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REVIEW ARTICLE

Challenges in integrating automation into on-site waste management in residential construction

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Abstract: As global sustainability initiatives grow in intensity, the residential construction sector is confronted with major inefficiencies in on-site waste management, revealing a considerable disparity between traditional manual techniques and current technological solutions. Despite the proven capability of Internet of Things (IoT), Artificial Intelligence (AI), and robotics to enhance the precision and speed of waste sorting and disposal, these technologies have yet to be successfully integrated into on-site residential construction workflows. Existing literature lacks an integrated perspective on automation readiness, leaving industry stakeholders without a clear understanding of the systemic challenges that must be addressed to transition from manual to automated waste handling on residential sites. To address this gap, this study aims to identify the challenges hindering the integration of automation into on-site waste management within residential construction projects. A qualitative research strategy was employed, using semi-structured interviews with consultants, contractors, technology developers, government officials, and waste management officers to gain in-depth insights into industry perspectives. Through thematic analysis, five major challenge themes were identified: i) economic, ii) regulatory, iii) human, iv) data, and v) technical. The findings reveal that these challenges are deeply interdependent; for instance, technical site constraints and material variability exacerbate economic risks by undermining the projected return on investment (ROI) and system scalability. Beyond theme identification, this study contributes a conceptual framework to help practitioners evaluate project suitability and for cross-sector automation integration. These findings offer actionable guidance for policymakers to design targeted incentives and for technology providers to develop modular solutions tailored to the spatial and material constraints of residential sites.

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1. Introduction

While rapid urbanization and population growth have escalated the volume and complexity of construction waste, residential on-site management remains tethered to fragmented, manual practices. This reliance on traditional sorting and monitoring not only contributes to environmental degradation and rising operational costs but also creates a critical challenge to regulatory compliance and circular economy goals [1, 2, 4]. Globally, automation technologies such as robotics, Artificial Intelligence (AI), and the Internet of Things (IoT) are defined in this study as integrated systems that minimize manual intervention in waste handling. These technologies have demonstrated success in enhancing sorting accuracy and safety [3, 5]. However, the residential construction sector significantly lags behind international practices in terms of integration, which refers to the successful embedding of these technologies into active site workflows, with adoption remaining stagnant despite localized proof-of-concept studies [6].

This stagnant adoption indicates that the challenges faced extend beyond technological availability. Current literature highlights that there is a critical need for systematic approaches and improvements tailored specifically to the waste types generated in residential projects [7]. While research highlights a need for waste reduction at its source [8], implementing such strategies requires high-fidelity data on waste generation patterns. In this context, on-site automation serves as a critical bridging strategy; by providing precise, real-time analytics, it enables the evidence-based decision-making necessary to design and validate future source-reduction protocols.

However, the integration of these advanced technologies faces significant socio-technical hurdles. Theoretical concerns regarding Machine Learning (ML), including a lack of transparency, accountability, and inclusivity, manifest in this study as practical Data Challenges [9]. For instance, recognition errors lead to industry distrust, while data imbalances complicate the tracking of diverse, mixed-waste streams. Furthermore, there is a distinct lack of research regarding implementation best practices on congested residential sites [10, 11]. Consequently, an integrated understanding of the interrelated challenges that cause automation to struggle beyond the pilot stage is missing, particularly regarding scalability, or the ability of a system to maintain performance and cost-effectiveness across varying project sizes.

To address this research gap, the study aims to identify the challenges hindering the integration of automation into on-site waste management within residential construction projects. Accordingly, this study is guided by the following research objectives:

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1. To identify the core multidimensional challenges affecting automation integration in waste management within residential construction.
2. To categorize these challenges through thematic analysis.
3. To examine the interdependence between identified challenges.

Given the context-specific and multidimensional nature of these challenges, a qualitative research approach was adopted to capture in-depth perspectives from industry experts. This is due to these complex and interrelated challenges that cannot be sufficiently captured through quantitative performance assessments alone, necessitating an exploratory qualitative approach.

2. Methods and Materials

In residential construction, the automation of construction waste management (CWM) on-site is a relatively underexplored area [4]. As a result, qualitative research was used to collect information from specialists in the waste management and construction industries. The study's research methodology is shown in Figure 1 for each of the three phases: interview preparation, data collection, and data analysis. A qualitative approach was deemed most appropriate due to the exploratory nature of the study and the necessity of capturing in-depth context-specific insights regarding industry barriers that quantitative methods often fail to detect [12].

To establish a theoretical foundation and develop the interview protocol, a preliminary literature review was conducted. This review utilized keywords such as "challenges in automation integration", "challenges in construction waste management", and "challenges in residential construction". While the literature review provided a global understanding of general barriers, the specific challenges unique to the residential context were identified and investigated through the primary data collection phase which is the semi-structured interviews. The semi-structured interviews allow for an exploratory approach while maintaining alignment with the research objectives. This ensures that the findings are grounded in current industry realities rather than purely theoretical constructs.

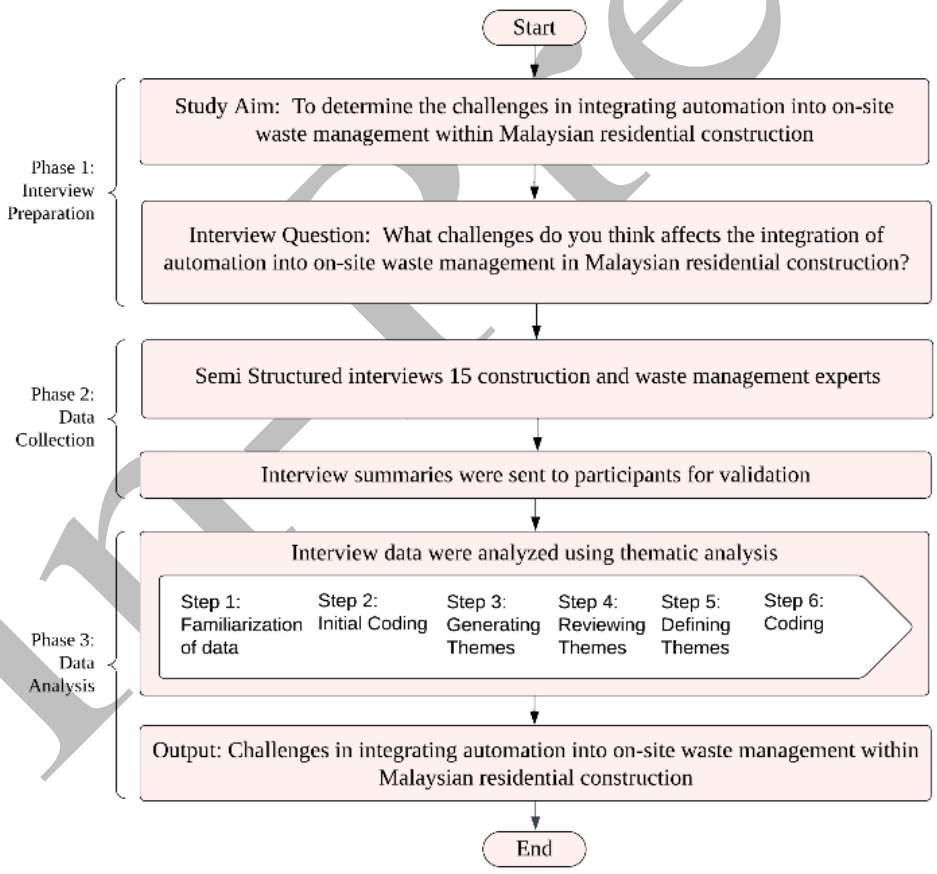


Figure 1. Research Methodology

2.1 Interview Preparation

To ensure a methodical and effective interview procedure, a formal interview protocol was developed. This protocol acted as a guide, outlining the study's objectives, core subjects, and the structured flow of the conversation [13]. The design of the protocol emphasized the interviewee's autonomy and voluntary involvement to foster an open and collaborative environment for the interviewees. The protocol was structured to include not only the primary questions but also a series of follow-up and probing questions. These secondary questions were designed to extract valuable information by allowing the researcher to probe deeper into specific challenges mentioned by the respondents. The use of this semi-structured

format is widely supported in qualitative literature for its ability to obtain expert perspectives while remaining flexible enough to capture unexpected insights [14, 15, 16].

2.2 Data Collection

The data collection process was conducted in three distinct stages: recruitment and sampling, the interview procedure, and verification. Participants were selected using a purposive sampling method to ensure the data was gathered from individuals with specific, high-level technical knowledge relevant to automation and waste management. This targeted approach is essential when the research aims to identify the challenges hindering the integration of automation into on-site waste management within residential construction projects [17].

To maintain the integrity of the data, specific inclusion criteria were established. Participants were required to have a minimum of three years of professional experience and active involvement in sectors such as automation development, regulatory enforcement, waste management, or site management. While this field is rapidly evolving, a three-year threshold was established to ensure that respondents had participated in at least one full residential project lifecycle. This experience was necessary to identify practical integration barriers such as procurement, site-level budgeting, and regulatory hurdles, rather than purely theoretical possibilities. Crucially, this criterion was low enough to include "digital native" technology developers (e.g., Z7) while ensuring their insights were grounded in the operational realities and comparative baselines of the construction sector [17].

The interviews were conducted online via Google Meet and Microsoft Teams, enabling participant flexibility. Each session began with an introduction to the research objectives, followed by the primary question: "What challenges hinder the integration of automation into on-site waste management in Malaysian residential construction?". During the sessions, pre-planned follow-up questions were utilized to clarify ambiguous answers or encourage participants to elaborate on personal experiences. When a respondent's explanation was insufficient, questions were rephrased to ensure a comprehensive response. The interviews had an average duration of 40 minutes and were recorded with consent.

Following this process, a total of 15 industry professionals were interviewed. Data collection continued until data saturation was achieved, which occurred at the fifteenth interview. Saturation was operationally defined through the 'principle of redundancy,' where the final three interviews (Z13, Z14, and Z15) were found to replicate existing codes without generating new thematic categories, suggesting that the full range of challenges within the study's scope had been captured [18]. To enhance credibility of the findings, member checking was performed by returning the interview summaries to the participants to ensure the interpretations accurately reflected their perspectives [19].

Based on Table 1, the final cohort represented a diverse range of stakeholders, including consultants, government agencies, and technology developers. The respondents possessed an average of 16 years of experience, demonstrating a high level of proficiency and providing a balance between technical innovation and deep industry process knowledge.

Table 1. Respondent Background

Code	Gender	Type of organization	Type of position	Experience in construction waste management
Z1	M	Consultant	Resident Engineer	14
Z2	M	Governmental Waste Agency	Project Manager	24
Z3	M	Contractor	Managing Director	15
Z4	M	Governmental Waste Agency	Head Section	21
Z5	M	Government Agency	Senior Assistant Director	20
Z6	M	Developer	Head of Division C&S	25
Z7	M	Tech Developer	Engineer	3
Z8	M	Consultant	Resident Engineer	18
Z9	M	Contractor	Director	30
Z10	M	Government Agency	Senior Manager	20
Z11	F	Governmental Waste Agency	Head Section	15
Z12	M	Tech Developer	Engineer	10
Z13	M	Contractor	Site Engineer	15
Z14	F	Consultant	Civil Engineer	17
Z15	M	Governmental Agency	Engineer	21

2.3 Data Analysis

Following a commonly used technique to identify, examine, and document data patterns, the qualitative data from the interviews were coded and subjected to thematic analysis [20]. The six steps thematic analysis described by Braun and Clarke were used to conduct the study as shown in Figure 1 [20]. In the first step, interview transcripts were read multiple times to achieve data familiarization and generate initial impressions. In the second step, initial codes were systematically developed through open coding, where meaningful text segments related to automation challenges were labelled. In the

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third step, similar codes were reviewed, refined, and grouped into broader categories, which formed the basis for preliminary themes. These themes were then reviewed and validated against the entire dataset to ensure internal consistency and distinctiveness. A thematic map as shown in Figure 2 was developed in the fourth step to visualize the relationships among the themes. The fifth step involved defining and naming themes to accurately reflect their conceptual meaning. The final step consisted of interpreting and reporting the findings.

To enhance the trustworthiness of the analysis, the researchers addressed coding rigor and reflexivity throughout the process. A formal codebook was maintained to ensure consistency in labeling across all 15 transcripts, following an inductive approach that allowed themes to emerge directly from the raw data. Furthermore, the researchers engaged in reflexivity by acknowledging their academic background in construction management. To mitigate potential insider bias, peer debriefing sessions were held with co-authors to verify that the final themes were grounded strictly in the participants' perspectives rather than the researchers' preconceptions.

The analysis specifically utilized investigator triangulation to balance the diverse views within the sample of experts. Insights from technology developers with specialized technical fluency (e.g., Z7 and Z12) were cross-referenced against the process-depth of industry veterans possessing over 20 years of experience (e.g., Z2 and Z9). This allowed the study to distinguish between purely technical hurdles and the long-standing operational bottlenecks inherent in the residential sector. By contrasting these viewpoints, the thematic development captured a 360-degree view of the integration gap, ensuring that the findings reflect both the innovation potential and the practical site-level constraints. In addition, triangulation with existing literature was used to validate the consistency and credibility of the identified themes [21].

3. Results and Discussion

3.1 Overview of Theme Development

The thematic analysis of the interview transcripts resulted in the identification of five core themes: Economic, Regulatory, Human, Data and Technical challenges. These themes represent the primary challenges affecting the integration of automation into on-site waste management within residential construction. Figure 2 presents the thematic map illustrating the relationships among these identified themes and their associated subthemes, following Braun and Clarke's six step approach, beginning with open coding of interview transcripts.

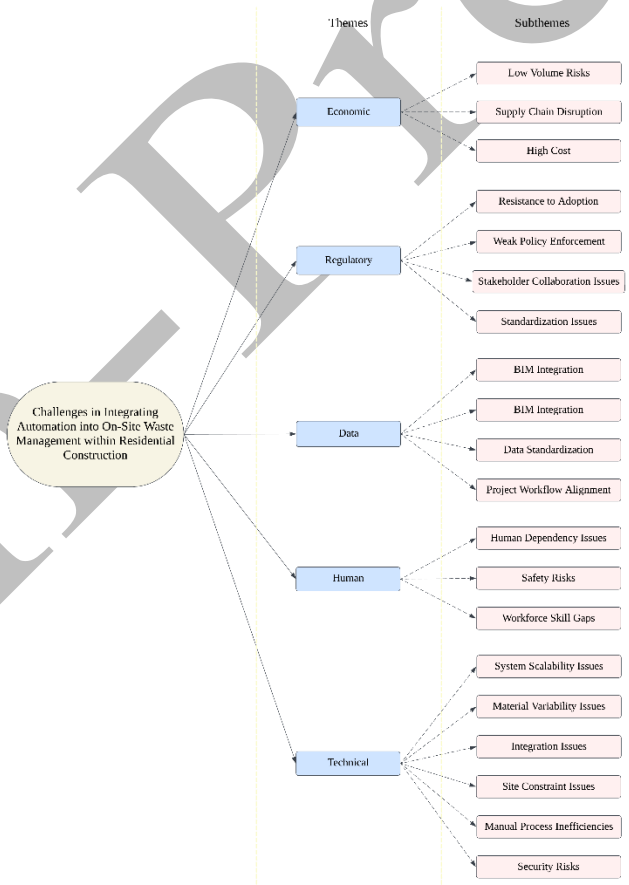


Figure 2. Thematic map of challenges in integrating automation into on-site waste management within residential construction

3.2 Identified Themes

The analysis resulted in five main themes which are economic, regulatory, human, data, and technical challenges. Table 2 summarizes the themes, subthemes, and frequency of references (hits) across the 15 respondents. While Table 2 displays the frequency of 'hits' for each subtheme, these counts are utilized primarily to indicate the breadth of consensus among

the sample of experts. In this qualitative framework, the significance of a challenge is determined by its systemic impact on adoption rather than its numerical frequency alone. For example, 'Recognition Errors' (4 hits) may be mentioned less frequently than 'High Cost' (15 hits), yet they represent a fundamental technical bottleneck that must be resolved to build industry trust.

Table 2. Findings Obtained from Thematic Analysis

Theme	Code	Subtheme	Respondent	Hits
Economic	1	High Cost	Z1 – Z15	15
	2	Low Volume Risks	Z2, Z3, Z6, Z7, Z10, Z11, Z15	7
	3	Supply Chain Disruption	Z1 – Z15	15
Regulatory	4	Resistance to Adoption	Z1 – Z15	15
	5	Weak Policy Enforcement	Z1 – Z15	15
	6	Standardization Issues	Z1 – Z15	15
	7	Stakeholder Collaboration Issues	Z1 – Z15	15
Human	8	Workforce Skill Gaps	Z1 – Z15	15
	9	Human Dependency Issues	Z1, Z2, Z3, Z5, Z8, Z9, Z13, Z15	8
	10	Safety Risks	Z6, Z9, Z13	3
Data	11	Data Limitations	Z2, Z4, Z5, Z7, Z8, Z12, Z14	7
	12	Recognition Errors	Z7, Z12, Z13, Z15	4
	13	Waste Identification Issues	Z5, Z7, Z12, Z13	4
	14	Data Imbalance Issues	Z7, Z12, Z15	3
Technical	15	System Scalability Issues	Z1, Z2, Z3, Z4, Z7, Z10, Z11, Z12, Z13, Z15	10
	16	Material Variability Issues	Z2, Z3, Z7, Z9, Z12, Z13	6
	17	Integration Issues	Z3, Z4, Z7, Z12, Z14	5
	18	Site Constraint Issues	Z1, Z2, Z4, Z6, Z9, Z10, Z13, Z15	8
	19	Manual Process Inefficiencies	Z3, Z9, Z13, Z14	4
	20	Security Risks	Z4, Z7, Z12, Z14	4

3.3 Supporting Evidence from Interview Excerpts

To ensure transparency and traceability of the findings, representative excerpts from respondents are presented in Table 3. These excerpts justify the emergence of each subtheme and reflect the lived experiences of industry practitioners across multiple stakeholder groups.

Table 3. Representative Excerpts from Respondents

Code	Subtheme	Respondent
1	High Cost	*"We can't simply spend millions on machines and software when our margins are already thin."* **(Z9)**
2	Low Volume Risks	*"The risk is that we pay a lot for the technology, but the waste volume is too low to justify it."* **(Z15)**
3	Supply Chain Disruption	*"Sometimes the parts or software have to come from overseas, and delays disrupt the whole plan."* **(Z6)**
4	Resistance to Adoption	*"Considering how long it took for contractors to implement BIM; it might take 10 more years for them to be open to automation"* **(Z14)**
5	Weak Policy Enforcement	*"Companies know the rules, but nobody checks if they follow them."* **(Z2)** *"Policies are there on paper, but at the ground level, enforcement is weak."* **(Z11)**
6	Standardization Issues	*"We need proper guidelines or standards, otherwise the technology can't scale properly."* **(Z4)**
7	Stakeholder Collaboration Issues	*"Everyone has their own agenda. Getting them on the same page is harder than the technology itself."* **(Z13)**
8	Workforce Skill Gaps	*"Even if we buy the technology, we don't have enough skilled workers to operate it."* **(Z2)**
9	Human Dependency Issues	*"You can't remove human dependency completely. There are always cases the system can't handle."* **(Z9)**
10	Safety Risks	*"Automation handling is still unknown, how will we know if something could bring safety risk to the workers?"* **(Z13)**

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11	Data Limitations	*"We don't have reliable waste data. The gaps make automation less effective."* **(Z2)**
12	Recognition Errors	*"Clutter and poor lighting confuse the sensors."* **(Z7)**
13	Waste Identification Issues	*"It really depends on what kind of automation you will be using, if it is for sorting, automation struggles to separate materials when they're mixed together."* **(Z13)**
14	Data Imbalance Issues	*"AI doesn't perform well because the training data is unbalanced."* **(Z15)**
15	System Scalability Issues	*"It works fine in pilots, but scaling up is a major issue."* **(Z10)**
16	Material Variability Issues	*"Every site has different waste compositions, which complicates sorting."* **(Z12)**
17	Integration Issues	*"During the first integration of BIM, we faced workflow disruptions because systems don't match."* **(Z3)**
18	Site Constraint Issues	*"Not every site is suitable, some are too tight or congested."* **(Z1)**
19	Manual Process Inefficiencies	*"People get tired, and mistakes happen with manual processes. But traditional methods are still the most optimal solution for contractors despite the disadvantages."* **(Z14)**
20	Security Risks	*"With everything digital, there's always risk of hacking."* **(Z7)**

3.4 Discussion

Economic Challenges

As shown in Table 2, economic challenges were among the most frequently mentioned challenges to automation integration, with high cost and supply chain disruption mentioned by all respondents, while low-volume risk was highlighted by seven respondents. The interview excerpts presented in Table 3 further illustrate that respondents perceived automation as requiring substantial upfront investment, particularly in equipment, software, and technology procurement, with additional concerns related to return on investment and supply chain reliability. These concerns were particularly emphasized by contractors and developers managing cost-sensitive residential projects. These findings are consistent with previous literature, emphasizing how small and medium-sized enterprises (SMEs), which dominate Malaysia's construction sector, often struggle to absorb these initial costs [22, 23].

Previous literature has also reported that construction supply chains are highly dependent on overseas suppliers, making automation projects vulnerable to delays and cost escalation during periods of disruption [24]. A study highlighted that the construction industry depends on multiple suppliers, many of which are overseas [24]. Hence, the delays and shortages increase the project costs and risks. For example, The COVID-19 pandemic and Brexit have been highlighted as major disruptive events that increased material and logistics costs and caused significant delays in project deliveries [25]. The present findings reinforce these observations by demonstrating how supply instability directly undermines confidence in long-term automation planning at the project level.

Although mentioned less frequently, the issue of low volume risks remains a significant factor that holds back firms from adopting. Smaller or short-term residential projects may not generate enough waste to justify high capital investment; this leads to a perceived lack of financial 'density' per project. To mitigate this, several respondents (Z3, Z7, Z15) discussed shifting away from traditional ownership models toward agile procurement strategies. For instance, participants suggested 'Automation-as-a-Service' (AaaS) and 'performance-based contracting,' where the cost of automation is tied to the volume of waste processed rather than a flat upfront fee. Furthermore, some respondents envisioned a geographic pooling strategy involving shared regional facilities or mobile waste-sorting units that move between multiple residential sites. By treating automated assets as modular utilities that serve a cluster of projects, the industry can achieve the necessary economies of scale that a single residential site lacks. This shared-resource approach effectively transforms automation from a project-specific financial burden into a scalable operational utility, reflecting a broader industry shift toward risk-sharing models that are more viable for the Malaysian residential sector [26].

According to the respondents, they are aware of ROI challenges when automation technologies are underutilized in smaller or lower-volume projects because of their extensive experience in waste management and innovation adoption. While previous literature tends to assess automation feasibility based on technological performance or cost-efficiency alone, the findings of this study reveal that the scale of the project and the volume of waste can critically shape ROI perceptions which will influence adoption decisions even when technology is viable.

Regulatory Challenges

Regulatory challenges such as weak policy enforcement, standardization gaps, and stakeholder collaboration issues were identified by all respondents in Table 2. Interview excerpts from Table 3 further illustrate that resistance to adoption is often driven by cultural aversion to change, fear of job displacement, and limited awareness of automation's long-term benefits. This finding aligns with previous research that associates regulatory resistance with friction encountered during technological transitions as it mainly stems from a lack of familiarity with new processes and an attachment to traditional

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methods [27]. The fear of job loss particularly stems among low-skilled workers who perform routine tasks that are more susceptible to automation due to their worry that automation will replace their roles [27]. Respondents shared that they may not fully understand how automation can lead to long term benefits as there is lack of practical knowledge about critical success factors, tools, technique and enabling technology which aligns with previous study [28].

Respondents consistently emphasized that weak policy enforcement significantly undermines regulatory effectiveness. While Malaysia has introduced initiatives such as the Industrialised Building System (IBS) Score and Site Waste Management Plans (SWMPs), respondents noted that enforcement remains inconsistent, particularly in residential developments, due to limited infrastructure and a lack of penalising severeness. As current regulations are not seen as strict, the adoption of these technologies is often voluntary and based on whether a company sees value in them rather than a fear of being punished [29]. This finding aligns with respondents' perspectives indicating that regulatory instruments in Malaysia tend to function as guidelines rather than enforceable mechanisms. Although, unlike previous literature that focus primarily on policy formulation, the present findings highlight enforcement gaps as primary challenges suggesting that the effectiveness of adoption depends on both policy availability and measurable compliance.

Standardization issues equally complicate regulatory implementation as reflected in Table 2. Respondents highlighted the absence of a unified protocol for automated waste management systems. This results in a fragmented implementation and limited interoperability. This finding is consistent with previous research identifying standardization as a prerequisite for scalable digital construction solutions [30, 31]. However, this study adds context to the standardization challenges by particularly focusing on residential construction project scale due to the varied waste composition, and stakeholder structure.

Stakeholder collaboration issues were also identified as a regulatory constraint, with respondents noting misaligned objectives and weak coordination among government agencies, contractors, and technology providers (Table 3). While previous literature has acknowledged collaboration challenges in construction governance [32], this study highlights how regulatory ambiguity can contribute to coordination failures by creating uncertainty in roles, responsibilities, and compliance expectations. These findings indicate that regulatory challenges to automation adoption are not isolated issues, but interdependent constraints embedded in Malaysia's construction governance structure, particularly in the residential sector. As illustrated in Table 3, respondents repeatedly drew parallels between delayed BIM adoption and anticipated resistance to automation, reinforcing the persistence of institutional inertia within the Malaysian construction sector.

Human Challenges

In terms of human-related challenges affecting the integration of automation into on-site construction waste management, workforce skill gaps emerged as the most dominant challenge, being highlighted by all respondents in Table 2. This finding aligns with previous research which indicate that the construction industry's workforce readiness often lags behind the pace of technological advancement, particularly in developing economies [33]. Despite the ongoing initiatives by the government to upskill local workforce, including implementing Technical and Vocational Education (TVET) and digital economy blueprints, respondents consistently noted that training efforts remain insufficient to meet the rapidly evolving requirements of automation-enabled systems. Several interviewees emphasized that even foundational digital tools, such as Building Information Modelling (BIM), are still not fully understood or effectively utilized at the site level (Table 3).

Compared to existing literature, this study shows that skill gaps are not limited to technical operators but also affect supervisors and site managers who are expected to coordinate automated workflows and interpret system outputs. Evidence suggests that conventional upskilling alone is insufficient without direct on-site application [32]. Respondents noted that limited exposure to automation in residential projects restricts experiential learning, indicating that structural adaptation depends more on real-world experience than classroom education.

In addition, respondents also emphasized safety risks and human dependency issues as interrelated human challenges (Table 3). While automation is intended to reduce manual hazards, respondents warned that partial implementation can introduce new safety risks. Technical hazards, such as exposure to moving parts, high noise levels, and repetitive stress, remain significant concerns [34]. Furthermore, misused systems often stem from 'mis-calibrated trust,' where workers over-rely on automation and disengage from safety monitoring, ultimately increasing the likelihood of accidents [35]. These findings are consistent with the previous literature by proving how partial automation in residential construction contexts may intensify hybrid risk environments, rather than resolve them.

Data Challenges

In terms of data-related challenges, data limitations emerged as a main challenge as it was highlighted by seven respondents (Table 2). As illustrated by the interview excerpts in Table 3, respondents consistently emphasized the lack of reliable, standardized, and complete datasets on construction waste generation and composition, which undermines the effectiveness of automation systems. This finding aligns with previous literature indicating that data scarcity and poor data quality remain a persistent challenge to digital transformation in the construction sector [36].

The evidence from this study demonstrates that data constraints in residential construction stems from inconsistent documentation practices, fragmented data ownership, and the absence of centralized waste databases. This finding expands upon the technical performance focus of previous research by proving that the "data gap" on-site is a result of organizational fragmentation. Previous research reported gaps in historical waste records and digitized planning data, and the present findings provide direct qualitative evidence that these gaps are what physically limits automation scalability and interoperability at site level [22].

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Data imbalance was mentioned by a smaller subset of respondents (Table 2). However, it still carries a significant challenge for automation performance. As noted in the interview excerpt in Table 3, training datasets tend to overrepresent common waste types while underrepresenting less frequent or irregular materials. This results in biased AI models that perform well in controlled scenarios but underperform when exposed to diverse waste streams typical of residential projects. Respondents suggested a shift toward collaborative data governance. Specifically, technology developers (Z7, Z12) proposed the establishment of a national construction waste data repository where firms could contribute 'raw' site images of mixed, cluttered, and occluded waste streams. By crowdsourcing diverse datasets from active Malaysian residential sites, the industry could develop more representative training sets for Machine Learning models. This would reduce recognition errors caused by the 'data gap' between controlled lab environments and the chaotic reality of congested construction sites. This study contributes to bridging the gap by presenting how data imbalance directly affects waste sorting accuracy and limits system reliability on-site.

Respondents highlighted recognition errors and waste identification issues as significant challenges (Table 2). Interviewees reported that automated systems struggle to accurately classify construction waste under real site conditions due to cluttered environments, overlapping materials, object occlusion, and poor lighting (Table 3). While previous studies note that sensors and computer vision struggle in unstructured environments [37], the evidence here proves that residential sites are uniquely difficult. This study confirms that recognition errors are not solely algorithmic weaknesses but are a direct result of the mismatch between trained models and real-world site conditions.

Technical Challenges

In terms of technical challenges, ten respondents raised concerns about the scalability of automation systems based on Table 2. Interview excerpts in Table 3 indicate that while automation systems may function effectively during pilot implementations, respondents consistently perceived significant performance degradation when such systems were scaled across diverse residential sites. This finding is consistent with previous literature that identify scalability as a persistent bottleneck in construction automation, particularly when transitioning from controlled environments to real-world project conditions [38].

The analysis reveals that scalability challenges in Malaysian residential projects are not solely computational or hardware related but are strongly driven by site heterogeneity and operational variability. While earlier research often focuses on algorithmic efficiency or processing speed, the present findings prove that the fluctuating waste volumes, irregular layouts, and limited space characteristics of residential projects create a compounded technical constraint that are distinct from those found in large-scale infrastructure studies [39].

Closely linked to scalability, site constraint issues were reported by eight respondents (Table 2), particularly by site engineers and project managers. As illustrated in Table 3, congested working areas, limited access routes, and adverse weather conditions restrict the deployment and movement of automated equipment. The findings of this study underscore that spatial constraints are especially acute in residential projects where compact sites and overlapping trades physically limit the feasibility of installing fixed or semi-fixed automation system as agreed by previous research [39]. This demonstrates a specific contextual reality that even when automation technology is technically viable, the physical environment of a residential site acts as a primary technical challenge to adoption. While site constraint issues remain a formidable barrier, industry experts did not view this as a fundamental limitation of automation itself, but rather as a failure of current hardware design. Respondents (Z4, Z10, Z13) highlighted the potential for modular and mobile robotic platforms that are specifically designed for 'plug-and-play' deployment in tight footprints. Unlike the large, fixed-base systems used in infrastructure projects, these flexible units could be track-mounted or palletized for easy relocation across congested sites. This suggests that the future of residential automation lies in 'agile' technology that adapts to the site, rather than requiring the site to be redesigned for the technology.

This highlights a critical distinction from current automation research, which predominantly focuses on large, open construction projects. Overall, the technical challenges identified demonstrate that automation adoption is constrained not only by system capabilities but also by misalignment between technology design and site-level realities.

3.5 Synthesis of Challenges

The findings of this study demonstrate that the barriers to automation are not isolated incidents but are embedded in a socio-technical feedback loop. As illustrated in the thematic map (Figure 2), the "Integration Gap" is sustained by the reinforcing relationship between institutional and technical hurdles. For example, Weak Policy Enforcement (Regulatory) creates a market environment where there is no penalty for manual waste sorting. This lack of regulatory pressure directly undermines the Return on Investment (Economic), leading firms to view automation as a high-risk expenditure rather than a compliance necessity.

Furthermore, this study identifies a critical "Data-Human" bottleneck. Because Workforce Skill Gaps (Human) prevent the high-quality collection of on-site information, Data Limitations persist. These limitations result in the Recognition Errors (Data) that cause industry distrust, further fueling the Resistance to Adoption (Regulatory). This interdependence suggests that the technical failure of a robot on a Congested Site (Technical) is often a symptom of upstream failures in policy and economic modeling. Consequently, achieving the "bridging strategy" mentioned in the introduction requires a simultaneous intervention across all five thematic domains rather than a fragmented technical fix.

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3.6 Study Implications

Practical Implications

The practical implication of this study is that it provides a clear and actionable framework for overcoming the barriers to automating on-site waste management in Malaysian residential construction. For policymakers and government agencies, the findings highlight the need for targeted financial incentives and stronger, better-enforced regulations to make adoption economically viable. For construction firms, the findings serve as a strategies checklist for planning investments, focusing on workforce upskilling and selecting scalable technologies that fit their specific project volumes and site constraints. For technology providers, the findings highlight the necessity of developing cost-effective, robust, and interoperable solutions tailored to the local market's needs. In conclusion, by translating these challenges into targeted strategies, the study can enable all stakeholders to move and collaborate effectively to transition towards more sustainable and efficient construction practices.

Theoretical Implications

The theoretical implication of this study lies in its significance, contributing to the extension of established technology adoption and construction management theories by contextualizing them within the specific domain of automated waste management in a developing country, like Malaysia. The findings empirically validated and enriched frameworks like the Technology-Organization-Environment (TOE) framework by providing highly specific context-dependent factors. For example, fragmented regulations and material variability issues, which acts as a formidable challenge in the residential construction sector, an area often underexplored in theoretical models. Furthermore, by identifying the challenges, this study challenges linear adoption models and proposes a more nuanced, systemic theoretical understanding where economic, human, regulatory, data, and technical challenges are co-dependent. This qualitative, expert-driven approach generates novel theoretical propositions about the prerequisites for successful technological integration in construction. It suggests that existing theories must be adapted to account for high-impact challenges of low volume risks and site constraint issues which are unique to residential projects. Hence, it provides a refined theoretical lens for future research in similar contexts.

4. Conclusions

This study set out to identify the challenges in integrating automation into on-site waste management within residential construction. Through a qualitative analysis of expert interviews, five themes of challenges were uncovered: i) economic, ii) regulatory, iii) human, iv) data, and v) technical. The results demonstrate that these barriers are not isolated technical failures but are rooted in socio-technical interdependencies. Consequently, the study proposes a conceptual framework where the "Integration Gap" is sustained by reinforcing loops between regulatory enforcement, economic return, and workforce readiness. This suggests that tackling these issues in a compartmentalized manner is likely to be unsuccessful; for example, investing in cutting-edge technology without concurrent regulatory reform and workforce upskilling will yield minimal impact.

The main contribution of this study is the development of this conceptual framework, which offers stakeholders a precise, fact-based point of reference. For policymakers and regulatory bodies, the findings suggest the need for highly targeted financial incentives to be effective. Specifically, the results point toward the introduction of tax rebates for digital upskilling, preferential scoring in public residential tenders for firms utilizing automated waste systems, and "sandbox" grants for pilot projects to mitigate high upfront investment risks. For industry practitioners, the framework serves as a decision-support tool to evaluate project suitability and select modular, agile technologies that fit the spatial and operational constraints of residential sites.

Although this study provides insightful information, its primary limitation is its focus on the Malaysian residential context. Future research should involve comparative studies with other developing economies to highlight regional quirks. Additionally, further investigation could involve the quantitative validation of this conceptual framework to objectively evaluate the weight of each obstacle. By methodically tackling the complex issues uncovered in this study, the residential sector can pave the way for automation to promote more sustainable and efficient waste management practices.

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Conflict of Interest

The authors declare no conflicts of interest.

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Scopus AI was used to support the literature review process by assisting with the identification and summarization of relevant scholarly publications. The authors independently reviewed all sources and are solely responsible for the content, analysis, and conclusions of this manuscript.

Authors' Contribution
Rabiatul Anisa Zainal (Conceptualization; Methodology; Data Curation; Formal Analysis; Investigation; Writing – Original Draft & Revised Draft)
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Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author

Ethics Statement

Not applicable.

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