fluctuate more significantly.
FREQUENCY OF RANKINGS ACROSS ITERATIONS	OF	Risk management is ranked highest in most iterations, while economic viability fluctuates between mid and lower ranks.

RANK	TRANSITION	Significant rank transitions occur for regulatory compliance and technological innovation, suggesting these factors are subject to varying perspectives within this group.
ACROSS ITERATIONS		

5.3.3 Group 3: Researchers

Group 3 – Researcher, including academic experts and policymakers, prioritize industry output and economic viability but assign greater importance to social considerations.

Table 19 : AHP weight ranking for Group 3

RANK	CRITERIA	WEIGHT
1	Industry output	0.1174
2	Economic	0.1115
3	Social	0.1057
4	Regulatory	0.1014
	Innovation	0.1004
6	Existing Waste Structure	0.0987
7	Risk	0.0921
8	Petrochemical Hub Proximity	0.0921
9	Environment	0.0911
10	Technology	0.0892

As **Table 19** , Industry output ranks highest, emphasizing the need for site selection based on hazardous waste processing efficiency. Economic remain

important, aligning with the necessity for cost-effective hazardous waste management. Environment and Technology rank lower suggesting that which these factors matter, they are not primary concerns for researchers.

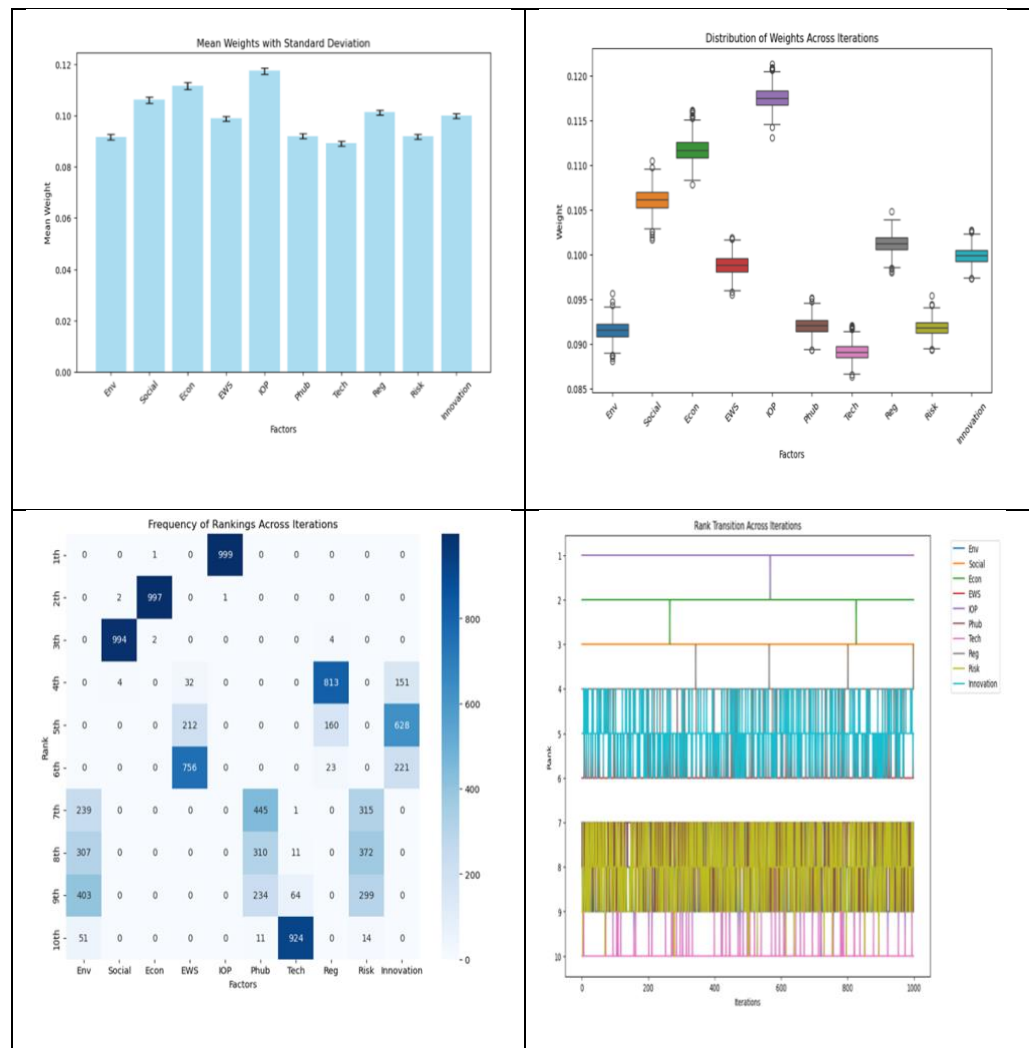


Figure 22 Monte Carlo observations for Group 3

Researchers prioritize long-term sustainability, regulatory alignment, and industry output while assigning greater weight to social considerations compared to other groups.

The Monte Carlo simulation results for Group 3 – Researchers provide insights into the stability and variability of decision-making priorities among researchers in hazardous waste management. **Figure 22** presents four critical aspects of the analysis: mean weight distribution, variability in weight assignments, frequency of rankings, and rank transitions over multiple iterations.

The bar chart (top left) illustrates the average importance assigned to each criterion, with error bars representing standard deviations. Industry Output (IOP) and Economic Viability (Econ) receive the highest weights, indicating that researchers emphasize high waste processing capacity and financial sustainability. Social considerations and environmental impact (Env) hold substantial weight, suggesting that researchers integrate community concerns and sustainability aspects into decision-making. Risk and innovation are ranked moderately, reflecting that while safety and technology matter, they are not the sole determining factors. Regulatory compliance (Reg) has a relatively lower weight compared to Groups 1 and 2, which suggests that researchers assume compliance is inherent in hazardous waste management frameworks.

The boxplot (top right) presents the distribution of weights across Monte Carlo iterations, showing the spread of expert opinions within the group. Industry Output and Economic Viability exhibit the highest median weights but also some variability, implying that different researchers may weigh economic

feasibility differently depending on their specializations. Innovation has a relatively narrow distribution, indicating a stronger consensus among researchers regarding its role in site selection. Social and environmental factors show higher standard deviations, reflecting ongoing debates on the trade-off between industrial expansion and sustainability.

The heatmap (bottom left) reveals how frequently each criterion appears at specific ranking positions throughout 1,000 iterations. Economic viability (Econ) and industry output (IOP) dominate the highest-ranked positions, confirming their importance for researchers. Environmental and social factors appear frequently in the mid-range rankings, reinforcing that researchers prioritize sustainability but balance it with economic concerns. Risk and innovation rankings vary across iterations, suggesting some level of debate within the research community about their relative importance. Regulatory compliance is consistently ranked lower, contrasting with Groups 1 and 2, which prioritized compliance more heavily.

The line plot (bottom right) illustrates how rankings fluctuate across multiple simulation runs. Economic viability and industry output maintain stable top positions, reinforcing their dominant role in decision-making. Environmental and social considerations display ranking variations, indicating some level of uncertainty in how they should be weighed relative to financial and industrial factors. Risk, innovation, and regulatory compliance exhibit noticeable rank shifts, suggesting that researchers adjust their priorities based on specific site

and policy contexts. The higher volatility of lower-ranked criteria shows that these factors may be considered secondary but are still subject to debate within the research community.

Table 20 : AHP weight ranking for Group 3

ANALYSIS ASPECT	FINDINGS
MEAN WEIGHTS WITH STANDARD DEVIATION DISTRIBUTION OF WEIGHTS ACROSS	Industry output and economic viability have the highest mean weights, with moderate standard deviations suggesting some divergence in views.
FREQUENCY OF RANKINGS ACROSS ITERATIONS	Regulatory compliance and industry output frequently hold the highest ranks, while petrochemical hub proximity and economic factors fluctuate.
RANK TRANSITION ACROSS ITERATIONS	While economic and regulatory factors remain stable in the top rankings, risk and innovation show higher variability.

Chapter 5 has provided a comprehensive analysis of the criteria influencing hazardous waste treatment plant site selection, using a structured AHP model supported by Monte Carlo Simulation. The findings reveal clear stakeholder

priorities, with consistent emphasis on industry output, economic feasibility, and regulatory considerations, while also illustrating nuanced differences across stakeholder groups. The use of Monte Carlo Simulation further enhanced the robustness of the model by capturing uncertainty and validating the stability of rankings under variable input conditions. This dual-method approach not only strengthens the decision-support framework but also offers actionable insights for policymakers and practitioners seeking to align hazardous waste infrastructure planning with sustainability goals. The subsequent chapter will synthesise these findings into broader implications and propose key recommendations for future research and policy development.

5.4 Comparative Discussion of Stakeholder Groups

The analysis reveals distinct differences in how the three stakeholder groups prioritize criteria for hazardous waste treatment plant siting. While there is partial convergence around environmental protection, regulatory compliance, and economic feasibility, the relative emphasis varies significantly, shaped by each group's institutional roles, operational contexts, and knowledge frameworks.

Importantly, it should be clarified how the two methodological tools- AHP and Monte Carlo Simulation individually contribute to this comparative analysis. AHP provided the deterministic baseline, translation stakeholder judgments into quantifiable weights and producing weights and producing structured criteria rankings. Monte Carlo Simulation then added a probabilistic layer, repeatedly

varying those weights across thousands of iterations to test the robustness of the results. This dual approach ensures that the observed differences across stakeholder groups are not artifacts of subjective input alone but are validated under conditions of uncertainty, thereby strengthening the credibility of the comparative findings.

Group 1 Industry stakeholders placed the highest priority on economic viability, ranking it above environmental and regulatory considerations (**Table 15**). This reflects their core concern with cost-efficiency and profitability amid rising compliance obligations. Monte Carlo simulations confirm the stability of this ranking, with minimal variation across iterations (Figure 5.7). The relatively low emphasis on innovation and social factors suggests a preference for proven, cost-effective solutions. Similar findings have been reported in India, where industries consistently prioritized output and cost minimization over social acceptability (Kharat and Kamble, 2008), and in China, where economic feasibility outweighed social and environmental considerations in facility siting (Zhang et al., 2012).

Group 2: Other Industry Representatives, comprising logistics, technology, and service providers, diverged sharply by prioritizing risk management and innovation, with economic feasibility falling into a lower tier (**Table 17**). Their operational focus on safety, competitiveness, and technological advancement outweighs short-term cost concerns. Monte Carlo outputs (Figure 5.8) show

wider variability, indicating internal diversity—particularly around regulatory and technological dimensions. Comparable trends are reported in Thailand, where service providers emphasised risk mitigation and technology adoption in hazardous waste logistics (Komoo and Lim, 2009).

Group 3: Researchers and Academics adopted a broader sustainability lens, prioritizing industry output, economic feasibility, and social acceptability (**Table 19**). Their elevated concern for social factors reflects awareness of community resistance to hazardous waste facilities, often framed as the “Not in My Backyard” (NIMBY) phenomenon. Radar chart results (Figure 5.6) show a balanced profile, integrating economic, industrial, social, and environmental priorities. This emphasis on social legitimacy mirrors findings from the European Union, where public participation and social license are recognized as critical to facility siting (Morrissey and Browne, 2004; UNECE, 2014).

Comparative Insights. The comparative summary **Table 21** underscores these divergences industry players emphasize economic feasibility and compliance., other industry representatives emphasize risk and innovation. researchers emphasize social acceptability and output. These divergences underscore that hazardous waste siting is not merely a technical optimization exercise, but a negotiation among competing stakeholder values. For Malaysia, these findings expose a fundamental tension: industries priorities short-term cost efficiency, service providers emphasize safety and innovation, and researchers advocate for social legitimacy and long-term sustainability.

Bridging these perspectives requires a multi-pronged approach economic instruments by introduce tax incentives and subsidies to ease the financial burden on industries adopting safer, innovative technologies—mirroring South Korea’s circular economy initiatives (Park and Chertow, 2014). Participatory planning institutionalizes community engagement processes to ensure public concerns are not marginalized. The EU’s Aarhus Convention offers a robust model for inclusive environmental governance (UNECE, 2014). Balanced regulation by design frameworks that uphold environmental and risk standards while remaining responsive to economic realities, enabling adaptive compliance pathways. Decision support tools to apply multi-criteria frameworks such as the AHP–Monte Carlo model developed here, which explicitly accounts for stakeholder variability and uncertainty.

Table 21 : Comparative summary for Group 1, 2 & 3

Criteria	Group 1: Industry Players	Group 2: Other Industry Representatives	Group 3: Researchers/Academics
Economic Feasibility	Highest priority – driven by profitability and cost-effectiveness	Low priority – overshadowed by risk and innovation concerns	Moderate to high – important for long-term feasibility
Environment	Second priority – compliance-driven, avoid legal penalties	Moderate – necessary but not dominant	Lower priority than social and industry output
Regulatory Compliance	Critical for operations, ranked high consistently	Important, but flexible in interpretation	Assumed inherent in governance, ranked lower
Risk Management	Secondary to economics, not the highest concern	Top priority – critical for logistics, safety, and liability	Moderate – balanced with other social and economic concerns
Innovation	Low priority – reliance on proven, established solutions	Very high priority – focus on technological competitiveness	Moderate – valued but not dominant
Industry Output	Important but secondary to economic feasibility	Moderate importance	Highest priority – emphasis on efficiency and capacity
Social Acceptability	Lowest priority – considered non-critical	Lowest priority – not significant in decision-making	Significantly higher – reflects awareness of NIMBY concerns

By explicitly comparing and synthesizing stakeholder perspectives, this discussion identifies both areas of consensus (economic, regulatory, environmental concerns) and areas of divergence (risk, innovation, social). These insights are essential for crafting siting policies that are scientifically rigorous, socially legitimate, and aligned with Malaysia's commitments under the Twelfth Malaysia Plan (2021–2025) and the Sustainable Development Goals (SDG 3, SDG 12, SDG 13).

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This study has developed a comprehensive decision-support framework for the selection of hazardous waste treatment plant sites, combining the Analytic Hierarchy Process (AHP) with Monte Carlo Simulation. By structuring complex decision-making processes into a transparent, multi-criteria hierarchy and validating the outcomes through probabilistic modelling, the research offers both methodological rigor and practical applicability. The model was applied in the context of Malaysia, a developing country experiencing significant industrial growth and increasing volumes of hazardous waste. The findings demonstrate how integrating expert judgment, stakeholder engagement, and uncertainty analysis can produce reliable and context-sensitive solutions to infrastructure planning challenges.

Through the design and application of a ten-criterion Hazardous Waste Management (HWM) index, the study identified and weighted relevant factors, including environmental impact, economic feasibility, social acceptance, technological readiness, regulatory compliance, and industry output. The use of AHP allowed for the systematic comparison and prioritization of these criteria

based on inputs from three key stakeholder groups—industry players, broader industrial representatives, and academic researchers. The results reveal notable patterns: industry stakeholders tend to prioritize regulatory compliance and operational feasibility, while researchers placed greater emphasis on economic output and long-term sustainability. This diversity of views highlights the importance of incorporating multiple perspectives into environmental decision-making to ensure both technical soundness and policy relevance.

Monte Carlo Simulation was employed to assess the robustness of the AHP results under conditions of input uncertainty. The simulation confirmed the stability of top-ranked criteria, particularly industry output, economic viability, and regulatory considerations. The model also highlighted the sensitivity of lower-ranked criteria, such as innovation and social considerations, which showed greater variability across simulation runs. These insights enhance the reliability of the decision model and underscore the value of integrating deterministic and probabilistic methods in environmental planning.

6.2 Contributions of the Study

This research provides several novel contributions to both theory and practice. Methodologically, it offers a hybrid framework that merges structured judgment elicitation with statistical robustness—an approach not widely explored in hazardous waste management literature. The development of a locally validated Hazardous Waste Management (HWM) index comprising ten comprehensive

criteria demonstrates the applicability of multi-criteria decision analysis in complex environmental planning. Practically, the framework provides a structured tool for planners, regulators, and industry stakeholders that is grounded in empirical input and adaptable to regional and national contexts. Although developed for Malaysia, the model has relevance for other developing nations facing similar governance and infrastructural challenges.

6.3 Limitations

Despite its strengths, the study has several limitations. The stakeholder sample size, though diverse, was limited and may not capture the full spectrum of perspectives. The model also relied on expert judgment for some criteria due to limited empirical data availability, introducing a degree of subjectivity despite consistency checks. Furthermore, the framework is static in nature and does not account for time-based shifts in policy, technology, or population. Finally, the absence of spatial analysis, such as GIS integration, constrains the framework's ability to visually or geographically identify specific optimal locations.

6.4 Recommendations for Future Research

Future research should build upon the foundation established in this study by expanding its analytical depth and application scope. One important enhancement would be the integration of Geographic Information Systems (GIS)

into the AHP-Monte Carlo framework, enabling spatially explicit modelling and improved visualization of site suitability across geographic regions. Further refinement could include public and community stakeholder input to strengthen inclusiveness, transparency, and social legitimacy. Another avenue for advancement is the incorporation of scenario-based modelling to account for dynamic changes in policy, industrial growth, population density, and environmental regulation. Additionally, future research could customize the HWM index for specific waste streams—such as e-waste, clinical waste, or agrochemical waste—each of which poses unique challenges and requires tailored siting considerations. Cross-country comparative applications, especially within Southeast Asia or the broader Global South, would further validate the model’s adaptability and could support regional harmonization of hazardous waste governance and infrastructure planning.

Overall, this thesis contributes a replicable, flexible, and policy-relevant model for hazardous waste facility planning. The integration of expert-based judgment with quantitative simulation represents a significant step forward in bridging the gap between scientific modelling and decision-making under uncertainty. As Malaysia and similar developing countries continue their transition towards sustainability and circular economy objectives, frameworks like the one developed in this study will play a critical role in supporting informed, inclusive, and forward-looking environmental planning.

References

- Abdullah, A., 1995. Environmental pollution in Malaysia: trends and prospects. *TrAC Trends Anal. Chem.* 14, 191–198. [https://doi.org/10.1016/0165-9936\(95\)91369-4](https://doi.org/10.1016/0165-9936(95)91369-4)
- Abhay, G., 2021. Importance of Waste Segregation: Why Should We Segregate Waste. URL <https://justeco.in/importance-of-waste-segregation/> (accessed 7.26.23).
- Abid, S., Mhada, F.Z., 2021. Simulation optimisation methods applied in reverse logistics: a systematic review. *Int. J. Sustain. Eng.* 14, 1463–1483. <https://doi.org/10.1080/19397038.2021.2003470>
- Adami, L., Schiavon, M., 2021. From circular economy to circular ecology: A review on the solution of environmental problems through circular waste management approaches. *Sustainability* 13, 1–20. <https://doi.org/10.3390/su13020925>
- Adetunji, A.I., Olaniran, A.O., 2021. Treatment of industrial oily wastewater by advanced technologies: a review. *Appl. Water Sci.* 11, 98. <https://doi.org/10.1007/s13201-021-01430-4>
- Aja, O.C., Al-Kayiem, H.H., Zewge, M.G., Joo, M.S., 2016a. Overview of hazardous waste management status in Malaysia, in: *Management of Hazardous Wastes*. InTech, pp. 69–88. <https://doi.org/10.5772/63682>
- Aja, O.C., Al-Kayiem, H.H., Zewge, M.G., Joo, M.S., 2016b. Overview of Hazardous Waste Management Status in Malaysia, in: Saleh, H.E.-D.M., Abdel Rahman, R.O. (Eds.), *Management of Hazardous Wastes*. InTech.
- Alao, M.A., Popoola, O.M., Ayodele, T.R., 2022. Waste-to-energy nexus: An overview of technologies and implementation for sustainable

- development. *Clean. Energy Syst.* 3, 100034–100034.
<https://doi.org/10.1016/j.cles.2022.100034>
- Amirul, 2021. Circular Economy: Where Are We Now and How Do We Even Begin. MIDA Malays. Invest. Dev. Auth. URL
<https://www.mida.gov.my/circular-economy-where-are-we-now-and-how-do-we-even-begin/> (accessed 9.19.23).
- Ampofo, S., Issifu, J.S., Kusibu, M.M., Mohammed, A.S., Adiali, F., 2023a. Selection of the final solid waste disposal site in the Bolgatanga municipality of Ghana using analytical hierarchy process (AHP) and multi-criteria evaluation (MCE). *Heliyon* 9, e18558.
<https://doi.org/10.1016/j.heliyon.2023.e18558>
- Ampofo, S., Issifu, J.S., Kusibu, M.M., Mohammed, A.S., Adiali, F., 2023b. Selection of the final solid waste disposal site in the Bolgatanga municipality of Ghana using analytical hierarchy process (AHP) and multi-criteria evaluation (MCE). *Heliyon* 9, e18558.
<https://doi.org/10.1016/j.heliyon.2023.e18558>
- Anwar, Z., 2020. Development of Policy and Regulations for Hazardous Waste Management in Malaysia.
- Asase, M., Yanful, E.K., Mensah, M., Stanford, J., Amponsah, S., 2009. Comparison of municipal solid waste management systems in Canada and Ghana: A case study of the cities of London, Ontario, and Kumasi, Ghana. *Waste Manag.* 29, 2779–2786.
<https://doi.org/10.1016/j.wasman.2009.06.019>
- Basel, C., 2011. Basel Convention.

- Biakhmetov, B., You, S., Dostiyarov, A., 2022. Sustainable waste management and circular economy, in: *Low Carbon Stabilization and Solidification of Hazardous Wastes*. Elsevier, pp. 545–554. <https://doi.org/10.1016/B978-0-12-824004-5.00032-3>
- Bogner, J., 2007. Hazards of heavy metal contamination | *British Medical Bulletin* | Oxford Academic [WWW Document]. URL <https://academic.oup.com/bmb/article-abstract/68/1/167/421303?redirectedFrom=fulltext&login=false> (accessed 8.21.25).
- BRS, B., 2025. BRS Conventions > Decision-making > COPs and ExCOPs > Overview [WWW Document]. Barsel Rotterdam Stockh. Conv. URL <https://www.brsmeas.org/Decisionmaking/COPsandExCOPs/Overview/tabid/2617/language/en-US/Default.aspx> (accessed 4.10.25).
- Calderón Márquez, A.J., Rutkowski, E.W., 2020. Waste management drivers towards a circular economy in the global south – The Colombian case. *Waste Manag.* 110, 53–65. <https://doi.org/10.1016/j.wasman.2020.05.016>
- Çalış Boyacı, A., Sisman, A., Sarıcaoğlu, K., 2021. Site selection for waste vegetable oil and waste battery collection boxes: a GIS-based hybrid hesitant fuzzy decision-making approach. *Environ. Sci. Pollut. Res.* 28, 1–14. <https://doi.org/10.1007/s11356-020-12080-5>
- CELITRON, 2022a. Healthcare risk waste and its disposal how should be handled [WWW Document]. celitron.com. URL <https://celitron.com/en/blog/what-is-healthcare-risk-waste-and-how-should-its-disposal-be-handled> (accessed 7.26.23).

- CELITRON, 2022b. Healthcare risk waste and its disposal how should be handled [WWW Document]. celitron.com. URL <https://celitron.com/en/blog/what-is-healthcare-risk-waste-and-how-should-its-disposal-be-handled> (accessed 7.26.23).
- Che Jamin, N., Mahmood, N.Z., 2015. Scheduled Waste Management in Malaysia: An Overview. *Adv. Mater. Res.* 1113, 841–846. <https://doi.org/10.4028/www.scientific.net/AMR.1113.841>
- Cheng, H., Dong, S., Li, F., Yang, Y., Li, Y., Li, Z., 2019. A circular economy system for breaking the development dilemma of ‘ecological Fragility–Economic poverty’ vicious circle: A CEEPS-SD analysis. *J. Clean. Prod.* 212, 381–392. <https://doi.org/10.1016/j.jclepro.2018.12.014>
- Cobos-Mora, S.L., Guamán-Aucapiña, J., Zúñiga-Ruiz, J., 2023. Suitable site selection for transfer stations in a solid waste management system using analytical hierarchy process as a multi-criteria decision analysis: a case study in Azuay-Ecuador. *Environ. Dev. Sustain.* 25, 1944–1977. <https://doi.org/10.1007/s10668-022-02134-8>
- Diaz, L.F., 2017. Waste management in developing countries and the circular economy. *Waste Manag. Res. J. Sustain. Circ. Econ.* 35, 1–2. <https://doi.org/10.1177/0734242X16681406>
- DoE, 2019. Environmental quality (Scheduled Wastes) Regulations 2005, PU (A) 294/2005 [WWW Document]. Dep. Environ. Minist. Nat. Resour. Environ. Clim. Change. URL <https://www.doe.gov.my/en/environmental-quality-scheduled-waste-regulations-2005-p-u-a-294-2005/>

- DoE, 2015. Electronic scheduled waste information systems (eSWIS) hands-on guideline.
- DOE, 2014. Guidelines for packaging, labelling and storage of scheduled waste in Malaysia.
- DOE, 1974, 1974. Environmental Quality Act 1974 – ACT 127 – Department of Environment. URL <https://www.doe.gov.my/en/environmental-quality-act-1974-act-127-2/> (accessed 4.10.25).
- DOE, D., 2005. Environmental Quality (Scheduled Wastes) Regulations 2005 – P.U. (A) 294/2005 – Department of Environment. URL <https://www.doe.gov.my/en/environmental-quality-scheduled-waste-regulations-2005-p-u-a-294-2005/> (accessed 4.10.25).
- DoOSH, 1994. Law of Malaysia Occupational safety and health act 1994.
- DOSM, 2022. Compendium of Environment Statistics, Malaysia 2022.
- DoSM, 2022. Compendium of environment statistics, Malaysia, 2022 [WWW Document]. Dep. Stat. Malays. URL <https://www.dosm.gov.my/portal-main/release-content/compendium-of-environment-statistics-malaysia-2022>
- DOSM, 2021. Compendium of Environment Statistics, Malaysia 2021.
- EEA, 2023. Chemicals [WWW Document]. URL <https://www.eea.europa.eu/en/topics/in-depth/chemicals> (accessed 9.17.23).
- EEA, W., 2003. Waste electrical and electronic equipment (WEEE) Directive 2012/19/EU — European Environment Agency [WWW Document]. URL <https://www.eea.europa.eu/policy-documents/waste-electrical-and-electronic-equipment> (accessed 8.20.23).

- El-Saadony, M.T., Saad, A.M., El-Wafai, N.A., Abou-Aly, H.E., Salem, H.M., Soliman, S.M., Abd El-Mageed, T.A., Elrys, A.S., Selim, S., Abd El-Hack, M.E., Kappachery, S., El-Tarabily, K.A., AbuQamar, S.F., 2023. Hazardous wastes and management strategies of landfill leachates: A comprehensive review. *Environ. Technol. Innov.* 31, 103150. <https://doi.org/10.1016/j.eti.2023.103150>
- EPA, 2020. United States Environmental Protection Agency.
- eSWIS, D., 2024. eSWIS [WWW Document]. URL <https://eswis.doe.gov.my/facilityList.aspx> (accessed 3.28.24).
- Eswis, D., 2019. Eswis -ECN. Jab. Alam Sekitar Kementerian. Sumber Asli Alam Sekitar Dan Perubahan Iklim.
- EU, E., 2025. 13 persons arrested for illegally disposing 35 000 tonnes of hazardous waste [WWW Document]. Europol. URL <https://www.europol.europa.eu/media-press/newsroom/news/13-persons-arrested-for-illegally-disposing-35000-tonnes-of-hazardous-waste> (accessed 4.10.25).
- European, C., 2023. Waste Framework Directive - European Commission [WWW Document]. URL https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en (accessed 4.10.25).
- Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E.H., Rooney, D.W., Yap, P.-S., 2023. Artificial intelligence for waste management in smart cities: a review. *Environ. Chem. Lett.* 21, 1959–1989. <https://doi.org/10.1007/s10311-023-01604-3>

- Farrokhi-Asl, H., Makui, A., Ghousi, R., Rabbani, M., 2020. Developing a hazardous waste management system with consideration of health, safety, and environment. *Comput. Electr. Eng.* 82, 106553–106553. <https://doi.org/10.1016/j.compeleceng.2020.106553>
- FDES, U., 2021. Quantity of clinical waste in Malaysia rose last year due to Covid-19, says Statistics Dept | Malay Mail [WWW Document]. URL https://www.malaymail.com/news/malaysia/2021/11/29/quantity-of-clinical-waste-in-malaysia-rose-last-year-due-to-covid-19-says/2024655#google_vignette (accessed 8.21.25).
- Feng, J., 2022. An integrated multi-criteria decision-making method for hazardous waste disposal site selection. *Environ. Dev. Sustain.* 24, 8039–8070. <https://doi.org/10.1007/s10668-021-01772-8>
- Fikri, E., Purwanto, P., Sunoko, H.R., 2015. Modelling of Household Hazardous Waste (HHW) Management in Semarang City (Indonesia) by Using Life Cycle Assessment (LCA) Approach to Reduce Greenhouse Gas (GHG) Emissions. *Procedia Environ. Sci.* 23, 123–129. <https://doi.org/10.1016/j.proenv.2015.01.019>
- Gawatre, D.W., Kandgule, M.H., Kharat, S.D., 2016. Comparative Study of Population Forecasting Methods. *IOSR J. Mech. Civ. Eng.* 13, 16–19. <https://doi.org/10.9790/1684-1304051619>
- Gill, D.A., Mix, T.L., 2020. Love canal: a classic case study of a contaminated community, in: *An Introduction to Interdisciplinary Toxicology*. Elsevier, pp. 341–352. <https://doi.org/10.1016/B978-0-12-813602-7.00025-9>
- Guo, W., Xi, B., Huang, C., Li, J., Tang, Z., Li, W., Ma, C., Wu, W., 2021. Solid waste management in China: Policy and driving factors in 2004–2019.

Resour. Conserv. Recycl. 173, 105727.

<https://doi.org/10.1016/j.resconrec.2021.105727>

Hamlat, A., Kadri, C.B., Sekkoum, M., Guidoum, A., Remada, A., 2022. Multi-criteria decision-making approach for selecting an alternative wastewater treatment plant site in urban areas of Laghouat (North-Central Algeria). *Euro-Mediterr. J. Environ. Integr.* 7, 511–530. <https://doi.org/10.1007/s41207-022-00333-3>

Hamzah, N., Marzuki, N.S., Baharudin, F., Rahim, N.L., Mohd Kamil, N.A.F., Akbar, N.A., Mohd Zin, N.S., 2022. Knowledge, Attitudes, Awareness and Practices on Household Hazardous Waste Disposal Among Undergraduate Students in Selangor, Malaysia, in: Mohamed Noor, N., Sam, S.T., Abdul Kadir, A. (Eds.), *Proceedings of the 3rd International Conference on Green Environmental Engineering and Technology, Lecture Notes in Civil Engineering*. Springer Nature, Singapore, pp. 103–113. https://doi.org/10.1007/978-981-16-7920-9_13

Harinderan, K., 2023. Waste Management In Malaysia: Generate Less, Separate More - BusinessToday [WWW Document]. <https://www.businesstoday.com.my/>. URL <https://www.businesstoday.com.my/2023/12/06/waste-management-in-malaysia-generate-less-separate-more/> (accessed 3.28.24).

Hossain, Md.U., Wang, L., Chen, L., Tsang, D.C.W., Ng, S.T., Poon, C.S., Mechtcherine, V., 2020. Evaluating the environmental impacts of stabilization and solidification technologies for managing hazardous wastes through life cycle assessment: A case study of Hong Kong. *Environ. Int.* 145, 106139. <https://doi.org/10.1016/j.envint.2020.106139>

- Hosseinzadeh-Bandbafha, H., Nizami, A.-S., Kalogirou, S.A., Gupta, V.K., Park, Y.-K., Fallahi, A., Sulaiman, A., Ranjbari, M., Rahnama, H., Aghbashlo, M., Peng, W., Tabatabaei, M., 2022. Environmental life cycle assessment of biodiesel production from waste cooking oil: A systematic review. *Renew. Sustain. Energy Rev.* 161, 112411. <https://doi.org/10.1016/j.rser.2022.112411>
- Hrouga, M., Sbihi, A., Chavallard, M., 2022. The potentials of combining Blockchain technology and Internet of Things for digital reverse supply chain: A case study. *J. Clean. Prod.* 337, 130609. <https://doi.org/10.1016/j.jclepro.2022.130609>
- Ilyas, S., Srivastava, R.R., Kim, H., Das, S., Singh, V.K., 2021. Circular bioeconomy and environmental benignness through microbial recycling of e-waste: A case study on copper and gold restoration. *Waste Manag.* 121, 175–185. <https://doi.org/10.1016/j.wasman.2020.12.013>
- IRCR, E.T., 2011. Medical waste management.
- Ismail, H., Hanafiah, M.M., 2019. Discovering opportunities to meet the challenges of an effective waste electrical and electronic equipment recycling system in Malaysia. *J. Clean. Prod.* 238, 117927–117927. <https://doi.org/10.1016/j.jclepro.2019.117927>
- Jamin, N.C., Mahmood, N.Z., 2015. Scheduled waste management in Malaysia: An overview. *Adv. Mater. Res.* 1113, 841–846. <https://doi.org/10.4028/www.scientific.net/amr.1113.841>
- Järup, L., 2003. Hazards of heavy metal contamination. *Br. Med. Bull.* 68, 167–182. <https://doi.org/10.1093/bmb/ldg032>

- Jerry A, N., 2023. Hazardous-waste management | Types, Examples, Treatment, & Facts | Britannica [WWW Document]. URL <https://www.britannica.com/technology/hazardous-waste-management> (accessed 7.22.23).
- Jessie Yeung, 2020a. Malaysia finds 1800 tonnes of illegal toxic waste dumped at port. CNN.
- Jessie Yeung, 2020b. Malaysia finds 1800 tonnes of illegal toxic waste dumped at port. CNN.
- KA, I., 2018. TECHNICAL VISIT: KUALITI ALAM WASTE MANAGEMENT CENTRE (WMC) & [WWW Document]. IEMNS. URL <https://www.iemns.org.my/index.php/activities/110-kejohanan-bowling-terbuka-iemns-2022> (accessed 4.10.25).
- Kumar, A., Thakur, A.K., Gaurav, G.K., Klemeš, J.J., Sandhwar, V.K., Pant, K.K., Kumar, R., 2023. A critical review on sustainable hazardous waste management strategies: a step towards a circular economy. *Environ. Sci. Pollut. Res.* 30, 105030–105055. <https://doi.org/10.1007/s11356-023-29511-8>
- Lee, D., Kim, J., Park, H.-S., 2022a. Characteristics of industrial hazardous waste generation in South Korea from 2008 to 2018 based on decoupling and decomposition analysis. *Waste Manag. Res. J. Sustain. Circ. Econ.* 40, 1322–1331. <https://doi.org/10.1177/0734242X211063728>
- Lee, D., Kim, J., Park, H.-S., 2022b. Characteristics of industrial hazardous waste generation in South Korea from 2008 to 2018 based on decoupling and decomposition analysis. *Waste Manag. Res. J. Sustain. Circ. Econ.* 40, 1322–1331. <https://doi.org/10.1177/0734242X211063728>

- Liu, Z., Adams, M., Walker, T.R., 2018. Are exports of recyclables from developed to developing countries waste pollution transfer or part of the global circular economy? *Resour. Conserv. Recycl.* 136, 22–23. <https://doi.org/10.1016/j.resconrec.2018.04.005>
- Loy, A.C.M., Lim, J.Y., How, B.S., Yiin, C.L., Lock, S.S.M., Lim, L.G., Alhamzi, H., Yoo, C., 2023. Rethinking of the future sustainable paradigm roadmap for plastic waste management: A multi-nation scale outlook compendium. *Sci. Total Environ.* 881, 163458. <https://doi.org/10.1016/j.scitotenv.2023.163458>
- Ma, W., Wang, Y., Xing, P., Yang, M., 2025. A Monte Carlo-based modeling method for the spatial-temporal evolution process of multi-hazard and higher-order domino effect. *Reliab. Eng. Syst. Saf.* 253, 110532. <https://doi.org/10.1016/j.ress.2024.110532>
- Manay, N., 2023. Mercury tragedies: Incidents and effects, in: Reference Module in Biomedical Sciences. Elsevier. <https://doi.org/10.1016/B978-0-12-824315-2.01048-4>
- Maresca, A., Bisinella, V., Astrup, T.F., 2022. Life cycle assessment of air-pollution-control residues from waste incineration in Europe: Importance of composition, technology and long-term leaching. *Waste Manag.* 144, 336–348. <https://doi.org/10.1016/j.wasman.2022.03.032>
- Margallo, M., Ziegler-Rodriguez, K., Vázquez-Rowe, I., Aldaco, R., Irabien, Á., Kahhat, R., 2019. Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A review for policy support. *Sci. Total Environ.* 689, 1255–1275. <https://doi.org/10.1016/j.scitotenv.2019.06.393>

- Meena, M.D., Dotaniya, M.L., Meena, B.L., Rai, P.K., Antil, R.S., Meena, H.S., Meena, L.K., Dotaniya, C.K., Meena, V.S., Ghosh, A., Meena, K.N., Singh, A.K., Meena, V.D., Moharana, P.C., Meena, S.K., Srinivasarao, Ch., Meena, A.L., Chatterjee, S., Meena, D.K., Prajapat, M., Meena, R.B., 2023. Municipal solid waste: Opportunities, challenges and management policies in India: A review. *Waste Manag. Bull.* 1, 4–18. <https://doi.org/10.1016/j.wmb.2023.04.001>
- MIDA, 2023. Malaysia's Petrochemical Industry: Poised for Strategic Growth.
- | | | | | | |
|--|---------|---------|------|-------|-----|
| MIDA | Malays. | Invest. | Dev. | Auth. | URL |
| https://www.mida.gov.my/publications/malaysias-petrochemical-industry-poised-for-strategic-growth/ (accessed 10.28.23). | | | | | |
- MIDA, 2021a. Sustainable Waste Management in Malaysia: Opportunities and Challenges.
- MIDA, 2021b. Sustainable Waste Management in Malaysia: Opportunities and Challenges.
- Ministry of Economy, 2021. Sustainable development goals [WWW Document].
- | | | | | |
|---|--------|---------|-------|-----|
| Off. | Protal | Minist. | Econ. | URL |
| https://www.ekonomi.gov.my/en/sustainable-development-goals | | | | |
- Mmereki, D., Baldwin, A., Hong, L., Li, B., 2016. The management of hazardous waste in developing countries, in: *Management of Hazardous Wastes*. InTech. <https://doi.org/10.5772/63055>
- MoE, M., 2021. Twelfth Malaysia Plan, 2021-2025 [WWW Document]. URL <https://rmke12.ekonomi.gov.my/en> (accessed 4.10.25).
- NRES, D., 2025. Department of Environment – NRES. URL <https://www.doe.gov.my/en/utama-english/> (accessed 4.10.25).

- Otwong, A., Jongmeewasin, S., Phenrat, T., 2021a. Legal obstacles for the circular economy in Thailand: Illegal dumping of recyclable hazardous industrial waste. *J. Clean. Prod.* 302, 126969–126969. <https://doi.org/10.1016/J.JCLEPRO.2021.126969>
- Otwong, A., Jongmeewasin, S., Phenrat, T., 2021b. Legal obstacles for the circular economy in Thailand: Illegal dumping of recyclable hazardous industrial waste. *J. Clean. Prod.* 302, 126969–126969. <https://doi.org/10.1016/J.JCLEPRO.2021.126969>
- PMO, 2019. Pelan Hala Tuju Malaysia Ke Arah Sifar Penggunaan Plastik Sekali Guna 2018-2030 - Pejabat Perdana Menteri Malaysia [WWW Document]. URL <https://www.pmo.gov.my/ms/2019/07/pelan-hala-tuju-malaysia-ke-arrah-sifar-penggunaan-plastik-sekali-guna-2018-2030/> (accessed 8.14.23).
- Qian, G., Duanmu, C., Ali, N., Khan, A., Malik, S., Yang, Y., Bilal, M., 2022a. Hazardous wastes, adverse impacts, and management strategies: a way forward to environmental sustainability. *Environ. Dev. Sustain.* 24, 9731–9756. <https://doi.org/10.1007/s10668-021-01867-2>
- Qian, G., Duanmu, C., Ali, N., Khan, A., Malik, S., Yang, Y., Bilal, M., 2022b. Hazardous wastes, adverse impacts, and management strategies: a way forward to environmental sustainability. *Environ. Dev. Sustain.* 24, 9731–9756. <https://doi.org/10.1007/s10668-021-01867-2>
- Saaty, T.L., 2008. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–98. <https://doi.org/10.1504/IJSSCI.2008.017590>

- Salihoglu, G., 2010. Industrial hazardous waste management in Turkey: Current state of the field and primary challenges. *J. Hazard. Mater.* 177, 42–56. <https://doi.org/10.1016/j.jhazmat.2009.11.096>
- Schilling, D.R., 2017. The Challenges & Opportunities of Hazardous Waste Management. *Ind. Tap.* URL <https://www.industrytap.com/challenges-opportunities-hazardous-waste-management/41377> (accessed 9.17.23).
- Sethurajan, M., van Hullebusch, E.D., Fontana, D., Akcil, A., Deveci, H., Batinic, B., Leal, J.P., Gasche, T.A., Ali Kucuker, M., Kuchta, K., Neto, I.F.F., Soares, H.M.V.M., Chmielarz, A., 2019. Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes - a review. *Crit. Rev. Environ. Sci. Technol.* 49, 212–275. <https://doi.org/10.1080/10643389.2018.1540760>
- Shi, W., Zhao, Y., Li, Z., Zhang, W., Zhou, T., Lin, K., 2023. Transformer-based enhanced model for accurate prediction and comprehensive analysis of hazardous waste generation in Shanghai: Implications for sustainable waste management strategies. *Chemosphere* 338, 139579. <https://doi.org/10.1016/j.chemosphere.2023.139579>
- Silva López, J.O., Salas López, R., Rojas Briceño, N.B., Gómez Fernández, D., Terrones Murga, R.E., Iliquín Trigos, D., Barboza Castillo, E., Oliva Cruz, M., Barrena Gurbillón, M.Á., 2022. Analytic Hierarchy Process (AHP) for a Landfill Site Selection in Chachapoyas and Huancas (NW Peru): Modeling in a GIS-RS Environment. *Adv. Civ. Eng.* 2022, e9733322. <https://doi.org/10.1155/2022/9733322>
- Song, G., Lu, Y., Feng, H., Lin, H., Zheng, Y., 2022. An implementation framework of blockchain-based hazardous waste transfer management

- system. Environ. Sci. Pollut. Res. 29, 36147–36160.
<https://doi.org/10.1007/s11356-021-17489-0>
- Stropnik, R., Lotrič, A., Bernad Montenegro, A., Sekavčnik, M., Mori, M., 2019. Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. Energy Sci. Eng. 7, 2519–2539. <https://doi.org/10.1002/ese3.441>
- Trevisan, A.H., Zacharias, I.S., Liu, Q., Yang, M., Mascarenhas, J., 2021. CIRCULAR ECONOMY AND DIGITAL TECHNOLOGIES: A REVIEW OF THE CURRENT RESEARCH STREAMS. Proc. Des. Soc. 1, 621–630. <https://doi.org/10.1017/pds.2021.62>
- UN, D., 2025. UNdata | search results [WWW Document]. URL <https://data.un.org/Search.aspx?q=Malaysia> (accessed 8.21.25).
- UNECE, 2022. Waste Management toward a more Circular Economy.
- UNEP, 2021. Global Chemicals and Waste Indicator Review Document.
- UNEP, 2015. Global Waste Management Outlook.
- UNEP, 2024, 2024. World must move beyond waste era and turn rubbish into resource: UN Report [WWW Document]. URL <https://www.unep.org/news-and-stories/press-release/world-must-move-beyond-waste-era-and-turn-rubbish-resource-un-report> (accessed 8.21.25).
- UNEP, E., 2021. Indicator 12.4.2 | UNEP - UN Environment Programme [WWW Document]. URL <https://www.unep.org/indicator-1242> (accessed 4.10.25).
- United Nations Environment Programme, 2021. Global chemicals and waste indicator review document. United Nations Environment Programm.

- Upadhyay, R., Ramayya, P.J., 2023. Role of Biotechnological Approaches for the Valorization of Precious Metals from E-waste, in: Debbarma, P., Kumar, S., Suyal, D.C., Soni, R. (Eds.), *Microbial Technology for Sustainable E-Waste Management*. Springer International Publishing, Cham, pp. 319–335. https://doi.org/10.1007/978-3-031-25678-3_20
- US EPA, O., 2015. Resource Conservation and Recovery Act (RCRA) Laws and Regulations [WWW Document]. URL <https://www.epa.gov/rcra> (accessed 9.17.23).
- Uvarova, I., Atstaja, D., Volkova, T., Grasis, J., Ozolina-Ozola, I., 2023. The typology of 60R circular economy principles and strategic orientation of their application in business. *J. Clean. Prod.* 409, 1–19. <https://doi.org/10.1016/j.jclepro.2023.137189>
- Vesilind, P.A., Peirce, J.J., Weiner, R.F., 2013. *Environmental Pollution and Control*. Elsevier.
- Walker, T.R., MacAskill, D., Weaver, P., 2013. Legacy contaminant bioaccumulation in rock crabs in Sydney Harbour during remediation of the Sydney Tar Ponds, Nova Scotia, Canada. *Mar. Pollut. Bull.* 77, 412–417. <https://doi.org/10.1016/j.marpolbul.2013.09.036>
- White, R., Heckenberg, D., 2011. Key Vulnerabilities and Limitations in the Management of Hazardous Waste and Its Disposal: A Checklist Assessment Tool. *J. Environ. Prot.* 02, 1257–1263. <https://doi.org/10.4236/jep.2011.29145>
- WHO, 2018. World Health Organization.
- Willems, J., Pauwels, T., Van Hassel, E., Vanelslander, T., Sel, S., 2022. A qualitative assessment tool for innovative waste logistics scenarios: a

- case study for Flanders. *J. Shipp. Trade* 7, 7.
<https://doi.org/10.1186/s41072-022-00107-8>
- Wilson, D.C., Velis, C.A., 2015. Waste management – still a global challenge in the 21st century: An evidence-based call for action. *Waste Manag. Res. J. Sustain. Circ. Econ.* 33, 1049–1051.
<https://doi.org/10.1177/0734242X15616055>
- Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. *Renew. Sustain. Energy Rev.* 68, 825–833. <https://doi.org/10.1016/j.rser.2016.09.123>
- World Bank, 2023. World Bank Open Data [WWW Document]. World Bank Open Data. URL <https://data.worldbank.org> (accessed 8.11.23).
- World Bank, 2022. World Bank Open Data [WWW Document]. World Bank Open Data. URL <https://data.worldbank.org> (accessed 8.11.23).
- Xavier, L.H., Ottoni, M., Lepawsky, J., 2021. Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks. *J. Clean. Prod.* 297, 126570.
<https://doi.org/10.1016/j.jclepro.2021.126570>
- Ya, X., Guangyuan, Y., Yuqiang, L., Jingcai, L., Rui, X., Can, Q., 2023. Theory, framework, and methodology for physical lifespan prediction of hazardous waste landfills. *Sci. Total Environ.* 888, 163154–163154.
<https://doi.org/10.1016/j.scitotenv.2023.163154>
- Yang, D., Gao, S., Hong, J., Ye, L., Ma, X., Qi, C., Li, X., 2019. Life cycle assessment of rare earths recovery from waste fluorescent powders – A case study in China. *Waste Manag.* 99, 60–70.
<https://doi.org/10.1016/j.wasman.2019.08.038>

- Zarin, R., Azmat, M., Naqvi, S.R., Saddique, Q., Ullah, S., 2021. Landfill site selection by integrating fuzzy logic, AHP, and WLC method based on multi-criteria decision analysis. *Environ. Sci. Pollut. Res.* 28, 19726–19741. <https://doi.org/10.1007/s11356-020-11975-7>
- Zhao, H., Liu, H., Wei, G., Wang, H., Zhu, Y., Zhang, R., Yang, Y., 2021. Comparative life cycle assessment of emergency disposal scenarios for medical waste during the COVID-19 pandemic in China. *Waste Manag.* 126, 388–399. <https://doi.org/10.1016/j.wasman.2021.03.034>
- Zhao, J., Ke, G.Y., 2019. Optimizing Emergency Logistics for the Offsite Hazardous Waste Management. *J. Syst. Sci. Syst. Eng.* 28, 747–765. <https://doi.org/10.1007/s11518-019-5429-5>
- Zhou, Y., Liu, L., Li, H., 2022. Reliability estimation and optimisation of multistate flow networks using a conditional Monte Carlo method. *Reliab. Eng. Syst. Saf.* 221, 108382. <https://doi.org/10.1016/j.ress.2022.108382>
- Zhu, Q., Geng, Y., Lai, K., 2010. Circular economy practices among Chinese manufacturers varying in environmental-oriented supply chain cooperation and the performance implications. *J. Environ. Manage.* 91, 1324–1331. <https://doi.org/10.1016/j.jenvman.2010.02.013>