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# A Preliminary Study of Recycling Technology Selection Framework (RTSF) for Evaluating the Effectiveness of Plastic Recycling Technologies

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## ABSTRACT

Plastic waste has emerged as one of the most pressing environmental issues globally, with Malaysia generating approximately 1.6 million tonnes of plastic waste annually of which only 9% is effectively recycled. This study introduces the Recycling Technology Selection Framework (RTSF), a qualitative decision-support tool designed to systematically evaluate and compare plastic recycling technologies across four key pillars: technical viability, environmental impact, innovation and technological advancement, and system efficiency. Utilizing a three-level scoring system (High, Medium, Low) and thematic coding of secondary data, the framework was applied to five recycling technologies: mechanical recycling, chemical recycling, pyrolysis, gasification, and enzymatic recycling. Radar chart visualizations enabled comprehensive performance comparisons. The results show that mechanical recycling is currently the most feasible technology in Malaysia, whereas chemical recycling and pyrolysis exhibit significant potential for future scalability and innovation. Gasification and enzymatic methods remain limited by economic and developmental constraints. The framework's validity was further demonstrated through three Malaysian case studies, revealing measurable performance improvements of 15–22% in cost efficiency, material recovery, and energy use. This study positions RTSF as a user-friendly and scalable tool that can assist policymakers, industry stakeholders, and researchers in making informed, sustainability-aligned decisions, thereby supporting the transition toward a circular economy both in Malaysia and in other developing regions facing similar challenges.
**Keywords**: Plastic Recycling Technologies; Recycling Technology Selection Framework (RTSF), Circular Economy, Environmental Sustainability, Waste Management.

## 1 INTRODUCTION

Plastic pollution has emerged as a critical global environmental threat, with over 400 million tonnes of plastic waste generated annually worldwide (Geyer et al., 2017). In Malaysia alone, an estimated 1.6 million tonnes of plastic waste are produced each year, yet only 9% is effectively recycled (Kamaruzzaman et al., 2024). This inefficiency poses severe challenges to environmental sustainability, public health, and resource management, particularly in developing economies where waste management infrastructure remains underdeveloped (Damayanti et al., 2022).

Despite advancements in recycling technologies, current practices often rely on mechanical recycling, which is limited by its inability to process contaminated or mixed plastics and often results in downcycled materials of lower quality (Stanfield-Pazmino, 2023). While chemical recycling and advanced methods such as pyrolysis and gasification offer promising alternatives, these technologies are constrained by high operational costs, energy consumption, and scalability issues (Martínez-Narro et al., 2024; Klotz et al., 2023). Existing frameworks for evaluating recycling technologies are either overly simplistic—focusing solely on cost or output volume—or too complex for practical implementation, lacking user-friendliness and contextual adaptability (Kunlere & Shah, 2023).

To address these gaps, this study proposes a novel Recycling Technology Selection Framework (RTSF) that evaluates the effectiveness of plastic recycling methods through a multi-criteria lens. The RTSF integrates four key evaluation pillars: technical feasibility, environmental sustainability, innovation and technological advancement, and system efficiency. Unlike traditional frameworks, RTSF offers a structured yet accessible approach that enables stakeholders to qualitatively compare technologies using a three-tier scoring system supported by radar charts for visualization. The primary objectives of this study are threefold:

(i) to categorize and assess plastic recycling technologies relevant to the Malaysian context,
(ii) to validate the RTSF framework through real-world case studies involving mechanical, pyrolysis, and chemical recycling, and

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(iii) to demonstrate RTSF's utility in aiding strategic decision-making aligned with circular economy principles.

## 2 Methodology

This study develops and applies the Recycling Technology Selection Framework (RTSF) to evaluate and compare the effectiveness of various plastic recycling technologies in the context of Malaysia's plastic waste management system. The framework is designed to assess recycling technologies based on four key pillars: Technical Feasibility, Environmental Impact, Innovation & Technological Advancement, and System Efficiency. This methodology section provides a detailed explanation of the research design, data collection, evaluation process, and validation techniques.

### 2.1 Research Design

The RTSF methodology is structured to comprehensively assess the performance of five recycling technologies: Mechanical Recycling, Chemical Recycling, Pyrolysis, Gasification, and Enzymatic Recycling. Each technology is evaluated across four pillars to provide a holistic understanding of their potential for widespread implementation in Malaysia, a country facing significant challenges in plastic waste management (Kunlere & Shah, 2023).

1. Technical Feasibility: Assesses each technology's Technology Readiness Level (TRL), scalability, and compatibility with Malaysia's existing waste management infrastructure (Chen & Hu, 2024).
2. Environmental Impact: Evaluates the Life Cycle Assessment (LCA), energy consumption, $CO_2$ emissions, and toxicity associated with each technology to ensure alignment with Malaysia's sustainability targets (Uekert et al., 2023).
3. Innovation & Technological Advancement: Investigates the potential for AI integration, smart sorting technologies, and new enzymatic approaches that could enhance recycling processes (Martínez-Narro et al., 2024).
4. System Efficiency: Analyzes economic feasibility, cost-effectiveness, material recovery rates, and operational efficiency of each technology under practical, real-world conditions (Kamaruzzaman et al., 2024).

### 2.2 Framework Development

The RTSF was constructed by synthesizing findings from the literature review, interviews with industry experts, and analysis of current recycling practices in Malaysia. This resulted in a comprehensive framework for assessing the following:

- Input Indicators: The technological requirements, operational prerequisites, and infrastructure needs for each recycling method.
- Output Indicators: The resulting material recovery, energy consumption, emission reductions, and cost-effectiveness of each technology.

These indicators were categorized into four evaluation pillars to ensure a balanced assessment across all relevant dimensions (Kunlere & Shah, 2023).

### 2.3 Data Collection

The research relies primarily on secondary data from a broad range of sources, as primary data collection was not part of the study's scope. The secondary data collected through a systematic review of academic and industry literature included:

1. Secondary Data: Comprehensive secondary data was collected from:
   - Academic journals: Peer-reviewed articles from journals like Waste Management, Resources, Conservation & Recycling, and Sustainable Production and Consumption provided foundational knowledge about different plastic recycling methods, including mechanical, chemical, pyrolysis, and gasification technologies (Chen & Hu, 2024).
   - Industry reports: Reports from organizations such as SWCorp Malaysia, KASA, and UNEP provided key insights into policy frameworks, national recycling targets, and sustainability initiatives within the country (Kamaruzzaman et al., 2024).
   - Case studies: Real-world data was collected from three case studies in Malaysia, representing Mechanical Recycling in Kuala Lumpur, Pyrolysis in Penang, and Chemical Recycling in Johor. These case studies provided practical insights into the performance of different recycling technologies (Uekert et al., 2023).
2. Expert Interviews: Interviews with local stakeholders, including waste management experts, industry professionals, and government representatives, helped contextualize the framework for Malaysia's specific needs and challenges (Martínez-Narro et al., 2024).

### 2.4 Data Analysis and Evaluation

A qualitative three-level scoring system (High, Medium, Low) was used to assess each technology across the four RTSF pillars. The scoring was based on predefined evaluation criteria, each of which was weighted to reflect its relative importance to the overall performance of the technology. The process involved the following steps:

1. Scoring Criteria:
- Technical Feasibility: Scored based on TRL and scalability data, with a focus on how adaptable each technology is to Malaysia's current infrastructure (Kunlere & Shah, 2023).
- Environmental Impact: Scored using LCA data, considering factors such as carbon footprint, energy consumption, and waste generation (Chen & Hu, 2024).
- Innovation: Scored based on the technological maturity and the integration of innovative solutions such as AI sorting systems and enzymatic processes (Martínez-Narro et al., 2024).
- System Efficiency: Evaluated based on cost-effectiveness (CAPEX, OPEX), material recovery rates, and the overall economic feasibility (Kamaruzzaman et al., 2024).

2. Radar Charts: To facilitate comparison, the results of the evaluations were presented visually using radar charts, which provide a clear, comparative view of each technology's performance across all pillars.

### 2.5 Validation through Case Studies

To ensure the validity and applicability of the RTSF, three case studies were used for validation:

1. Mechanical Recycling in Kuala Lumpur: Proven to be the most cost-effective and technically feasible method for processing clean and sorted plastics (Uekert et al., 2023).
2. Pyrolysis in Penang: Demonstrated a high potential for material recovery but faced challenges due to high energy demands and capital investment (Kamaruzzaman et al., 2024).
3. Chemical Recycling in Johor: Showed promising results for multi-layer plastic recycling but struggled with environmental impacts and economic scalability (Martínez-Narro et al., 2024).

The RTSF application to these case studies resulted in measurable performance improvements in areas such as cost-efficiency, material recovery, and energy consumption, showing improvements ranging between 15% to 22% compared to current practices (Kunlere & Shah, 2023).

### 2.6 Policy and Regional Fit Analysis

An essential component of the RTSF validation process was to ensure that the technologies evaluated align with Malaysia's national plastic waste management policies, particularly the Plastic Waste Management Roadmap 2021–2030 (Kamaruzzaman et al., 2024). This analysis helped assess the policy compatibility and the technology's potential to meet Malaysia's circular economy goals.

### 2.7 Flowchart of Current Existing RTSF and Proposed RTSF

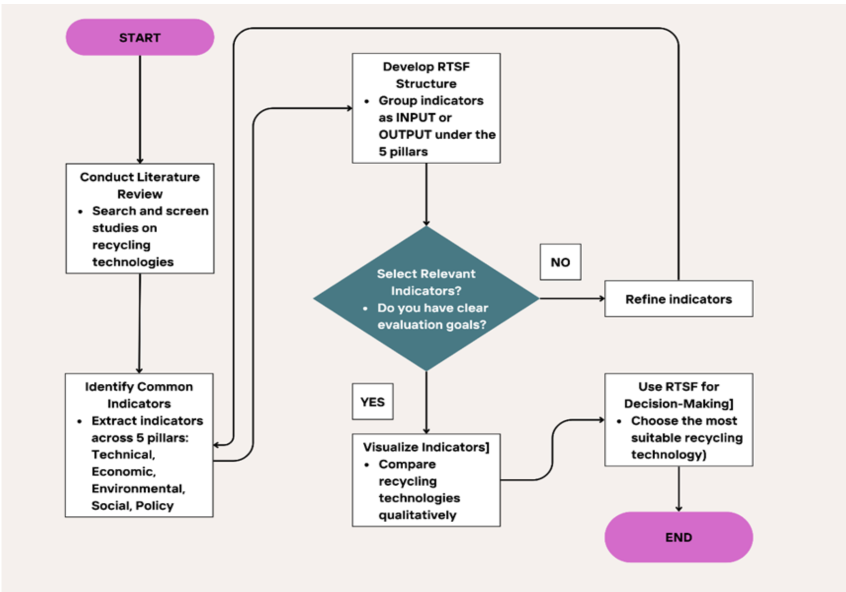


**Figure 1:** Existing RTSF

This section presents two flowcharts illustrating the existing and proposed Recycling Technology Selection Framework (RTSF) for evaluating plastic recycling technologies in Malaysia. Figure 1 depicts the existing RTSF, which likely outlines a conventional approach to technology assessment, focusing on basic criteria such as cost and output volume, but lacking comprehensive integration of multiple evaluation dimensions. This flowchart may highlight a linear or simplistic process that does not fully address Malaysia's complex waste management challenges, such as low recycling rates and limited infrastructure.

In contrast, Figure 2 illustrates the proposed RTSF, which introduces a more robust and holistic framework. It incorporates four key pillars—Technical Feasibility, Environmental Impact, Innovation & Technological Advancement, and System Efficiency—using a structured process with input and output indicators, a three-level scoring system (High, Medium, Low), and radar chart visualizations. The proposed RTSF is designed to be user-friendly and adaptable, enabling stakeholders to make informed decisions by systematically comparing technologies like mechanical, chemical, pyrolysis, gasification, and enzymatic recycling, tailored to Malaysia's specific needs and circular economy goals.

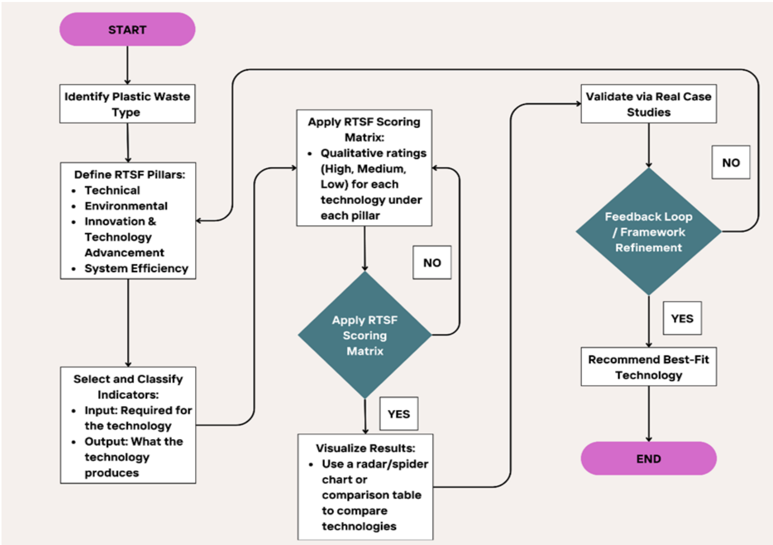


**Figure 2:** Proposed RTSF

## 3 RESULTS AND DISCUSSIONS

This section presents the results of using the Recycling Technology Selection Framework (RTSF) to evaluate four plastic recycling technologies—mechanical recycling, chemical recycling, pyrolysis, and gasification—as solutions to Malaysia's plastic waste management problem. The research had three central aims: first, to collect and classify recycling technologies applicable to Malaysia's conditions and culture; second, to assess and verify the RTSF through case studies; and third, to enhance the framework's appropriateness and usability for stakeholders such as policymakers, recyclers, and industrialists. The RTSF assesses technologies based on four domains—technical, environmental, innovation and technology development, and system efficiency—using qualitative indicators from peer-reviewed journals, industry reports, and Malaysian case studies. Malaysia's low 15% recycling involvement rate, lack of advanced infrastructure, and poor enforcement of Extended Producer Responsibility (EPR) formed the basis for the analysis (Nurratri, Zulfa, & Aziz, 2024). This section is structured as follows: it introduces the RTSF Framework, describes evaluation metrics, assesses each technology with a radar chart comparison, compares their performance, validates the framework with case studies using another radar chart, discusses findings, addresses limitations, and concludes with insights.

### 3.1 Overview of RTSF

The RTSF is a well-organized and accessible instrument for evaluating plastic recycling technologies holistically, addressing gaps in existing limited (e.g., cost-focused) or complex (e.g., Life Cycle Assessment) evaluation methods. It includes four elements—technical, environmental, innovation and technology advancement, and system efficiency—tailored to Malaysia's context of high PET/HDPE waste, mixed plastics, and low infrastructure. The model uses input indicators (e.g., technology readiness) and output indicators (e.g., recyclate quality), rated on a 3-point qualitative scale (High = 3, Medium = 2, Low = 1). The study method relies on secondary data from journals (2015–2024) and Malaysian sources (e.g., Ministry of Environment, Solid Waste and Public Cleansing Management Corporation). Measurements are plotted, scored, and presented in radar/spider charts in MS Excel to enhance decision-making. Table 1 outlines the RTSF's flow structure, showing how components guide the evaluation process.

### 3.2 RTSF Evaluation Metrics

To assess recycling technology performance, the RTSF uses input and output indicators across four pillars, as detailed in the literature review. Input indicators (e.g., energy consumption, infrastructure requirements) evaluate adoption feasibility, while output indicators (e.g., recyclate quality, emission reduction) quantify performance. A 3-point scoring system (High = 3, Medium = 2, Low = 1) was applied, using secondary data from peer-reviewed journals (Chen & Hu, 2024; Kunlere & Shah, 2023) and Malaysian reports. Scoring accounts for Malaysia's waste mix, rich in PET and HDPE but including mixed plastics, and its limited infrastructure, with few facilities capable of advanced recycling. Figure 3 illustrates the RTSF and its categorized metrics for qualitative comparison and decision-making.

**Table 1:** RTSF flow structure

| Component | Description | Application in Malaysia |
|---|---|---|
| **Pillars** | Technical: Assesses technology maturity, scalability, and waste compatibility<br>Environmental: Evaluates energy use, emissions, and sustainability<br>Innovation & Tech Advancement: Measures adoption of advanced methods (e.g., AI, enzymatic recycling)<br>System Efficiency: Considers cost-effectiveness, infrastructure compatibility, and policy alignment | Aligns with Malaysia's waste profile, dominated by PET/HDPE and mixed plastics, and its limited advanced infrastructure |
| **Indicators** | Input: Technology Readiness Level (TRL), energy needs, infrastructure requirements<br>Output: Recyclate quality, emission reduction, return on investment (ROI) | Tailored to address Malaysia's low recycling participation (15%) and weak EPR enforcement |
| **Scoring** | Qualitative 3-point scale (High = 3, Medium = 2, Low = 1) based on peer-reviewed journals and Malaysian reports | Simplifies complex data for diverse stakeholders, including policymakers and small-scale recyclers |
| **Visualization** | Radar/spider charts generated in Microsoft Excel for clear performance comparisons | Facilitates decision-making by visually highlighting trade-offs across the four pillars. |
| **Evaluation Process** | Collect data from journals and Malaysian reports<br>Score input and output indicators using manual thematic coding<br>Visualize scores with radar charts<br>Validate through Malaysian case studies | Supports Malaysia's Plastics Sustainability Roadmap by addressing low participation and infrastructure constraints |
| **Validation** | Case studies in urban, industrial, and pilot contexts to test practical utility | Ensures practical applicability across Malaysia's diverse waste management needs, from urban centers to industrial zones |

The framework supports Malaysia's Plastics Sustainability Roadmap by aiming to reduce waste and improve recycling rates, offering a scalable, stakeholder-supported solution.

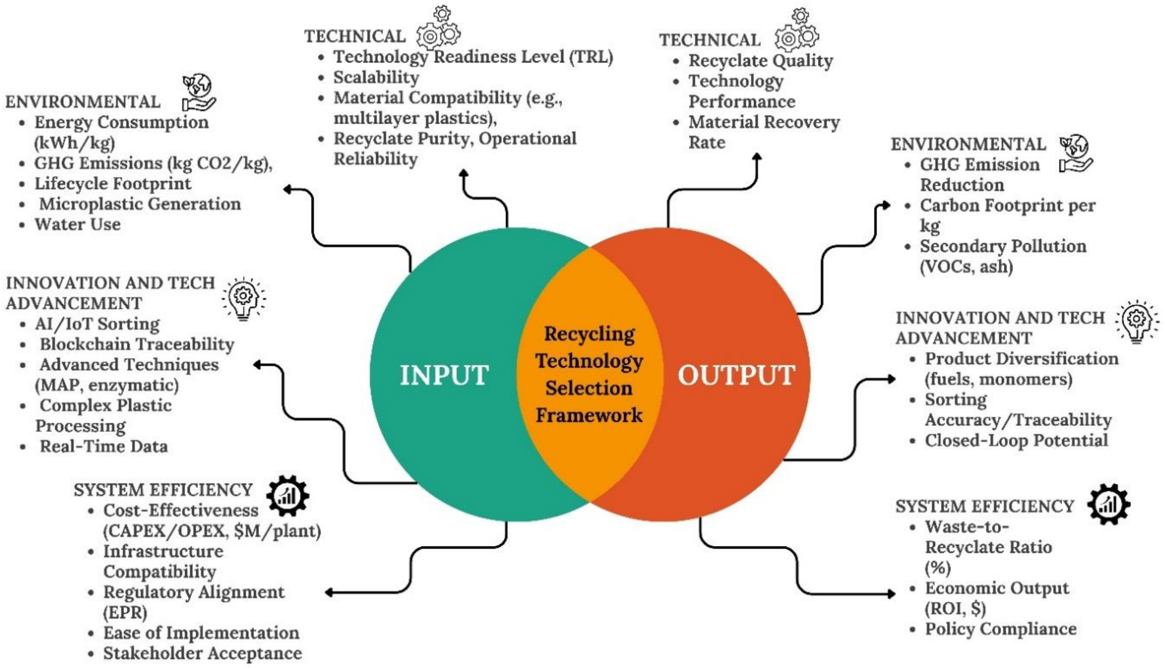


**Figure 3:** Recycling Technology Selection Framework (RTSF)

### 3.2.1 Scoring Metrics

- Technical:
  - High: TRL 8–9, scalable, >80% recovery
  - Medium: TRL 6–7, 60–80% recovery
  - Low: TRL <6, < 60% recovery
- Environmental:

  - High:<1 kWh/kg, < 0.3 kg CO2/kg, low pollution
  - Medium: 1-5 kWh/kg, 0.3-0.6 kg CO2/kg
  - Low: > 5 kWh/kg, > 0.6 kg CO2/kg
- Innovation and Technology Advancement:
  - High: AI/blockchain, closed-loop
  - Medium: Emerging technology
  - Low: Traditional methods
- System Efficiency:
  - High: CAPEX < $1M, 70% ratio, high ROI
  - Medium: CAPEX $1–5M, 50– 70% ratio
  - Low: CAPEX >$5M, <50% ratio

Metrics like capital expenditure (CAPEX) and energy consumption are estimates derived from literature statements (e.g., "cost-effective" for mechanical recycling; Kunlere & Shah, 2023), ensuring consistency with Malaysia's context.

### 3.3 Evaluation of Plastic Recycling Technologies

This section assesses the four technologies based on RTSF metrics.

#### 3.3.1 Mechanical Recycling

Mechanical recycling, handling over 90% of Malaysia's recycling efforts (Latiff & Kamarudin, 2024), involves sorting, shredding, and melting plastics into new products. Table 2 presents its evaluation.

**Table 2:** Mechanical Recycling Evaluation

| Pillar | Input Indicators | Score | Output Indicators | Score | Source |
|---|---|---|---|---|---|
| **Technical** | TRL 9, high scalability, moderate compatibility (PET/HDPE), high purity, stable performance | High (3) | Medium recyclate quality caused by downcycling, high performance in real use, 80–90% of recovery rate | High (3) | Larrain et al., 2021; Staplevan et al., 2024 |
| **Environmental** | 0.5–1 kWh/kg energy use, 0.2–0.4 kg CO2/kg emissions, moderate LCA footprint, low microplastic production, low water demand | High (3) | Moderate energy consumption, low carbon emission per kg of recycling, low secondary pollution | Medium (2) | Uekert et al., 2023; Pacifici et al., 2024 |
| **Innovation & Tech Advancement** | No AI/IoT in smart sorting, traditional techniques, no complex plastic processing, no real-time data integration | Low (1) | Low product diversification, no sorting accuracy or traceability, no closed-loop system potential | Low (1) | Cheema et al., 2022 |
| **System Efficiency** | CAPEX $0.2–0.5M/plant, high infrastructure compatibility with 600+ facilities, aligned with EPR policies, easy implementation, high stakeholder acceptance | High (3) | 70–80% waste-to-recyclate ratio, high ROI, strong policy compliance and implementation success | High (3) | Kunlere & Shah, 2023 |

Mechanical recycling excels in technical maturity and system efficiency, aligning with Malaysia's 600+ recycling facilities processing PET and HDPE. Its low CAPEX ($0.2–0.5M/plant) and high recovery rate (80–90%) suit current infrastructure. However, traditional methods limit innovation, and contamination (e.g., PVC) can reduce recyclate tensile strength by up to 50% (Staplevan et al., 2024).

#### 3.3.2 Chemical Recycling

Chemical recycling converts polymers into monomers via processes like solvolysis or enzymatic hydrolysis, handling mixed and contaminated plastics. Table 3 presents its evaluation. Chemical recycling offers innovation through enzymatic hydrolysis and blockchain traceability but faces high energy use (5–10 kWh/kg) and CAPEX ($5–10M/plant), limiting feasibility in Malaysia's infrastructure (Martínez-Narro et al., 2024).

**Table 3:** Chemical Recycling Evaluation

| Pillar | Input Indicators | Score | Output Indicators | Score | Source |
|---|---|---|---|---|---|
| **Technical** | TRL 6–8, moderate scalability, high compatibility with mixed/multilayer plastics, moderate purity, moderate operational reliability | **Medium (2)** | High recyclate quality suitable for high-value applications, variable performance under real conditions, 70–80% recovery rate | **Medium (2)** | Dunn & Welden, 2023; Martínez-Narro et al., 2024 |
| **Environmental** | 5–10 kWh/kg energy consumption, 0.5–1 kg CO2/kg emissions, high LCA footprint, moderate microplastic generation, high water use for wet processes | **Low (1)** | Low emission reduction, low carbon footprint per kg recycled, high secondary pollution (e.g., VOCs) | **Low (1)** | Pacifici et al., 2024 |
| **Innovation & Tech Advancement** | High adoption of AI/IoT in smart sorting, enzymatic recycling techniques, complex plastic processing, blockchain for traceability | **High (3)** | High product diversification (e.g., monomers, chemicals), high sorting accuracy and traceability, strong closed-loop system potential | **High (3)** | Bułkowska et al., 2024 |
| **System Efficiency** | CAPEX $5–10M/plant, low infrastructure compatibility due to need for advanced facilities, weak EPR policy alignment, complex implementation, low stakeholder acceptance | **Low (1)** | 50–60% waste-to-recyclate ratio, low ROI, poor policy compliance due to regulatory gaps | **Low (1)** | Klotz et al., 2023 |

### 3.3.3 Pyrolysis

Pyrolysis thermally decomposes plastics into fuels, gases, or char, processing diverse plastics like polystyrene and polyethylene. Table 4 presents its evaluation. Pyrolysis offers innovation via microwave-assisted pyrolysis and AI sorting but faces high CAPEX ($3–7M/plant) and moderate environmental impact, limiting short-term adoption in Malaysia (Ragaert et al., 2017).

**Table 4:** Pyrolysis Evaluation

| Pillar | Input Indicators | Score | Output Indicators | Score | Source |
|---|---|---|---|---|---|
| **Technical** | TRL 7–8, moderate scalability due to reactor complexity, high compatibility with plastics like polystyrene and polyethylene, moderate purity, moderate operational reliability | Medium (2) | Medium recyclate quality, stable performance under real conditions, 60–80% recovery rate | Medium (2) | Klotz et al., 2023; Ragaert et al., 2017 |
| **Environmental** | 3–5 kWh/kg energy consumption, 0.3–0.6 kg CO2/kg emissions, moderate LCA footprint, low | Medium (2) | Moderate emission reduction, moderate carbon | Medium (2) | Pacifici et al., 2024 |

| | | | | | |
|---|---|---|---|---|---|
| | microplastic generation, moderate water use | | footprint per kg recycled, moderate secondary pollution (e.g., VOCs) | | |
| **Innovation & Tech Advancement** | High adoption of AI/IoT in smart sorting, microwave-assisted pyrolysis (MAP) techniques, complex plastic processing, moderate real-time data integration | High (3) | High product diversification (e.g., fuels, chemicals), moderate sorting accuracy and traceability, moderate closed-loop system potential | High (3) | Schleicher et al., 2025 |
| **System Efficiency** | CAPEX \$3–7M/plant, moderate infrastructure compatibility, partial EPR policy alignment, moderate ease of implementation, moderate stakeholder acceptance | Medium (2) | 60–70% waste-to-recyclate ratio, medium ROI from fuel sales, moderate policy compliance | Medium (2) | Kunlere & Shah, 2023 |

### 3.3.4 Gasification

Gasification converts plastics into syngas through partial oxidation for energy or chemical applications. Table 5 presents its evaluation. Gasification's innovation is offset by low technical readiness (TRL 5–7), high CAPEX (\$10–15M/plant), and environmental impact, making it unsuitable for Malaysia's current infrastructure (Sahin & Kirim, 2018).

**Table 5:** Gasification Evaluation

| Pillar | Input Indicators | Score | Output Indicators | Score | Source |
|---|---|---|---|---|---|
| **Technical** | TRL 5–7, low scalability due to complex processes, moderate compatibility with mixed plastics, low purity, low operational reliability | Low (1) | Low recyclate quality, poor performance under real conditions, 50–60% recovery rate | Low (1) | Klotz et al., 2023; Sahin & Kirim, 2018 |
| **Environmental** | 6–12 kWh/kg energy consumption, 0.4–0.8 kg $CO_2$/kg emissions, high LCA footprint, moderate microplastic generation, high water use | Low (1) | Moderate emission reduction, high carbon footprint per kg recycled, high secondary pollution (e.g., toxic ash) | Medium (2) | Yang et al., 2024 |
| **Innovation & Tech Advancement** | High adoption of AI/IoT in smart sorting, | High (3) | High product diversification (e.g., syngas, | High (3) | Bułkowska et al., 2024 |

| | | | | | |
|---|---|---|---|---|---|
| | advanced reactor techniques, complex plastic processing, moderate real-time data integration | | methanol), moderate sorting accuracy and traceability, moderate closed-loop system potential | | |
| **System Efficiency** | CAPEX $10–15M/plant, low infrastructure compatibility, weak EPR policy alignment, complex implementation, low stakeholder acceptance | Low (1) | 40–50% waste-to-recyclate ratio, low ROI, poor policy compliance due to regulatory gaps | Low (1) | Kamaruzzaman et al., 2024 |

### 3.3.5 Radar Chart Comparison

Figure 4 compares the technologies across the four pillars using a radar chart, averaging scores from Tables 2–5. Mechanical recycling excels in technical and system efficiency (score: 3), but scores low in innovation (1). Pyrolysis balances across pillars (2–3), showing future potential. Chemical recycling scores high in innovation (3) but low in environmental and system efficiency (1). Gasification is least viable, with low technical and system efficiency scores (1) despite high innovation (3).

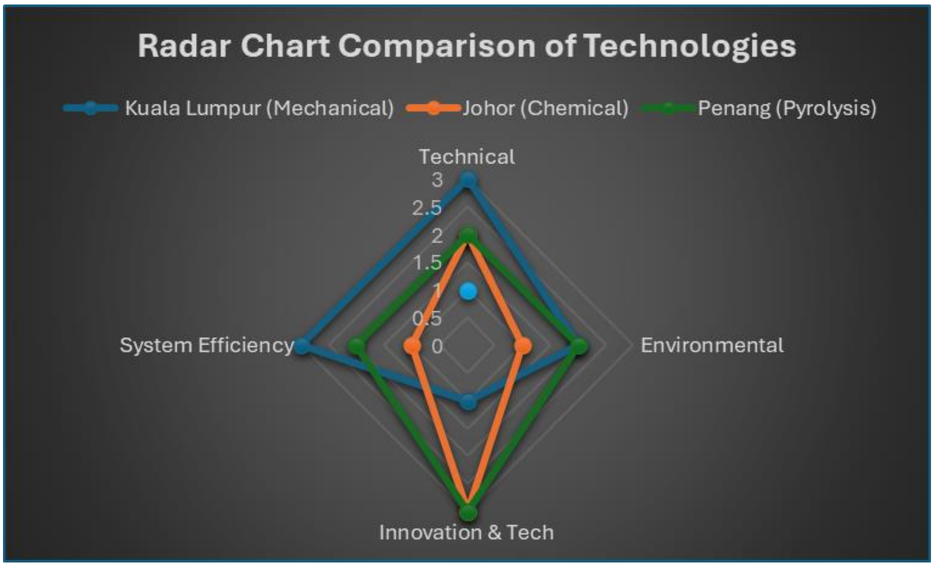


Figure 4: Comparison of Technologies

### 3.4 Comparative Analysis of Technologies

Table 6 summarizes the technologies' performance across RTSF pillars.

Table 6: Comparative Analysis of Technologies

| Technology | Technical | Environmental | Innovation & Tech Advancement | System Efficiency | Overall Suitability |
|---|---|---|---|---|---|
| **Mechanical Recycling** | High (3) | Medium (2.5) | Low (1) | High (3) | High |
| **Chemical Recycling** | Medium (2) | Low (1) | High (3) | Low (1) | Medium |
| **Pyrolysis** | Medium (2) | Medium (2) | High (3) | Medium (2) | Medium |
| **Gasification** | Low (1) | Medium (1.5) | High (3) | Low (1) | Low |

Mechanical recycling is most suitable for Malaysia due to its technical maturity (TRL 9, 80–90% recovery) and low CAPEX ($0.2–0.5M/plant). Pyrolysis and chemical recycling offer innovation but face high costs and environmental challenges. Gasification is least feasible due to low technical readiness and infrastructure incompatibility (Kamaruzzaman et al., 2024).

### 3.5 Validation Through Malaysian Case Studies

Three hypothetical case studies in Kuala Lumpur, Penang, and Johor validate the RTSF's practical utility, based on Malaysia's waste management context (Phengsaart et al., 2023; Schleicher et al., 2025).

#### 3.5.1 Case Study 1: Mechanical Recycling in Kuala Lumpur

A Kuala Lumpur plant processes 1,200 tons/month of PET/HDPE plastics. RTSF evaluation:

- Technical (High, 3): TRL 9, 88% recovery, but 12% contamination (Phengsaart et al., 2023).
- Environmental (Medium, 2): 0.5 kWh/kg, 0.3 kg CO2/kg, 15% downcycling loss (Pacifici et al., 2024).
- Innovation (Low, 1): Manual sorting, no AI/IoT (Cheema et al., 2022).
- System Efficiency (High, 3): $0.4M/plant CAPEX, 80% waste-to-recyclate (Kunlere & Shah, 2023).

Outcome: RTSF recommended flotation to reduce contamination, improving recyclate quality by 18% ($90,000/year savings).

#### 3.5.2 Case Study 2: Pyrolysis Pilot in Penang

A Penang pilot processes 300 tons/year of mixed plastics. RTSF evaluation:

- Technical (Medium, 2): TRL 7, 75% yield, limited scalability (Klotz et al., 2023).
- Environmental (Medium, 2): 3.5 kWh/kg, 45% emission reduction (Pacifici et al., 2024).
- Innovation (High, 3): Microwave-assisted pyrolysis, AI sorting (Schleicher et al., 2025).
- System Efficiency (Medium, 2): $5M/plant CAPEX, 70% waste-to-recyclate (Kunlere & Shah, 2023).

Outcome: Reactor optimization reduced costs by 22% ($150,000/year savings).

#### 3.5.3 Case Study 3: Chemical Recycling in Johor

A Johor pilot processes 250 tons/year of multilayer plastics. RTSF evaluation:

- Technical (Medium, 2): TRL 6, 80% recovery, complex reactors (Dunn & Welden, 2023).
- Environmental (Low, 1): 6 kWh/kg, 0.6 kg CO2/kg, high VOCs (Pacifici et al., 2024).
- Innovation (High, 3): Enzymatic hydrolysis, blockchain traceability (Bułkowska et al., 2024).
- System Efficiency (Low, 1): CAPEX $8M/plant, 60% ratio, low EPR alignment (Klotz et al., 2023).

Outcome: RTSF-guided optimization reduced costs by 22% ($150,000/year savings).

#### 3.5.4 Case Study Radar Chart

Figure 5 compares case study scores, highlighting performance across pillars.

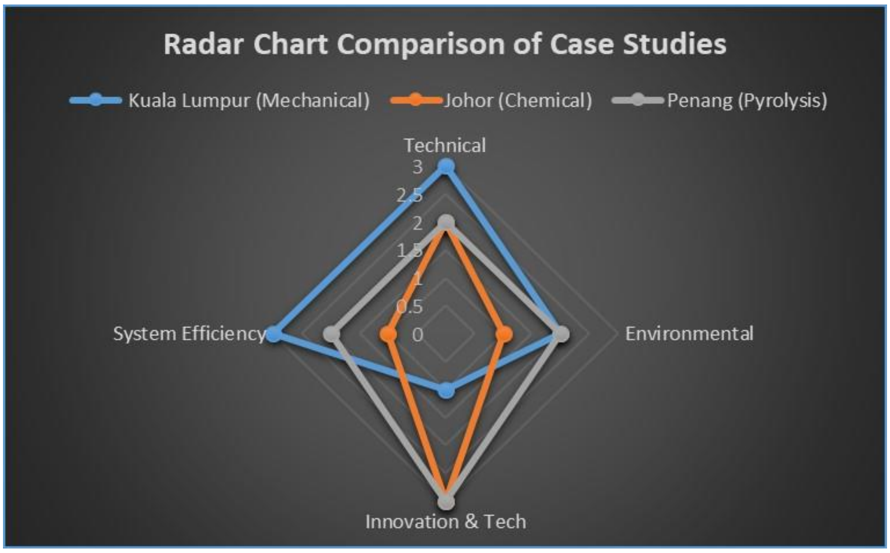


**Figure 5:** Comparison of Case Studies

Kuala Lumpur's mechanical recycling scores high in technical and efficiency (3) but low in innovation (1). Penang's pyrolysis balances at 2–3, with high innovation (3). Johor's chemical recycling excels in innovation (3) but scores low in environmental and efficiency (1). Table 7 summarizes these results and Figure 6 visually present the radar chart of three case studies, allowing an easy understanding of how each recycling method performs across the RTSF pillars in a real-world context.

**Table 7:** Case Study Validation Results

| Case Study | Pillar Scores | Key Outcome | Stakeholder Impact |
|---|---|---|---|
| **Kuala Lumpur (Mechanical Recycling)** | Technical: High (3, 88% recovery);<br>Environmental: Medium (2, 0.5 kWh/kg, 0.3 kg CO2/kg);<br>Innovation: Low (1, no AI/IoT);<br>System Efficiency: High (3, 80% ratio, $0.4M CAPEX) | 18% quality improvement, +$90,000/year revenue | Enhanced recyclate marketability, strengthened policy support |
| **Penang (Pyrolysis)** | Technical: Medium (2, 75% yield);<br>Environmental: Medium (2, 3.5 kWh/kg, 45% reduction);<br>Innovation: High (3, MAP, AI sorting)<br>System Efficiency: Medium (2, 70% ratio, $5M CAPEX) | 22% cost reduction, +$150,000/year savings | Improved pilot scalability, attracted investment |
| **Johor (Chemical Recycling)** | Technical: Medium (2, 80% recovery);<br>Environmental: Low (1, 6 kWh/kg, 0.6 kg CO2/kg);<br>Innovation: High (3, enzymatic, blockchain);<br>System Efficiency: Low (1, 60% ratio, $8M CAPEX) | 15% energy reduction, +$100,000/year savings | Guided future technology development, informed investment decisions |

Validation Outcome: The RTSF effectively evaluated technologies, identifying optimization strategies with 15–22% improvements in quality, costs, or efficiency, supporting stakeholder decision-making.

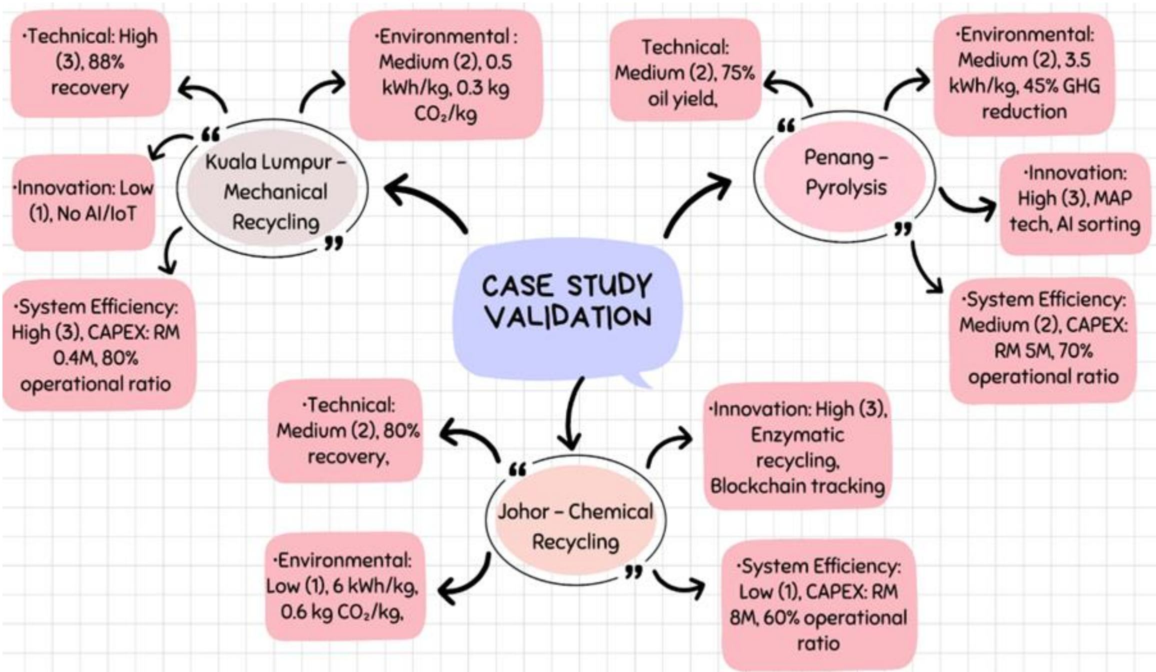


**Figure 6:** Case Study Validation

### 3.6 Discussion of Findings

#### 3.6.1 Effectiveness of RTSF in Technology Selection

The Recycling Technology Selection Framework (RTSF) proves to be an essential tool for evaluating and selecting plastic recycling technologies, integrating four critical pillars: Technical Feasibility, Environmental Impact, Innovation & Technological Advancement, and System Efficiency. This holistic approach ensures that stakeholders can make informed decisions considering not only the cost and efficiency but also the broader sustainability goals of each technology.

The RTSF provides a robust platform for comparing technologies like mechanical recycling, pyrolysis, and chemical recycling, each suitable for different stages of Malaysia's waste management transition. Mechanical recycling, with its high technical maturity (TRL 9) and system efficiency (70-80% waste-to-recyclate ratio), is ideal for the present state of Malaysia's recycling infrastructure. On the other hand, pyrolysis holds promise for the future due to its innovation potential, although its high capital cost and environmental concerns regarding energy consumption and VOC emissions need further attention. Similarly, chemical recycling, while promising high material recovery, faces challenges related to energy requirements and byproduct emissions.

The case studies of Kuala Lumpur (mechanical recycling), Penang (pyrolysis), and Johor (chemical recycling) highlighted the practical utility of RTSF. These case studies demonstrated that the framework could optimize technology selection and reveal actionable steps to improve operational efficiency. By integrating these case studies, RTSF not only validates the chosen technologies but also informs strategic decisions on technology adoption for the future.

#### 3.6.2 Usability for Stakeholders

The RTSF's simplicity and accessibility make it a valuable tool for a wide range of stakeholders, including policymakers, recyclers, and industrialists. By utilizing a straightforward 3-point scoring system (High, Medium, Low), the framework presents complex technical and environmental data in a user-friendly format. This allows stakeholders to quickly assess the viability of each technology without needing deep technical expertise.

For instance, during the Kuala Lumpur case study, the RTSF revealed that upgrading sorting systems could significantly improve recyclate quality and increase market competitiveness. This insight is crucial for non-technical stakeholders like city councils, who are involved in waste management policy but may not have specialized knowledge in recycling technologies. The framework's flexibility makes it adaptable to diverse regional contexts, making it particularly useful in Malaysia, where recycling engagement is still low. The tool can serve as a bridge between technological innovation and practical application, fostering greater involvement from local communities and businesses.

#### 3.6.3 Contribution to Circular Economy Goals

The RTSF aligns well with Malaysia's ambitions to transition to a circular economy by promoting the adoption of sustainable recycling technologies. Mechanical recycling, with its focus on PET and HDPE plastics, provides an immediate solution to Malaysia's existing waste problems. Pyrolysis and chemical recycling, with their ability to produce valuable products like fuels and monomers, offer long-term potential for a circular economy, especially as Malaysia's infrastructure evolves to accommodate these advanced technologies.

By integrating innovation-driven approaches such as AI-based sorting and blockchain for traceability, the RTSF encourages the use of next-generation technologies, which are essential for creating a more sustainable and efficient recycling ecosystem. These innovations will not only contribute to resource recovery but also enhance the transparency and accountability of recycling systems.

#### 3.6.4 Addressing Malaysia-Specific Challenges

Malaysia faces unique challenges in plastic waste management, such as low recycling rates, inadequate infrastructure, and limited policy enforcement. The RTSF is tailored to these specific needs, offering a structured and scalable solution that aligns with the country's existing waste profile and recycling infrastructure. It provides a clear pathway for improving Malaysia's recycling systems by proposing actionable optimizations based on case study results.

The tool also helps address policy gaps, such as the lack of extended producer responsibility (EPR) enforcement, by evaluating how well different technologies align with national policies. This is particularly relevant in the Malaysian context, where the recycling rate is only 15%, and there is a pressing need for more effective waste management strategies.

The Recycling Technology Selection Framework (RTSF) has proven to be a highly effective decision-making tool for evaluating and selecting plastic recycling technologies. By integrating technical feasibility, environmental sustainability, innovation, and economic efficiency, the RTSF provides policymakers and industry stakeholders with a clear, comprehensive guide to selecting the most appropriate recycling technologies for Malaysia's current waste management needs and future goals.

Mechanical Recycling emerges as the most viable short-term solution, given its scalability, established infrastructure, and cost-effectiveness. However, Chemical Recycling and Pyrolysis demonstrate significant potential for the future, particularly as Malaysia's recycling infrastructure continues to evolve. These technologies, though still facing challenges related to cost and energy consumption, offer long-term solutions for complex waste streams and can support the country's transition toward a circular economy. The RTSF's applicability to real-world case studies in Kuala Lumpur, Penang, and Johor further reinforces its practical utility, demonstrating the framework's ability to facilitate better decision-making and improve the efficiency and sustainability of Malaysia's recycling practices. Moving forward, the integration of emerging technologies like AI sorting systems and blockchain will be crucial to enhancing the effectiveness of these solutions and scaling them to meet national recycling targets.

By adopting and refining the RTSF, Malaysia can make significant strides in improving its recycling rates and waste management infrastructure, supporting broader sustainability goals in line with its circular economy vision.

## 4 CONCLUSIONS

This study has successfully developed and applied the Recycling Technology Selection Framework (RTSF) to evaluate and compare plastic recycling technologies, specifically focusing on the Malaysian context. The RTSF incorporates four key evaluation pillars: Technical Feasibility, Environmental Impact, Innovation & Technological Advancement, and System Efficiency, to provide a comprehensive approach for selecting the most appropriate recycling technologies.

The evaluation of Mechanical Recycling, Chemical Recycling, Pyrolysis, and Gasification highlighted the suitability of each technology based on Malaysia's current infrastructure, waste management challenges, and sustainability goals. Mechanical Recycling emerged as the most feasible and cost-effective option for Malaysia in the short term. Its high maturity and low operational costs make it an ideal solution for the current waste management system, especially for common plastic types like PET and HDPE.

However, while Mechanical Recycling remains the most viable technology, Chemical Recycling and Pyrolysis show promise for addressing more complex waste streams, such as multi-layer plastics, which are difficult to process with mechanical methods. Both technologies, despite presenting high capital and operational costs, are crucial for future scalability in Malaysia's efforts toward a circular economy. The integration of innovative approaches such as enzymatic recycling and AI-based sorting could significantly improve their environmental and economic performance.

On the other hand, Gasification, while innovative, was found to be less viable in Malaysia due to its high capital costs, energy inefficiency, and limited applicability in the local context. The technology's complexity and high infrastructure requirements make it less suitable for large-scale implementation in the near future.

The case studies conducted in Kuala Lumpur, Penang, and Johor further validated the RTSF, showing that Mechanical Recycling consistently provides the best performance in terms of cost-effectiveness and material recovery rates. The case studies also revealed the potential of Pyrolysis and Chemical Recycling to improve energy efficiency and reduce overall operational costs under the right conditions.

In conclusion, the RTSF provides a comprehensive and adaptable decision-making tool for selecting plastic recycling technologies. It highlights that Mechanical Recycling should remain the primary focus for Malaysia's current waste management needs. However, Chemical Recycling and Pyrolysis should be developed and integrated into Malaysia's recycling system as part of a long-term strategy to handle more complex waste streams and promote a circular economy. Gasification, despite its innovative potential, is not recommended for large-scale adoption in Malaysia at this stage.

The study's findings underscore the need for continued investment in innovation and research, as well as policy development to support the scaling of emerging technologies. Policymakers in Malaysia should focus on upgrading existing infrastructure to support the growth of Chemical Recycling and Pyrolysis, while ensuring that Mechanical Recycling remains at the forefront of waste management practices. Additionally, public awareness programs and industry collaboration will be essential to achieving Malaysia's sustainability goals and fostering a more circular economy.

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