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From Digital Technology to Sustainable Performance: The Mediating Role of Lean Management in Malaysia's Phone Waste Management Systems

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A B S T R A C T
This study examines the relationships among technological advancements, lean management, and the perceived effectiveness of phone waste management systems (PWMS) in Malaysia. Technological advancements were represented by digital monitoring, traceability, automation, data analytics, and integrated information systems, whereas lean management was represented by process standardization, continuous improvement, waste elimination, and efficient resource use. A quantitative cross-sectional survey was conducted with 482 respondents, and the data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The measurement model demonstrated satisfactory indicator reliability, internal consistency, convergent validity, and discriminant validity. Technological advancements positively influenced lean management ($\beta = 0.377$, $t = 10.696$, $p < 0.001$), and lean management positively influenced perceived PWMS effectiveness ($\beta = 0.194$, $t = 5.196$, $p < 0.001$). The specific indirect effect was also positive and statistically significant ($\beta = 0.073$, $t = 4.292$, $p < 0.001$). However, because the direct path from technological advancements to PWMS effectiveness was not reported, the evidence supports a significant indirect effect but does not permit the mediation to be classified as partial or full. The model explained 14.2% of the variance in lean management and only 3.8% of the variance in perceived PWMS effectiveness. The findings should therefore be interpreted cautiously and indicate that behavioral, regulatory, financial, and institutional factors remain important.

الكلمات الدالة:
التطورات التكنولوجية؛ الإدارة الرشيقة؛ أنظمة إدارة نفايات الهواتف المحمولة؛ فعالية إدارة نفايات الهواتف؛ النفايات الإلكترونية؛ الدور الوسيط؛ نمذجة المعادلات الهيكلية بالمربعات الصغرى الجزئية؛ ماليزيا.

الملخص
تتناول هذه الدراسة العلاقة بين التطورات التكنولوجية، والإدارة الرشيقة، والفعالية المتصورة لأنظمة إدارة نفايات الهواتف في ماليزيا. تمثلت التطورات التكنولوجية في المراقبة الرقمية، والتتبع، والأتمتة، وتحليلات البيانات، وأنظمة المعلومات المتكاملة، بينما تمثلت الإدارة الرشيقة في توحيد العمليات، والتحسين المستمر، والتخلص من النفايات، والاستخدام الأمثل للموارد. أُجري مسح كمي مقطعي شمل 482 مستجيبًا، وحُللت البيانات باستخدام نمذجة المعادلات الهيكلية للمربعات الصغرى الجزئية. أظهر نموذج القياس موثوقية جيدة للمؤشرات، واتساقًا داخليًا، وصحة تقارب، وصحة تمييز. أثرت التطورات التكنولوجية إيجابًا على الإدارة الرشيقة ($\beta = 0.377$، $t = 10.696$،

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$p < 0.001$)، كما أثرت الإدارة الرشيقة إيجابًا على الفعالية المتصورة لأنظمة إدارة نفايات الهواتف ($\beta = 0.194$، $t = 5.196$، $p < 0.001$). كان التأثير غير المباشر المحدد إيجابيًا وذا دلالة إحصائية ($\beta = 0.073$، $t = 4.292$، $p < 0.001$). ومع ذلك، نظرًا لعدم الإبلاغ عن المسار المباشر من التطورات التكنولوجية إلى فعالية نظام إدارة سلامة المرضى، فإن الأدلة تدعم وجود تأثير غير مباشر ذي دلالة إحصائية، لكنها لا تسمح بتصنيف الوساطة على أنها جزئية أو كاملة. وقد فسّر النموذج 14.2% من التباين في الإدارة الرشيقة، و3.8% فقط من التباين في فعالية نظام إدارة سلامة المرضى المُدركة. لذا، ينبغي تفسير النتائج بحذر، وتشير إلى أن العوامل السلوكية والتنظيمية والمالية والمؤسسية لا تزال ذات أهمية

JEL Classification: *O33; Q53; Q55; L23.*

1. Introduction

The rapid expansion of mobile-phone ownership and the shortening of device replacement cycles have created a growing stream of discarded phones worldwide. Although end-of-life mobile phones contain valuable metals, reusable components, and strategically important materials, they also include hazardous substances that can damage soil, water, ecosystems, and human health when stored indefinitely, discarded with municipal waste, or treated through informal recycling practices. The sustainable management of discarded phones has therefore become an important component of the circular economy and the global transition towards responsible production and consumption. The problem is not limited to the technical capacity to recycle electronic devices. Effective phone-waste management requires an integrated system that connects consumers, retailers, manufacturers, collection providers, logistics operators, recycling facilities, and regulatory agencies. This system must be capable of collecting end-of-life phones, recording and tracking their movement, sorting devices according to their condition, recovering reusable components and valuable materials, and ensuring that non-recoverable residues are disposed of safely. Weaknesses at any stage can reduce the overall effectiveness of the Phone Waste Management System (PWMS), even when appropriate recycling technologies are available.

Malaysia provides an important setting for investigating this issue because of its widespread mobile-phone use, developing electronic-waste infrastructure, and strategic position within regional electronic-waste flows. The country has introduced formal regulations and licensed recovery arrangements, but the effectiveness of phone-waste management continues to be affected by fragmented collection practices, uneven consumer participation, limited traceability, and coordination difficulties among relevant stakeholders. Faradillah et al. (2025) found that technological infrastructure, financial stability, and the regulatory landscape were among the strongest determinants of the readiness of Malaysia's recycling industry to manage sustainable transboundary e-waste. This finding demonstrates that technological capability is essential, but it also indicates that technology operates within a wider organizational and institutional system. Consumer behavior creates an additional challenge. Discarded phones are frequently stored at home instead of being transferred to formal recycling or recovery channels. In a large university-wide survey, Serranti et al. (2025) reported that 92.3% of respondents retained at least one unused phone, despite generally recognizing the environmental risks associated with improper disposal. The study also found limited awareness of official take-back arrangements, although 93.1% of participants expressed willingness to use an accessible collection system. Such findings suggest that positive attitudes alone are insufficient. Effective systems must provide visible, convenient, trustworthy, and well-coordinated mechanisms that convert consumer willingness into actual device returns.

Technological advancements offer important capabilities for addressing these operational and informational weaknesses. Technologies such as the Internet of Things, automated sorting, artificial intelligence, radio-frequency identification, GPS-enabled logistics, cloud platforms, blockchain-based traceability, digital product passports, and real-time analytical dashboards can improve the visibility and reliability of phone-waste flows. They can assist organizations in monitoring collection points, optimizing transportation routes, identifying different device and material categories, reducing sorting errors, improving stakeholder communication, and demonstrating regulatory compliance. Accordingly, technology can contribute directly to PWMS effectiveness by increasing the accuracy, speed, transparency, and traceability of collection and recovery activities. However, technological investment does not automatically produce operational or sustainability performance. Organizations may acquire advanced equipment or digital platforms without redesigning fragmented processes, clarifying responsibilities, or developing the routines needed to use the generated information. Zaman et al. (2025) found that digital technologies alone did not directly produce stronger digitalization performance in Lithuanian manufacturing firms. Instead, digitalization management mediated this relationship, demonstrating that organizational and managerial practices were necessary to translate technological resources into actual outcomes. Consequently, installing technology within an inefficient process may simply digitize existing waste, complexity, and duplication.

Lean management offers a potential mechanism through which technological capability can be converted into sustained operational improvement. It emphasizes the elimination of non-value-adding activities, process standardization, continuous improvement, employee involvement, efficient resource use, and the smooth flow of materials and information. In the context of phone-waste management, lean practices can help reduce waiting time, unnecessary transportation, repeated handling, inaccurate sorting, inconsistent recording, equipment downtime, and weak coordination among collection and recovery stages. The integration of lean management and advanced technology has gained increasing attention under the broader lean–digital or Lean 4.0 perspective. Digital technologies provide real-time information, connectivity, analytical capacity, and automation, whereas lean management provides the process discipline needed to direct these capabilities towards value creation and waste elimination. Silva et al. (2026) showed that process optimization, continuous improvement, data-driven decision-making, leadership commitment, and standardization were central enablers of advanced digital-technology adoption. Their findings suggest that lean and digital capabilities should be treated as complementary rather than competing approaches. Empirical evidence further indicates that lean management may function as a transmission mechanism between technology and sustainable performance. Buhaya and Metwally (2024) found that digital technologies positively influenced economic, environmental, and social sustainability performance and that lean manufacturing practices partially mediated these relationships. Similarly, Elnadi et al. (2025) demonstrated that Industry 4.0 technologies supported lean, agile, and circular manufacturing practices, which subsequently contributed to sustainability performance. These findings provide a strong foundation for examining whether lean management performs a comparable mediating role within phone-waste management.

Nevertheless, important gaps remain in the literature. Existing phone- and electronic-waste studies primarily focus on consumer disposal intentions, awareness, recycling regulations, collection behavior, and technological recovery methods. In contrast, the literature on lean–digital integration is concentrated mainly in conventional manufacturing. Comparatively little empirical attention has been given to the organizational mechanism through which technological advancements are converted into effective phone-waste collection, processing, and material recovery. In particular, the mediating role of lean management between technological advancements and PWMS effectiveness has not been adequately examined in the Malaysian context. This omission is theoretically and practically important. The operational characteristics of phone-waste management differ from those of conventional manufacturing. Returned devices arrive in uncertain quantities, differ in age and physical condition, contain heterogeneous components, and move across multiple independent stakeholders. Consequently, evidence obtained from controlled manufacturing environments cannot be applied automatically to a multi-actor PWMS. Context-specific investigation is required to determine whether lean management can translate technological capabilities into more effective phone-waste operations. Accordingly, the present study examines the effect of technological advancements on PWMS effectiveness in Malaysia and investigates lean management as a mediating mechanism. Specifically, it evaluates whether technological advancements directly enhance PWMS effectiveness, whether they strengthen lean management practices, whether lean management improves PWMS effectiveness, and whether lean management transmits part of the effect of technological advancements to system effectiveness. The proposed relationships are tested through Partial Least Squares Structural Equation Modeling using data from 482 respondents.

This study makes several contributions. First, it extends the phone- and electronic-waste literature by examining system effectiveness from an operational perspective rather than focusing exclusively on consumer intention or technological availability. Second, it contributes to lean–digital research by applying its central arguments to phone-waste management, an operationally complex and underexamined sustainability setting. Third, it explains the technology–performance relationship through lean management instead of assuming that technological adoption automatically produces better outcomes. Fourth, it provides empirical evidence from Malaysia, where the effective management of electronic waste has substantial environmental, regulatory, and circular-economy implications. The findings also have practical relevance for policymakers, producers, retailers, collection providers, recyclers, and technology developers. Investments in smart collection infrastructure, automated equipment, and traceability platforms should be accompanied by process mapping, standardized procedures, employee involvement, continuous improvement, and clearly assigned stakeholder responsibilities. This combined approach can help ensure that digital technology is used to remove operational waste rather than merely automate existing inefficiencies. The remainder of the paper is organized as follows. Section 2 reviews the relevant literature and develops the research hypotheses. Section 3 presents the research methodology, including the research design, sample, measurement instrument, and data-analysis procedures. Section 4 reports the measurement and structural model results. Section 5 discusses the findings in relation to the relevant literature and theoretical perspectives. Finally, Section 6 presents the study's conclusions, implications, limitations, and recommendations for future research.

2. Literature Review

This section critically reviews the theoretical and empirical literature related to technological advancements, lean management, and Phone Waste Management System (PWMS) effectiveness. It first establishes the conceptual foundations of PWMS effectiveness and explains its technological, operational, environmental, and multi-stakeholder dimensions. It then discusses the direct relationship between technological advancements and PWMS effectiveness, followed by the influence of technological advancements on lean management and the effect of lean management on PWMS effectiveness. The section subsequently examines lean management as the organizational mechanism through which technological capabilities may be translated into improved system performance. Based on this critical synthesis, the study hypotheses and conceptual model are developed, with particular attention to the Malaysian phone-waste management context.

2.1 Conceptual Foundations of Phone Waste Management System Effectiveness

Phone Waste Management System (PWMS) effectiveness refers to the ability of an integrated system to collect end-of-life mobile phones, transport them through authorized channels, classify their condition, recover reusable components and valuable materials, recycle non-reusable parts, and dispose of hazardous residues safely. An effective system must therefore achieve more than a high collection rate. It should also provide accessible return channels, reliable traceability, efficient processing, regulatory compliance, stakeholder coordination, resource recovery, and measurable environmental benefits. This multidimensional perspective is necessary because discarded phones contain economically valuable materials alongside substances that may threaten environmental and human health when improperly stored, dismantled, or disposed of. The effectiveness of PWMS depends on the interaction of consumers, manufacturers, retailers, collection providers, recyclers, technology suppliers, and regulatory authorities. Consumers determine whether unused devices enter formal recovery systems, while producers and retailers influence take-back availability and product-life-cycle responsibility. Collection and recycling organizations determine whether returned phones are transported, sorted, processed, and recovered efficiently. Government agencies establish regulatory requirements, monitor compliance, and create incentives for participation. Consequently, PWMS effectiveness should be viewed as a socio-technical and multi-stakeholder outcome rather than the responsibility of a single organization.

Consumer participation remains one of the most important system-level challenges. Serranti et al. (2025), in a survey of 11,163 respondents, found that 92.3% retained at least one unused mobile phone at home. Although many participants understood the environmental risks of improper disposal, awareness of formal take-back arrangements was limited. At the same time, 93.1% expressed willingness to use an accessible collection system. These findings reveal a persistent attitude–behavior gap: individuals may support sustainable disposal but fail to return their devices when collection points are inconvenient, information is unclear, incentives are insufficient, or concerns about personal data remain unresolved. The effectiveness of PWMS therefore depends on its ability to convert environmental awareness and stated willingness into actual participation. The retention of unused phones also represents a resource-efficiency problem. Stored devices contain materials that cannot be returned to productive use while they remain outside formal recovery channels. Delayed return can also reduce the potential for reuse or refurbishment because device components lose technological and economic value over time. Effective PWMS must therefore encourage timely returns through visible collection infrastructure, public communication, trusted data-removal arrangements, convenient take-back procedures, and suitable economic or non-economic incentives. Organizational and institutional readiness is equally important. Faradillah et al. (2025) examined Malaysia's recycling industry and found that regulatory conditions, financial stability, and technological infrastructure were among the strongest determinants of readiness for sustainable transboundary e-waste management. Their findings demonstrate that formal rules alone are insufficient when recycling organizations lack the financial resources, technology, workforce competence, or operational capacity needed to implement them. Conversely, advanced recovery facilities may not produce sustainable outcomes when regulatory monitoring is weak or waste flows are insufficiently documented. However, industry readiness and system effectiveness should not be treated as identical concepts. Readiness describes the availability of conditions and capabilities required for action, whereas effectiveness concerns the extent to which these capabilities produce reliable operational and sustainability outcomes. A recycling organization may possess appropriate equipment but continue to experience collection delays, inaccurate sorting, limited utilization, or poor stakeholder coordination. This distinction highlights the need to investigate the organizational mechanisms through which available resources are transformed into system performance.

Technological advancements offer one potential mechanism for strengthening PWMS. Digital tracking, automated sorting, Internet of Things sensors, artificial intelligence, data analytics, and integrated information platforms can increase process visibility and support more accurate decisions. Nevertheless, technological resources do not generate operational value automatically. Zaman et al. (2025) found that digital technologies alone did not sufficiently influence digitalization performance and that digitalization management mediated their effect. This finding suggests that organizations must align technology with managerial processes, responsibilities, and improvement routines before its performance benefits can be fully realized. Lean management provides an important complementary mechanism. It focuses on identifying non-value-adding activities, standardizing work, improving process flow, reducing errors, and continuously enhancing resource utilization. These principles correspond directly with common PWMS problems, including unnecessary transportation, repeated handling, excessive waiting, incorrect classification, processing interruptions, and poor coordination. Lyama and Salema (2025) found that lean practices, particularly continuous improvement and total productive maintenance, positively influenced the economic, environmental, and social performance of manufacturing firms. Although PWMS differs from conventional manufacturing, both settings require efficient material flow, reliable equipment, consistent procedures, and the reduction of operational waste. Recent evidence indicates that technology and lean management should be examined together. Buhaya and Metwally (2024) found that digital technologies positively affected lean practices and sustainability performance and that lean management partially mediated the technology–performance relationships. Elnadi et al. (2025) similarly demonstrated that Industry 4.0 technologies facilitated lean, agile, and circular manufacturing practices, which subsequently improved sustainability performance. These studies challenge the assumption that technological adoption should be evaluated independently of the operational system in which it is implemented. Despite these developments, the available literature remains divided into separate streams. Phone-waste studies typically emphasize consumer awareness, disposal intention, collection behavior, regulation, or recycling technology. Lean–digital studies predominantly focus on conventional manufacturing and firm-level sustainability performance. Limited research has investigated whether technological advancements improve the effectiveness of a multi-stakeholder phone-waste management system and whether lean management explains how this improvement occurs. This gap is particularly important in Malaysia, where PWMS must address widespread mobile-phone use, heterogeneous consumer behavior, fragmented collection arrangements, and the operational requirements of formal electronic-waste recovery. The present study connects these literature streams by examining PWMS effectiveness as the outcome of both technological capability and operational process management. Technological advancements are expected to improve monitoring, traceability, sorting, information exchange, and decision-making, whereas lean management is expected to convert these capabilities into standardized, efficient, and continuously improving operations. The following sections develop the direct relationship between technological advancements and PWMS effectiveness, the effect of technological advancements on lean management, the contribution of lean management to PWMS effectiveness, and the mediating role of lean management.

2.2 Technological Advancements and PWMS Effectiveness

Technological advancements represent the digital, automated, and data-driven capabilities used to improve the collection, transportation, identification, sorting, processing, recycling, and monitoring of discarded mobile phones. These advancements include Internet of Things sensors, artificial intelligence, automated sorting systems, radio-frequency identification, GPS-enabled transportation, cloud platforms, data analytics, digital traceability, and integrated information systems. Their relevance to Phone Waste Management System (PWMS) effectiveness arises from their ability to improve the visibility, speed, accuracy, and coordination of phone-waste operations. From a socio-technical perspective, PWMS effectiveness depends on the alignment of technological infrastructure with people, organizational procedures, and stakeholder responsibilities. Technology can improve the technical subsystem by producing real-time information about collection volumes, device locations, processing capacity, and material-recovery performance. Such information enables waste-management organizations to identify bottlenecks, improve collection schedules, optimize transportation routes, and direct returned devices toward appropriate refurbishment, recycling, or disposal channels. Technological advancements can also improve traceability across the phone-waste chain. Conventional waste-management systems frequently depend on disconnected records and limited information sharing among retailers, collectors, recyclers, producers, and regulatory agencies. These information gaps make it difficult to verify whether returned phones reach authorized facilities or are diverted into informal channels. Digital tracking and integrated information platforms can reduce this uncertainty by documenting the movement and treatment of devices from collection to final recovery. Greater traceability can consequently strengthen accountability, regulatory compliance, and stakeholder confidence in the formal PWMS. Faradillah et al. (2025) provide direct contextual evidence from Malaysia. Based on responses from 148 licensed collectors and recovery facilities, their study found that technological infrastructure was one of the strongest determinants of the readiness of the Malaysian recycling industry to manage transboundary electronic waste. This finding indicates that recycling organizations require suitable technologies to monitor waste flows, process complex materials, comply with regulations, and respond to increasing electronic-waste volumes.

Nevertheless, readiness does not necessarily represent actual system performance. Technological resources must be actively used in collection, sorting, processing, and decision-making before they can improve PWMS effectiveness. Evidence from mobile-phone waste research further shows why technology-enabled collection and information systems are necessary. Serranti et al. (2025) found that 92.3% of respondents retained at least one unused mobile phone, while knowledge of official take-back arrangements remained limited. Although that study was conducted in Italy, the results demonstrate a broader operational problem: potentially recoverable devices remain outside formal systems when collection channels are insufficiently visible, convenient, or trusted. Digital platforms, smart collection points, and technology-supported communication could reduce this gap by identifying available return locations, protecting disposal information, providing collection instructions, and connecting users to authorized recyclers. However, technology should not be treated as an automatic solution. Zaman et al. (2025) found that digital technologies alone did not directly generate stronger digitalization performance among Lithuanian manufacturing firms. Instead, managerial practices were required to convert technological resources into performance. This result suggests that the value of technology is conditional upon its operational integration. An organization may acquire sophisticated systems while continuing to experience fragmented workflows, poor coordination, and limited employee capability. Nevertheless, technologies that directly improve sorting accuracy, route planning, monitoring, and traceability are expected to produce a positive contribution to PWMS effectiveness even before wider organizational benefits are considered. In the Malaysian phone-waste context, technological advancements should enable faster collection, more accurate sorting, improved data exchange, better resource recovery, and stronger coordination between public and private stakeholders. The expected effect is therefore positive.

H1: Technological advancements have a positive and significant effect on Phone Waste Management System effectiveness in Malaysia.

2.3 Technological Advancements and Lean Management

Lean management is an operational approach that seeks to maximize value while systematically reducing activities that consume time, labor, materials, or financial resources without contributing to the intended outcome. Its principal practices include waste elimination, process standardization, continuous improvement, visual management, employee involvement, problem solving, and the efficient flow of materials and information. These practices are particularly relevant to phone-waste management, where returned devices pass through multiple collection, transportation, sorting, storage, refurbishment, dismantling, and recovery stages. The relationship between technological advancements and lean management can be explained through the Lean 4.0 perspective. Technology provides connectivity, automation, data visibility, and analytical capacity, whereas lean management uses these capabilities to identify waste and improve workflows. Sensors can monitor collection points, but lean analysis determines whether collection schedules contain unnecessary movement or waiting. Digital dashboards can reveal processing delays, but continuous-improvement routines are required to investigate their causes and implement corrective action. Technology therefore strengthens the informational foundation upon which lean management operates. Real-time information is especially important because conventional lean practices often depend on manual observation and periodic performance reports. Such methods may identify operational waste only after it has already affected collection or processing performance. In contrast, Internet of Things devices, automated records, and analytical dashboards can continuously show changes in waste volumes, equipment conditions, processing times, and transportation requirements. This visibility allows managers to respond more quickly and to base process improvements on consistent data rather than isolated observations. Silva et al. (2026) examined the relationship between lean-management enablers and the adoption of advanced digital technologies among 222 manufacturing practitioners. Their findings identified process optimization and continuous improvement, data-driven decision-making, leadership commitment, and standardization as central enablers of technologies such as the Internet of Things, cloud computing, cybersecurity, and big-data analytics. Although the direction of their model emphasized the contribution of lean capabilities to digital adoption, their results demonstrate the close interdependence between lean and technological systems. Digital transformation is more effective when organizations possess disciplined processes, while lean practices become more responsive when they are supported by accurate and timely technological information.

Buhaya and Metwally (2024) provide evidence for the direction proposed in the current study. Their analysis of 319 managers in Egyptian manufacturing firms showed that digital technologies had a strong positive effect on lean manufacturing practices. Blockchain, the Internet of Things, big-data analytics, cloud computing, and digital twins improved organizations' ability to simplify operations, reduce waste, exchange information, and support continuous improvement. These findings suggest that technology does not merely automate operational activities; it can also strengthen the organization's capacity to implement lean principles systematically. Elnadi et al. (2025) reached a similar conclusion in a study of 170 respondents from Saudi Arabian organizations. Industry 4.0 technologies facilitated the adoption of lean, agile, and circular manufacturing practices. Their integrated model showed that technological capability could function as an organizational enabler by providing the information and connectivity needed to redesign operational processes. The relevance to PWMS is substantial because phone-waste operations require both efficiency and adaptability. Collection volumes and device conditions are uncertain, while the system must maintain standardized environmental and processing requirements.

Nevertheless, technological advancement can create operational complexity when it is introduced without suitable training, process ownership, or improvement objectives. Digital systems may generate excessive data, incompatible procedures, or additional maintenance requirements. The relationship should therefore not be understood as technology automatically producing lean operations. Instead, technology creates capabilities (particularly visibility, synchronization, accuracy, and rapid feedback) that make lean-management practices easier to implement and sustain. Within PWMS, technological advancements can reveal delays between collection and recycling, identify unnecessary transportation, improve equipment monitoring, standardize device records, and support more efficient resource allocation. These capabilities should strengthen the implementation of lean-management practices throughout the phone-waste system.

H2: Technological advancements have a positive and significant effect on lean-management practices within Phone Waste Management Systems.

2.4 Lean Management and PWMS Effectiveness

Lean management is theoretically aligned with PWMS effectiveness because both emphasize the efficient use of resources and the reduction of avoidable waste. In manufacturing, lean practices traditionally focus on eliminating waiting, defects, unnecessary transportation, excess inventory, overprocessing, unnecessary movement, and underutilized employee capabilities. Comparable forms of waste can occur throughout phone-waste management. Returned phones may wait for collection, undergo repeated handling, be transported through inefficient routes, be classified incorrectly, or accumulate beyond the capacity of recycling facilities. Value-stream mapping can help PWMS organizations examine the entire movement of discarded phones from the user to the collection point and then to refurbishment, dismantling, material recovery, or final disposal. This system-wide perspective can identify stages that create delays without contributing to environmental or recovery value. Standardized procedures can then improve consistency in device registration, data protection, transportation, sorting, storage, and dismantling. Continuous improvement can address recurring operational problems and prevent inefficient practices from becoming permanent features of the system. Lean management may also improve collaboration between stakeholders. PWMS involves actors with different objectives and responsibilities, including consumers, producers, retailers, logistics providers, recyclers, and regulators. Inconsistent procedures across these actors can produce duplicated records, unclear responsibilities, and interrupted material flows. Lean coordination can clarify process ownership, standardize information exchange, and establish common performance indicators. This coordination is likely to improve the reliability and transparency of formal collection and recycling channels. Empirical evidence from sustainability research supports the proposed relationship. Lyama and Salema (2025) examined 236 manufacturing respondents in Tanzania and found that lean practices (particularly continuous improvement and total productive maintenance) positively affected economic, environmental, and social sustainability performance. Continuous improvement helped organizations reduce recurring inefficiencies, while productive maintenance supported equipment reliability and resource efficiency. In PWMS, these practices could reduce processing interruptions, equipment downtime, unnecessary energy consumption, and losses of recoverable materials.

Buhaya and Metwally (2024) similarly reported significant positive relationships between lean manufacturing practices and economic, social, and environmental sustainability performance. Their results indicated that lean practices reduced operating costs and improved productivity while also supporting environmental performance through better resource utilization and lower operational waste. These findings are particularly relevant to PWMS because environmental effectiveness cannot be separated from operational efficiency. A recycling system that consumes excessive energy, requires repeated transportation, or loses recoverable materials may reduce waste at one stage while creating new environmental and economic burdens elsewhere. Elnadi et al. (2025) further showed that lean manufacturing contributed positively to sustainability performance and supported the implementation of agile and circular practices. This finding demonstrates that lean management can play a foundational role in wider sustainability systems. In phone-waste management, lean practices can support circularity by improving the flow of returned devices into repair, reuse, refurbishment, remanufacturing, and material-recovery channels. However, the relationship must be adapted to the characteristics of phone waste. Conventional production processes generally involve relatively predictable input volumes and controlled internal workflows. In contrast, phone-waste systems receive heterogeneous devices in uncertain quantities and conditions. An excessively rigid interpretation of lean management could reduce the flexibility required to respond to this variability. Lean implementation within PWMS should therefore combine process discipline with sufficient operational flexibility. The objective is not to remove every buffer or variation but to eliminate activities that do not contribute to safe disposal, resource recovery, or stakeholder value. When appropriately adapted, lean management should reduce processing delays, unnecessary handling, operational errors, equipment interruptions, and inefficient resource consumption. These improvements are expected to enhance the environmental performance, coordination, consistency, and overall effectiveness of PWMS.

H3: Lean-management practices have a positive and significant effect on Phone Waste Management System effectiveness in Malaysia.

2.5 Mediating Role of Lean Management

The direct relationship between technological advancements and PWMS effectiveness does not fully explain how technological capability is translated into operational and environmental outcomes. Advanced technologies can provide accurate information, automation, traceability, and analytical capability, but these resources must be incorporated into organizational routines before their full value can be realized. Lean management is therefore proposed as an operational transmission mechanism between technological advancements and PWMS effectiveness. This mediation argument is consistent with the dynamic-capabilities perspective. Technological resources provide organizations with the ability to identify operational conditions and emerging problems, but performance depends on the capacity to reconfigure routines and allocate resources in response to that information. Lean management supplies this reconfiguration mechanism through standardized work, continuous improvement, process analysis, employee problem solving, and waste elimination. Technology makes inefficiencies visible, while lean management converts that visibility into corrective and preventive actions. The mediation process can be described as a sequence. First, technological advancements improve the quality, speed, and availability of information concerning phone collection, transportation, sorting, processing, and recovery. Second, lean-management practices use this information to identify bottlenecks, standardize procedures, remove unnecessary activities, and improve coordination. Third, these operational improvements enhance PWMS effectiveness through faster processing, fewer errors, more efficient resource use, higher material recovery, and stronger stakeholder integration. Zaman et al. (2025) provide empirical support for this general mechanism. Their study found that digital technologies did not independently generate digitalization performance. Digitalization management significantly mediated the relationship, indicating that managerial and organizational processes were necessary to transform digital resources into actual results. Although digitalization management is not identical to lean management, both emphasize coordinated implementation, process alignment, and the disciplined use of technological capability.

More direct evidence was reported by Buhaya and Metwally (2024). Their study found that lean manufacturing partially mediated the relationships between digital technologies and economic, social, and environmental sustainability performance. Digital technologies had both direct performance effects and indirect effects through lean manufacturing practices. This pattern supports the argument that some technologies generate immediate benefits, while an additional portion of their value is transmitted through improved organizational processes. Elnadi et al. (2025) also found that lean, agile, and circular manufacturing practices mediated the relationship between Industry 4.0 technologies and sustainability performance. Their results demonstrate that digital technologies act as enablers of operational practices and that these practices subsequently convert technological capabilities into sustainable outcomes. Lean manufacturing played a foundational role by supporting both agile and circular practices, highlighting its wider importance within technology-enabled sustainability systems. In PWMS, a tracking platform may directly reduce the loss of discarded phones from formal channels, but its broader performance benefits depend on how organizations respond to the information it provides. Similarly, automated sorting may directly improve classification accuracy, while lean practices determine whether the surrounding workflow minimizes waiting, unnecessary movement, repeated handling, and equipment downtime. Lean management therefore explains why organizations with comparable technologies may achieve different levels of PWMS effectiveness. Partial mediation is expected because technological advancements can directly enhance collection monitoring, sorting accuracy, transportation planning, and material identification. However, technology should also improve PWMS effectiveness indirectly by strengthening lean-management practices. The proposed indirect relationship recognizes that technological adoption is most valuable when accompanied by processes that consistently transform digital information and automation into operational improvement.

H4: Lean management significantly mediates the positive relationship between technological advancements and Phone Waste Management System effectiveness in Malaysia.

2.6 Development of the Study Model

The study model was developed by integrating evidence from phone-waste management, digital transformation, lean management, and sustainable operations literature. Previous research indicates that technological infrastructure improves the capacity of recycling systems to monitor waste flows, enhance traceability, automate sorting, coordinate stakeholders, and support more efficient recovery decisions (Faradillah et al., 2025). Technological advancements are therefore expected to influence PWMS effectiveness directly. However, technology does not necessarily produce improved performance when it is introduced into fragmented or inefficient processes. Zaman et al. (2025) demonstrated that managerial processes are needed to convert digital resources into performance, while Buhaya and Metwally (2024) found that digital technologies strengthen lean practices and that lean management transmits part of their effect to sustainability performance. Similarly, Elnadi et al. (2025) showed that Industry 4.0 technologies support lean practices, which subsequently contribute to sustainable performance. Based on this evidence, the model positions technological advancements as the exogenous construct, PWMS effectiveness as the endogenous construct, and lean management as the mediating construct. It proposes a direct technological pathway to PWMS effectiveness and an indirect pathway through lean management. The direct path reflects the immediate contribution of technology to monitoring, sorting, traceability, and processing, whereas the indirect path explains how technological information and automation are converted into operational improvement through process standardization, continuous improvement, resource optimization, and waste elimination. Accordingly, the model contains three direct relationships (technological advancements to PWMS effectiveness, technological advancements to lean management, and lean management to PWMS effectiveness) and one mediating relationship in which lean management transmits the effect of technological advancements to PWMS effectiveness.

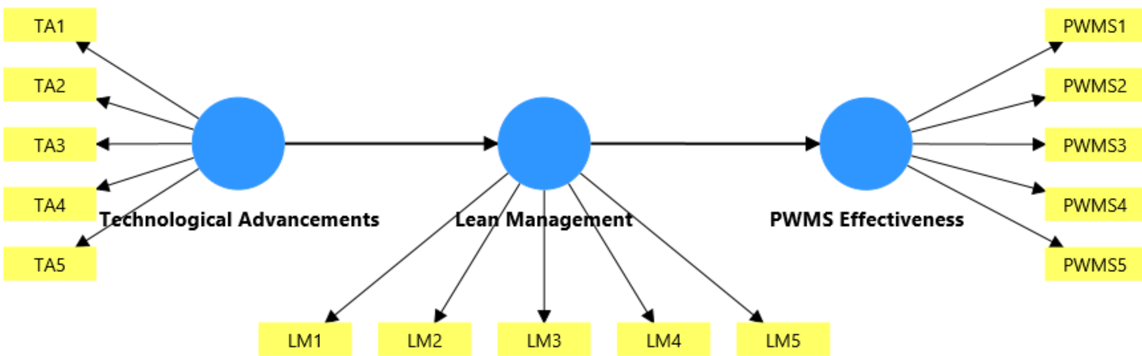

Figure 1. Conceptual model of the study

3. Methodology

3.1 Research Design

This study adopted a quantitative, explanatory, and cross-sectional research design to examine the relationships among technological advancements, lean management, and Phone Waste Management System (PWMS) effectiveness in Malaysia. A quantitative design was appropriate because the proposed relationships were derived from the theoretical and empirical literature and expressed as testable hypotheses. The study consequently followed a deductive approach in which the conceptual relationships were established before the collection and statistical analysis of the data. The data were collected at a single point in time using a structured questionnaire. This cross-sectional approach enabled the study to capture respondents' current perceptions of technological applications, lean-management practices, and PWMS effectiveness. It was also appropriate for obtaining a sufficiently large dataset from geographically dispersed mobile-phone users and relevant stakeholders in Malaysia. Nevertheless, because the variables were measured simultaneously and through the same survey instrument, the estimated relationships are interpreted as theory-consistent statistical associations rather than definitive evidence of temporal or causal effects. The present paper uses a focused model derived from the broader PWMS framework developed in the original study. The focused model contains three constructs: technological advancements as the exogenous variable, lean management as the mediator, and PWMS effectiveness as the endogenous variable. This specification was selected to isolate the internal operational mechanism through which technological capability may be translated into more effective phone-waste management. Four relationships were examined: the direct association between technological advancements and PWMS effectiveness, the association between technological advancements and lean management, the association between lean management and PWMS effectiveness, and the indirect relationship between technological advancements and PWMS effectiveness through lean management.

3.2 Population and Unit of Analysis

The target population comprised adult mobile-phone users residing in Malaysia. Eligible respondents were required to be at least 18 years old and to currently own a mobile phone or to have owned and disposed of one during the preceding three years. This eligibility criterion ensured that respondents possessed recent experience with mobile-phone purchasing, usage, replacement, storage, return, recycling, or disposal decisions. The population included individual consumers as well as respondents working in sectors connected directly or indirectly with mobile-phone and electronic-waste systems, such as retail, manufacturing, technology, recycling, waste management, education, and government. Including respondents with varied backgrounds was relevant because PWMS effectiveness depends upon the interaction of consumer behavior, organizational practices, technological infrastructure, and institutional arrangements. The unit of analysis was the individual respondent. Each observation represented one person's perceptions of technological advancements, lean-management practices, and PWMS effectiveness. This individual-level unit was consistent with the questionnaire design and with the use of Partial Least Squares Structural Equation Modeling (PLS-SEM), which estimates relationships between latent constructs using respondent-level observations. Accordingly, the results describe perceived system capabilities and effectiveness rather than audited organizational performance or objectively measured national recycling outcomes.

Measurement limitation. The unit of analysis is the individual user, whereas technological advancements and lean management are primarily organizational and operational capabilities. Many general users may therefore lack direct knowledge of recycling workflows, process standardization, traceability systems, and continuous-improvement routines. Accordingly, the constructs and findings are interpreted as respondents' perceptions rather than objective or audited organizational performance.

3.3 Sampling Procedure and Sample Size

A purposive sampling procedure was employed. Probability sampling would have required a complete and accessible list of all eligible adult mobile-phone users in Malaysia, which was unavailable because of the size and geographical dispersion of the target population. Purposive sampling therefore enabled the study to reach respondents who satisfied the eligibility requirements and had sufficient experience to evaluate the questionnaire statements. The questionnaire was distributed across several channels to improve respondent diversity and geographical coverage. Online distribution included email invitations and commonly used social-media and communication platforms, including Facebook, WhatsApp, LinkedIn, and Telegram. The survey was also circulated through universities, environmental and community organizations, mobile-phone retailers, recycling-related networks, and other groups connected with mobile-phone use or electronic-waste management. English and Bahasa Melayu versions were provided to reduce language-related barriers and enable participation from respondents with different educational and regional backgrounds. The required sample size was considered from both population-based and analytical perspectives. Using a 95% confidence level and a 5% margin of error, conventional sample-size references indicate that approximately 384–385 observations are adequate for a large population. From the analytical perspective, PLS-SEM requires a sample that is sufficient to estimate the proposed measurement and structural relationships reliably. The final sample of 482 valid cases exceeded the population-based benchmark and the commonly recommended minimum levels for structural equation modeling. Approximately 1,870 questionnaire invitations were initially distributed, from which 659 responses were received. The collected responses were screened before analysis. Ninety-eight cases with more than 15% missing information were excluded, leaving 561 substantially complete cases. Boxplot examination subsequently identified 79 cases with extreme univariate response patterns, which were removed to prevent unusually extreme observations from exerting disproportionate influence on the estimates. The resulting analytical sample consisted of 482 complete and usable responses. This represents approximately 73.1% of the returned questionnaires and provided an adequate basis for estimating the focused mediation model. Purposive sampling limits the extent to which sample percentages can be generalized statistically to every Malaysian mobile-phone user. However, the principal purpose of this study was to test theoretically derived relationships rather than estimate population prevalence. The sample was therefore considered appropriate for analytical generalization, provided that the findings are interpreted within the stated eligibility criteria and sampling limitations.

Because purposive recruitment and online circulation do not give all eligible Malaysian phone users a known and equal probability of selection, sampling error cannot be estimated reliably and the sample may overrepresent digitally active and better-educated participants. Consequently, the findings should not be generalized statistically to the entire Malaysian population.

3.4 Questionnaire Development and Measurement

Primary data were collected using a structured, closed-ended questionnaire. The measurement items were adapted from established literature and contextualized to phone-waste management in Malaysia. The questionnaire contained demographic and behavioural questions followed by multi-item measures of the theoretical constructs. All substantive items were measured on a five-point Likert scale ranging from 1, "strongly disagree," to 5, "strongly agree." The consistent response format facilitated comparison across items and was suitable for estimating latent constructs using PLS-SEM. For the focused model, technological advancements, lean management, and PWMS effectiveness were each operationalized reflectively using five indicators. The reflective specification assumed that the observed items represented manifestations of their respective underlying constructs and that variation in a construct would be reflected in its associated indicators. Technological advancements were measured using five items adapted from Porter and Heppelmann (2015) and contextualized to phone recycling and waste management. The items assessed whether technological innovations improve recycling efficiency, whether automation and advanced tools reduce recycling costs, whether technology strengthens the collection, sorting, and processing of discarded phones, whether artificial intelligence and data analytics streamline waste-management operations, and whether technological advancement improves the economic feasibility of phone recycling. Collectively, these indicators captured respondents' perceptions of the operational capabilities enabled by contemporary technologies. Lean management was measured using five items adapted from the principles advanced by Womack and Jones (2003). These indicators examined the minimization of resource consumption and operational waste, improvement in collection and recycling efficiency, streamlining of phone-waste operations, more effective resource utilization, and the maximization of value while minimizing waste generation. The scale therefore represented lean management as an operational discipline rather than merely a collection of isolated cost-reduction tools. PWMS effectiveness was measured using five items adapted from Widmer et al. (2005). The items assessed whether proper phone collection, recycling, and disposal reduce environmental harm; whether PWMS contributes to Malaysian sustainability objectives; whether a structured system minimizes the negative effects of discarded phones; whether greater awareness is required to strengthen system benefits; and whether effective recycling depends upon collaboration between public- and private-sector actors. The scale captured perceived environmental, structural, awareness, and coordination dimensions of PWMS effectiveness.

3.5 Instrument Validation and Pilot Study

The instrument underwent face- and content-validity assessment before the principal data collection. Nine experts with relevant academic, environmental, technological, or waste-management experience reviewed the questionnaire. They evaluated whether the items were clear, relevant to the study objectives, appropriately worded, and suitable for the Malaysian phone-waste context. Their comments were used to revise ambiguous wording, remove overlapping content, and improve the alignment between the indicators and their intended constructs. A pilot study was subsequently conducted with 32 undergraduate and postgraduate students from Malaysian public universities. The pilot respondents were regular smartphone users with sufficient exposure to mobile-phone consumption and basic electronic-waste issues. Their responses were used exclusively to evaluate item clarity and preliminary internal consistency and were excluded from the final analytical dataset. Cronbach's alpha was employed during the pilot stage to examine internal consistency. Most constructs exceeded the conventional benchmark of 0.70, while a small number of scales in the broader questionnaire produced coefficients slightly above 0.60. Values at this level can be considered adequate during exploratory instrument adaptation, particularly when established items are being modified for a new context. Feedback from the pilot participants and the reliability results informed minor revisions before the final English and Bahasa Melayu questionnaires were distributed.

3.6 Data Collection and Ethical Considerations

Participation in the survey was voluntary. Potential respondents were informed of the academic purpose of the study and were invited to participate only if they met the eligibility criteria. They were also informed that their responses would be handled confidentially and used exclusively for research and academic purposes. The questionnaire did not require respondents to provide information that would be necessary for estimating the proposed structural relationships but could directly identify them in the reported analysis. Adequate time was provided for completion, and follow-up reminders were issued after the initial distribution to improve participation. The use of an online questionnaire increased geographical accessibility and reduced interviewer influence, while the bilingual format helped respondents select the language in which they could understand the statements most accurately.

3.7 Data Screening and Preliminary Analysis

The collected data were prepared and screened using IBM SPSS Statistics version 29. The screening procedure examined missing values, unusual response patterns, univariate outliers, distributional characteristics, and potential multicollinearity. Frequency analysis was initially used to determine the extent of missing data. Cases containing more than 15% missing responses were removed rather than imputed because their incompleteness could undermine the reliability of the respondent-level construct scores. Univariate outliers were inspected using boxplots. Cases displaying extreme response patterns were reviewed and excluded when they could unduly distort the estimates. Normality was examined using skewness and kurtosis values. Although PLS-SEM does not require multivariate normality, assessing the distributions helped identify serious data anomalies and supported the interpretation of the descriptive statistics. Multicollinearity was examined using tolerance and variance inflation factor values to ensure that the predictor constructs did not contain problematic redundancy. Exploratory Factor Analysis (EFA) was conducted because several measurement items had been contextually adapted. Sampling adequacy was assessed using the Kaiser–Meyer–Olkin statistic, while Bartlett's test of sphericity was used to determine whether the inter-item correlations were sufficient for factor analysis. The EFA provided an initial assessment of whether the indicators grouped with their intended constructs before the confirmatory PLS-SEM assessment.

All three constructs were measured from the same respondents, through the same questionnaire, and at the same point in time. This design creates a risk of common-method bias. The analysis should therefore report an explicit diagnostic, such as full-collinearity VIFs or a marker-variable procedure, and future research should combine survey responses with organizational records or data from multiple informants.

3.8 PLS-SEM Analysis

The hypotheses were tested using SmartPLS version 4.1.0.9. PLS-SEM was selected because the study examined simultaneous relationships among multiple latent variables, included an indirect mediating pathway, and emphasized the explanation and prediction of PWMS effectiveness. PLS-SEM is also suitable for survey-based models that do not depend on the strict multivariate-normality assumptions associated with covariance-based structural equation modeling. The analysis followed a two-stage procedure. The measurement model was evaluated first to establish that the constructs were measured reliably and possessed satisfactory convergent and discriminant validity. Only after confirming the quality of the measurement model was the structural model evaluated to test the hypothesized relationships.

3.8.1 Measurement Model Assessment

Internal consistency reliability was examined using Cronbach's alpha and composite reliability. Values of 0.70 or higher were treated as evidence of acceptable reliability. Indicator reliability was evaluated through the standardized outer loadings. Loadings of 0.70 or above were preferred because they indicate that a substantial proportion of an indicator's variance is explained by its associated construct. Convergent validity was assessed using the Average Variance Extracted (AVE). An AVE value of at least 0.50 indicated that a construct explained more than half of the variance in its indicators. Discriminant validity was evaluated by comparing each indicator's loading on its intended construct with its cross-loadings on the other constructs and by applying the Fornell–Larcker criterion. These assessments determined whether technological advancements, lean management, and PWMS effectiveness were empirically distinguishable despite their theoretical relationships. The use of multiple reliability and validity criteria was necessary because high internal consistency alone does not confirm that a construct is conceptually distinct from the other variables. The measurement model was therefore accepted only after the indicator loadings, internal consistency measures, AVE values, and discriminant-validity evidence were collectively considered satisfactory.

3.8.2 Structural Model and Mediation Assessment

Following validation of the measurement model, the structural model was evaluated using the standardized path coefficients, coefficients of determination, effect sizes, predictive relevance, and statistical significance of the direct and indirect relationships. Collinearity among the predictor constructs was first reassessed using inner variance inflation factors. The coefficient of determination, (R^2), was used to evaluate the proportion of variance explained in the endogenous constructs, namely lean management and PWMS effectiveness. Effect size, (f^2), was examined to determine the contribution of each predictor to the explained variance of a particular endogenous construct. Values of approximately 0.02, 0.15, and 0.35 were interpreted as small, medium, and large effects, respectively. Predictive relevance was assessed using the blindfolding procedure, with a (Q^2) value greater than zero indicating that the model had predictive relevance for the relevant endogenous construct. The statistical significance of the structural relationships was assessed through nonparametric bootstrapping with 5,000 subsamples. The number of cases in each bootstrap sample corresponded to the final analytical sample of 482 observations. Two-tailed significance testing was applied, with a critical t-value of 1.96 and a p-value below 0.05 used as the principal criteria for determining statistical significance. The sign, magnitude, and confidence interval of each path coefficient were also examined to ensure that the empirical direction was consistent with the corresponding hypothesis. The mediating role of lean management was tested through the specific indirect effect linking technological advancements to PWMS effectiveness through lean management. Mediation was supported when the bootstrapped confidence interval for the indirect effect did not include zero and the associated p-value was below 0.05. The remaining direct effect of technological advancements on PWMS effectiveness was then examined to determine the nature of the mediation. A significant indirect effect accompanied by a significant direct effect indicated partial mediation, whereas a significant indirect effect accompanied by a nonsignificant residual direct effect indicated indirect-only or full mediation. This procedure enabled the study to determine not only whether technological advancements were associated with PWMS effectiveness, but also whether part of this association operated through the process discipline provided by lean management. The combined evaluation of the direct and indirect pathways therefore provided a more complete explanation of how technological capability may be converted into effective phone-waste management.

4. Findings

This section presents the results of the Partial Least Squares Structural Equation Modeling analysis. The analysis followed the two-stage procedure recommended for PLS-SEM. First, the measurement model was assessed to determine whether the indicators measured their respective constructs reliably and validly. Second, the structural model was evaluated to examine the hypothesized direct and indirect relationships among technological advancements, lean management, and PWMS effectiveness. The measurement-model assessment considered indicator loadings, Cronbach's alpha, composite reliability, and Average Variance Extracted (AVE). The subsequent structural-model assessment should examine collinearity, path coefficients, explanatory power, effect sizes, predictive relevance, and the significance of the direct and indirect effects through bootstrapping. Figure 2 presents the PLS-SEM algorithm results for the current model. The values associated with the indicators represent standardized outer loadings, while the values shown inside the endogenous constructs represent their coefficients of determination. The coefficients displayed on the arrows between the constructs represent preliminary standardized path estimates. These path estimates should not, however, be interpreted as statistically significant until their corresponding bootstrapped t-values, p-values, and confidence intervals have been examined.

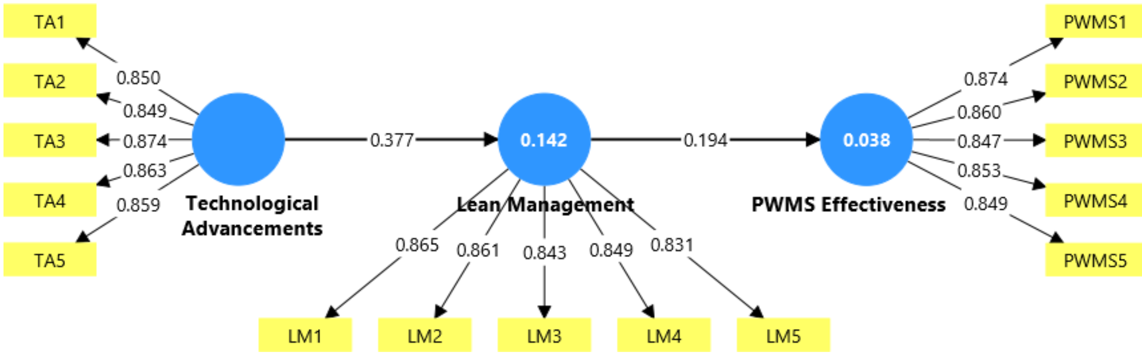

FIGURE 2. PLS-SEM ALGORITHM RESULTS FOR THE STUDY MODEL

4.1 Assessment of the Measurement Model

The measurement model was evaluated before interpreting the structural relationships. This sequence is necessary because conclusions about the relationships between latent constructs are meaningful only when those constructs have been measured with adequate reliability and validity. The assessment examined indicator reliability using standardized outer loadings and assessed internal consistency reliability and convergent validity using Cronbach's alpha, composite reliability, and AVE.

TABLE 1. MEASUREMENT MODEL ASSESSMENT RESULTS

	Indicator	Outer loading	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Lean Management	LM1	0.865	0.904	0.910	0.929	0.723
	LM2	0.861				
	LM3	0.843				
	LM4	0.849				
	LM5	0.831				
Technological Advancements	TA1	0.850	0.911	0.913	0.934	0.738
	TA2	0.849				
	TA3	0.874				
	TA4	0.863				
	TA5	0.859				
PWMS Effectiveness	PWMS1	0.874	0.910	0.921	0.932	0.734
	PWMS2	0.860				
	PWMS3	0.847				
	PWMS4	0.853				
	PWMS5	0.849				

As shown in Table 1, the outer loadings ranged from 0.831 to 0.874, and all exceeded the recommended threshold of 0.708. For Lean Management, LM1 recorded the highest loading at 0.865, while LM5 had the lowest at 0.831. For Technological Advancements, TA3 produced the highest loading at 0.874, whereas TA2 recorded the lowest at 0.849. The loadings for PWMS Effectiveness ranged from 0.847 to 0.874, with

PWMS1 recording the highest value. The results therefore demonstrate satisfactory indicator reliability, and all indicators were retained. Cronbach's alpha ranged from 0.904 to 0.911, rho_a ranged from 0.910 to 0.921, and rho_c ranged from 0.929 to 0.934. All coefficients exceeded the minimum threshold of 0.70 but remained below 0.95, demonstrating strong internal consistency without clear evidence of excessive indicator redundancy (Hair et al., 2017). The AVE values were 0.723 for Lean Management, 0.738 for Technological Advancements, and 0.734 for PWMS Effectiveness. Each value exceeded the recommended minimum of 0.50, confirming convergent validity because every construct explained more than half of the variance in its indicators.

4.1.3 Discriminant Validity

Discriminant validity determines whether each latent construct measures a concept that is empirically distinct from the other constructs in the model. Establishing discriminant validity is particularly important in the present study because Technological Advancements, Lean Management, and PWMS Effectiveness are theoretically related. Failure to establish discriminant validity would indicate that the constructs overlap excessively and could undermine the interpretation of the structural relationships. Discriminant validity was evaluated using the Fornell–Larcker criterion and the Heterotrait–Monotrait ratio of correlations. Under the Fornell–Larcker criterion, the square root of the AVE of each construct should be greater than its correlations with the other constructs (Fornell & Larcker, 1981). The square roots of AVE are presented in bold on the diagonal of Table 2, while the off-diagonal values represent the inter-construct correlations.

TABLE 2. DISCRIMINANT VALIDITY BASED ON THE FORNELL–LARCKER CRITERION

	Lean Management	PWMS Effectiveness	Technological Advancements
Lean Management	0.850		
PWMS Effectiveness	0.194	0.857	
Technological Advancements	0.377	0.317	0.859

As shown in Table 2, the square root of AVE for Lean Management was 0.850, which exceeded its correlations with PWMS Effectiveness (0.194) and Technological Advancements (0.377). Similarly, the square root of AVE for PWMS Effectiveness was 0.857, exceeding its correlations with Lean Management (0.194) and Technological Advancements (0.317). Technological Advancements recorded a square root of AVE of 0.859, which was also substantially higher than its correlations with the other constructs. These results demonstrate that each construct shared more variance with its own indicators than with the other latent variables. Therefore, the Fornell–Larcker criterion was satisfied. The relatively moderate correlation between Technological Advancements and Lean Management (0.377) is theoretically reasonable because technological resources can support lean processes, but the value remains sufficiently below the diagonal elements to indicate that the constructs are not empirically interchangeable. Because the Fornell–Larcker criterion may not always identify discriminant-validity problems, the HTMT ratio was also assessed. Values below 0.85 represent a conservative standard of discriminant validity, while values below 0.90 are commonly accepted when the constructs are conceptually related (Henseler et al., 2015).

TABLE 3. DISCRIMINANT VALIDITY BASED ON THE HETEROTRAIT–MONOTRAIT RATIO

	Lean Management	PWMS Effectiveness	Technological Advancements
Lean Management			
PWMS Effectiveness	0.208		
Technological Advancements	0.411	0.345	

Table 3 shows that all HTMT values were substantially below both the conservative threshold of 0.85 and the more permissive threshold of 0.90. The highest HTMT value was 0.411 between Technological Advancements and Lean Management, followed by 0.345 between Technological Advancements and PWMS Effectiveness. The lowest value was 0.208 between Lean Management and PWMS Effectiveness. These values provide strong evidence that the constructs were empirically distinct. Taken together, the Fornell–Larcker and HTMT results establish satisfactory discriminant validity. Combined with the outer loadings, reliability coefficients, and AVE values, these results support the adequacy of the measurement model.

4.2 Assessment of the Structural Model

Following confirmation of the reliability and validity of the measurement model, the structural model was evaluated. The assessment considered the model's explanatory power using R^2, the relative contribution of each predictor using f^2, and its out-of-sample predictive relevance using Q^2 predict. The standardized path coefficients and their statistical significance must subsequently be evaluated using bootstrapping before decisions are made regarding the hypotheses.

4.2.1 Explanatory Power of the Model

The coefficient of determination, R^2, indicates the proportion of variance in an endogenous construct explained jointly by its predictors. Higher values indicate stronger explanatory power, although the interpretation of R^2 should consider the research context and the maturity of the underlying theory. Hair et al. (2017) suggested values of approximately 0.75, 0.50, and 0.25 as substantial, moderate, and weak explanatory power, respectively. These values should be regarded as general guidelines rather than universal rules.

TABLE 4. COEFFICIENTS OF DETERMINATION FOR THE ENDOGENOUS CONSTRUCTS

	R-square	R-square adjusted
Lean Management	0.142	0.141
PWMS Effectiveness	0.038	0.036

As presented in Table 4, Technological Advancements explained 14.2% of the variance in Lean Management. The adjusted value was almost identical at 14.1%, indicating that the explanatory estimate was not materially inflated by model complexity. Nevertheless, the value falls below the general threshold of 0.25 for weak explanatory power. This indicates that technological capability is associated with lean-management practices but represents only one of several factors influencing their implementation. The remaining 85.8% of variance in Lean Management may be associated with factors not included in the focused model, such as leadership support, organizational culture, employee involvement, training, process maturity, resource availability, and resistance to organizational change. Therefore, the R^2 result does not imply that technological advancements are unimportant; rather, it indicates that lean management cannot be explained by technology alone. The R^2 value for PWMS Effectiveness was 0.038, while its adjusted value was 0.036. Thus, the predictor shown in the current structural specification explained only 3.8% of the variance in PWMS Effectiveness. This represents very limited explanatory power and suggests that PWMS effectiveness is a complex outcome shaped by a broader set of technological, regulatory, financial, behavioral, infrastructural, and stakeholder-related conditions.

4.2.2 Effect Sizes

Whereas (R^2) evaluates the combined explanatory power of the predictors, (f^2) determines how strongly an individual exogenous construct contributes to the (R^2) value of a particular endogenous construct. The effect size is calculated by comparing the (R^2) value of the complete model with the (R^2) obtained after removing the relevant predictor. Values of 0.02, 0.15, and 0.35 conventionally indicate small, medium, and large effects, respectively (Cohen, 1988).

TABLE 5. EFFECT SIZES OF THE STRUCTURAL RELATIONSHIPS

	Lean Management	PWMS Effectiveness	Technological Advancements
Lean Management		0.039	
PWMS Effectiveness			
Technological Advancements	0.165		

Table 5 shows that Technological Advancements had an (f^2) value of 0.165 for Lean Management. This exceeds the benchmark of 0.15 and therefore represents a medium effect. The result indicates that removing

Technological Advancements from the model would produce a meaningful reduction in the explained variance of Lean Management. This effect is consistent with the argument that digital visibility, automation, integrated information, and data-driven decision-making support process standardization and continuous improvement. Lean Management had an (f^2) value of 0.039 for PWMS Effectiveness. This value exceeds the minimum threshold of 0.02 but remains well below 0.15, indicating a small effect. Lean-management practices therefore contributed to explaining PWMS Effectiveness, but their isolated contribution was limited. This finding is consistent with the low (R^2) value and reinforces the conclusion that operational efficiency alone cannot account for the broader effectiveness of a multi-stakeholder phone-waste system. The small effect should not be dismissed automatically. PWMS effectiveness is influenced by multiple actors and institutional conditions, and a small effect may still possess theoretical or practical relevance when it concerns an operational mechanism that can be improved through managerial intervention. Nevertheless, the result does not support claims that Lean Management is a dominant determinant of PWMS Effectiveness. The f^2 table contains no value for the direct effect of Technological Advancements on PWMS Effectiveness. If H1 is part of the conceptual framework, the absence of this value indicates that the direct structural path was not included in the estimated model or that its effect-size result was not exported. The complete structural analysis should report this effect before final conclusions are drawn about the direct technological contribution or the mediating role of Lean Management.

Critical interpretation. The model explains only 3.8% of the variance in perceived PWMS effectiveness (adjusted $R^2 = 0.036$), and the effect of lean management is small ($f^2 = 0.039$). Statistical significance should therefore not be presented as strong practical explanatory power. The result indicates a limited association and suggests that regulatory enforcement, consumer participation, take-back accessibility, financial incentives, producer responsibility, recycler capacity, and stakeholder coordination should be incorporated into an expanded model.

4.2.3 Predictive Relevance

The model's predictive assessment was conducted using Q^2 predict, accompanied by the Root Mean Square Error and Mean Absolute Error. A positive Q^2 predict value indicates that the PLS-SEM model produces lower prediction errors than a naïve benchmark that relies only on the mean of the training data. RMSE penalizes larger prediction errors more strongly, whereas MAE represents the average absolute prediction error.

TABLE 6. PREDICTIVE ASSESSMENT OF THE ENDOGENOUS CONSTRUCTS

	Q^2predict	RMSE	MAE
Lean Management	0.137	0.932	0.761
PWMS Effectiveness	0.040	0.983	0.832

As shown in Table 6, Lean Management recorded a positive (Q^2) value of 0.137. This indicates that the model had predictive relevance for Lean Management and performed better than the naïve mean-based prediction benchmark. The RMSE and MAE values were 0.932 and 0.761, respectively. The positive (Q^2) result is consistent with the medium (f^2) effect of Technological Advancements on Lean Management, although the predictive improvement remained modest. PWMS Effectiveness produced a positive (Q^2) value of 0.040, with RMSE and MAE values of 0.983 and 0.832, respectively. The positive value indicates that the model possessed some out-of-sample predictive relevance for PWMS Effectiveness. However, the value was close to zero and should therefore be interpreted as marginal rather than strong predictive performance. This finding is consistent with the very low (R^2) value of 0.038 and the small (f^2) contribution of Lean Management. A positive (Q^2) value establishes predictive relevance, but it is insufficient to classify the model's predictive power as low, medium, or high. Such classification normally requires comparing the item-level prediction errors of the PLS-SEM model with those produced by a linear-model benchmark. Because the provided results include only the PLS prediction errors and not the benchmark errors, the analysis can conclude that the model has positive but limited predictive relevance; it cannot claim superior or strong predictive performance. The structural-quality results show that the model explains and predicts Lean Management more effectively than PWMS Effectiveness. Technological Advancements make a meaningful contribution to Lean Management, but Lean Management alone explains only a small proportion of PWMS Effectiveness. This pattern supports the theoretical relevance of the operational pathway while simultaneously demonstrating that the focused model captures only one part of the wider set of determinants underlying effective phone-waste management.

4.2.4 Structural Path and Mediation Results

The statistical significance of the structural relationships was evaluated using a nonparametric bootstrapping procedure with 5,000 subsamples. The assessment considered the original sample coefficient, bootstrap sample mean, standard deviation, t-statistic, and p-value. A relationship was considered statistically significant when its t-statistic exceeded 1.96 and its p-value was below 0.05. Figure 3 presents the bootstrapping output for the estimated structural model.

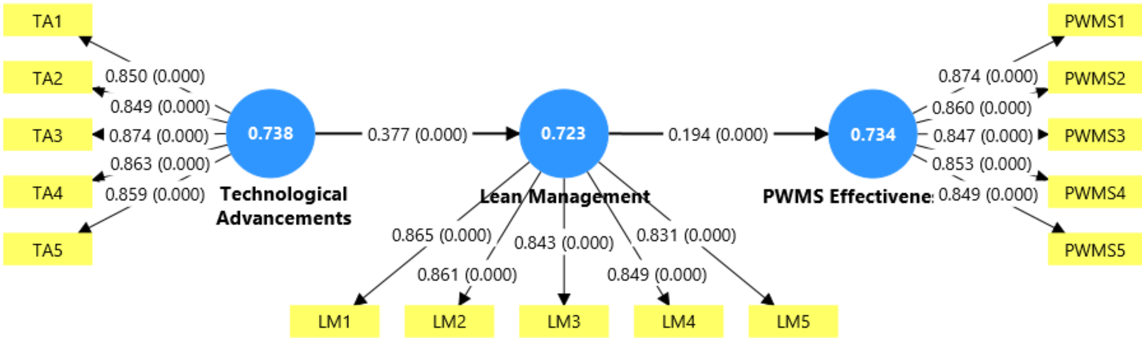

FIGURE 3. PLS-SEM BOOTSTRAPPING RESULTS FOR THE ESTIMATED STRUCTURAL MODEL

The values shown next to the indicators and structural paths are followed by their p-values in parentheses. The values displayed inside the three constructs, 0.738 for Technological Advancements, 0.723 for Lean Management, and 0.734 for PWMS Effectiveness; represent the AVE values selected for display in the SmartPLS output; they should not be interpreted as coefficients of determination.

TABLE 7. BOOTSTRAPPING RESULTS FOR THE DIRECT EFFECTS

Relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Lean Management → PWMS Effectiveness	0.194	0.198	0.037	5.196	0.000
Technological Advancements → Lean Management	0.377	0.379	0.035	10.696	0.000

As shown in Table 7, Technological Advancements had a positive and statistically significant effect on Lean Management ($\beta = 0.377$, $t = 10.696$, $p < 0.001$). The bootstrap sample mean of 0.379 was very close to the original coefficient, suggesting limited bootstrap bias and a stable estimate. The result supports H2 and indicates that technological capabilities are positively associated with the use of lean-management practices in phone-waste operations. Lean Management also had a positive and statistically significant effect on PWMS Effectiveness ($\beta = 0.194$, $t = 5.196$, $p < 0.001$). Its bootstrap mean of 0.198 closely approximated the original coefficient, providing additional evidence of estimation stability. H3 was therefore supported. Nevertheless, the coefficient was modest, which is consistent with the previously reported small f2 effect and low R2 value for PWMS Effectiveness. Lean Management consequently makes a statistically reliable but limited contribution to explaining system effectiveness.

TABLE 8. BOOTSTRAPPING RESULT FOR THE SPECIFIC INDIRECT EFFECT

Indirect relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Technological Advancements → Lean Management → PWMS Effectiveness	0.073	0.075	0.017	4.292	0.000

Table 8 shows that the specific indirect effect of Technological Advancements on PWMS Effectiveness through Lean Management was positive and statistically significant ($\beta = 0.073$, $t = 4.292$, $p < 0.001$). The value of the indirect effect corresponds to the product of the two constituent paths ($0.377 \times 0.194 \approx 0.073$). The bootstrap means of 0.075 was close to the original estimate, while the relatively small standard deviation of 0.017 indicates that the indirect coefficient remained stable across the bootstrap samples. The significant indirect effect supports H4. It indicates that technological advancements contribute to PWMS effectiveness by strengthening lean-management practices, which subsequently improve operational efficiency and system performance. However, the indirect coefficient is small in magnitude. The result should therefore be interpreted as evidence of a statistically reliable but limited mediation mechanism rather than a dominant explanation of PWMS effectiveness.

The direct effect of Technological Advancements on PWMS Effectiveness was not displayed as a separate structural path in Figure 3. The coefficient of 0.073 supplied under the direct-effect label is numerically identical to the specific indirect effect and is equal to the product of the Technological Advancements → Lean Management and Lean Management → PWMS Effectiveness coefficients. It should therefore not be reported as the direct effect. Consequently, H1 and the mediation type cannot be determined from the current output. A model containing the direct Technological Advancements → PWMS Effectiveness path must be estimated before mediation can be classified as partial or indirect-only.

TABLE 9. SUMMARY OF HYPOTHESIS-TESTING DECISIONS

Hypothesis	Relationship	Result
H1	Technological Advancements → PWMS Effectiveness	Not evaluated: direct path not reported
H2	Technological Advancements → Lean Management	Supported
H3	Lean Management → PWMS Effectiveness	Supported
H4	Technological Advancements → Lean Management → PWMS Effectiveness	Supported

The bootstrapping results provide strong statistical support for the technology-to-lean path, the lean-to-PWMS path, and the specific indirect effect. The strongest relationship was observed between Technological Advancements and Lean Management, whereas the effect of Lean Management on PWMS Effectiveness was smaller. The findings therefore support the proposed operational transmission mechanism but also show that the focused model explains only a limited portion of PWMS Effectiveness. Final evaluation of the complete mediation model requires estimation of the missing direct technological path.

5. Discussion

The results give empirical evidence of an operational mechanism to improve the effectiveness of the phone waste management system (PWMS) through strengthening lean management through technological advances. Technological advancements had a positive and statistically significant effect on lean management ($\beta = 0.377$, $t = 10.696$, $p < 0.001$), there was a strong relationship between them. Supporting H2, technological advancements had the strongest relationship in the model. The outcome shows that digital monitoring, traceability, automation, analytics and integrated information systems generate the visibility and timely information of the process thus helping to identify bottlenecks, standardise activities, minimise operational waste and facilitate continuous improvement. This result parallels Silva et al. (2026), who noted that digital technologies, process optimisation, data-driven decision-making and standardisation are interdependent. It also aligns with the findings of Zaman et al. (2025), who claimed that the technology resources can only produce relevant performance when they are transformed to operational capability through effective managerial practices. However, with the R^2 value of 0.142, it is clear that technology accounts for a small portion of lean management, which means that other factors such as leadership commitment, employee competence, organizational culture, training, and coordination of stakeholders are still significant.

Lean management further had a positive and statistically significant result with regard to PWMS effectiveness ($\beta = 0.194$, $t = 5.196$, $p < 0.001$) which supported H3. The result shows that standardized work, continuous improvement, minimization of waiting time, improvement of process flow and efficient use of resources can improve the activity of collecting, sorting, dismantling, recovering and recycling telephones. The finding is consistent with the study of Lyama and Salema (2025) which showed that Lean practices are associated with sustainability performance and that Nawanir and Moshood (2025) showed that Lean, Agile and Green principles are effective in enhancing the competitiveness of the operations in the Malaysian companies. The coefficient was however relatively small, the f^2 value was slight (0.039) and lean management accounted for only 3.8% of the variance in the effectiveness of PWMS. The discovery validates the notion that lean management, by itself, can have a significant positive impact on sustainable waste-management results. Lean practices cannot alone guarantee consumer participation, convenient collection network, formal recycling capacities, incentives, or proper compliance of regulatory frameworks. This interpretation is in line with Ho et al. (2026), who demonstrated that the contribution of leanness to performance could rely on complementary organizational capabilities, and Faradillah et al. (2025), who found that regulatory, financial and technological conditions were vital factors in determining readiness in e-waste management in Malaysia.

The specific indirect effect of technological advancements on the effectiveness of PWMS, through lean management was positive and statistically significant ($\beta = 0.073$, $t = 4.292$ and $p < 0.001$), and thus confirms H4. The result shows that lean management is an operational transmission mechanism that transforms technologies into better system results. Lean management takes technology and uses it to eliminate waste, coordinate workflow, and continuously improve information, visibility and automation. The findings are consistent with those of Buhaya and Metwally (2024) who reported that lean manufacturing is a key factor in understanding how digital technologies can impact sustainable performance and Elnadi et al. (2025) who reported lean and circular practices as operational pathways linking Industry 4.0 technologies with sustainability outcomes. The small indirect coefficient, however, suggests that the mediation mechanism is statistically sound but is not extensive. With just the improvements in internal processes, technological investments will not likely yield significant system-wide improvements if they are not matched by changes in consumer behavior, coverage of collections, producer responsibility, and coordination amongst stakeholders. Serranti et al. (2025) also showed that the outcomes of phone waste are closely linked to a broader level of public awareness and disposal practices, and Faradillah et al. (2025) identified the impact of the general institutional and industry-readiness environment.

H1 hypothesized a direct effect of technological developments on PWMS effectiveness, but it is not possible to test this hypothesis from the reported structural model as the direct path was not estimated. This coefficient is exactly the same as the specific indirect effect, and is equal to the product of the technology-to-lean and lean-to-effectiveness coefficients, as is reported. Therefore, it is only an indirect effect that is to be reported. Therefore, the mediation can only be defined as partial, full or indirect-only until the model is re-estimated including the direct path of technological-advancements-PWMS-effectiveness. While theoretical support for a direct technological effect (Faradillah et al., 2025) exists in prior literature a theoretical effect is not a substitute for an estimated structural effect.

Thus, the positive Q^2 predict values for lean management (0.137) and PWMS effectiveness (0.040) indicate some predictive relevance, but the low R^2 value for PWMS effectiveness and its RMSE and MAE values of 0.983 and 0.832 demonstrate limited predictive utility. The findings therefore support the proposed technology–lean–effectiveness mechanism while showing that it explains only a small proportion of PWMS effectiveness. The study extends Lean 4.0 reasoning into the phone waste and circular-economy context by demonstrating that technological resources require appropriate operational routines to generate performance improvements. Nevertheless, effective phone waste management requires an integrated approach combining digital technologies and lean practices with regulatory support, accessible take-back channels, financial incentives, recycler capability, stakeholder collaboration, and responsible consumer participation.

6. Conclusion

This study investigates the effectiveness of phone waste management system (PWMS) in Malaysia based on the use of technology in lean management. Technological advancements positively and significantly influenced lean management ($\beta = 0.377$, $t = 10.696$, $p < 0.001$), and lean management positively and significantly influenced the effectiveness of PWMS ($\beta = 0.194$, $t = 5.196$, $p < 0.001$). The specific indirect effect was also positive and significant ($\beta = 0.073$, $t = 4.292$, $p < 0.001$), which showed that there is an operational mechanism by which technological capabilities can positively affect the effectiveness of PWMS through lean management. However, the indirect effect was small and the proportion of explained variance in the effectiveness of PWMS was low ($R^2 = 0.038$), suggesting that it is an enabling process rather than a key one. For effective phone waste management, the technological infrastructure and the efficiency of the internal processes are not enough; the consumers should be involved as well, there should be collection channels available that are easy to use, there should be a regulatory enforcement system in place, financial support should be provided, the capability of the phone recyclers should be developed, producer responsibility is needed, and there should be a coordination system of the stakeholders. Theoretically, the study extends the technology–lean integration perspective to managing phone waste and the circular-economy context. It shows that sustainable results cannot be simply achieved by technological resources, but that they can be achieved in part by managerial routines that are based on process standardization, elimination of waste and continuous improvement. The findings provide practical implications for Malaysian policies, producers, retailers, recyclers, and technology suppliers to invest in smart collection, tracking, automated sorting, and analytical systems, along with value-stream mapping, standardized procedures, employee training, tracking performance, and constant improvements. There should be greater collaboration between the phone waste value chain, public awareness, convenient take-back schemes, financial incentives and extended producer responsibility (EPR) in tandem with these organizational initiatives. The results, however, should be interpreted with the limitations of the study in mind. Although the cross-sectional data do not imply any causality or chronological order, the three-construct focused model left out some behavioral, institutional and infrastructural factors that influence the effectiveness of PWMS. Furthermore, the Q2predict values were still positive – but the model's predictive relevance for the effectiveness of PWMS was still limited. Importantly, the structural model did not include a separate direct path from technological advancements to PWMS effectiveness; thus, a mediation test could not be performed and H1 could not be tested and the mediation cannot be determined to be full, partial or complementary. Future studies should provide the estimation of the complete mediation model, use longitudinal and multi-source data, compare relevant stakeholder groups, and use objective variables, such as collection volumes, recovery rate, processing time and material-recovery yield. Overall, the results support the view that technological innovation and lean management are interdependent elements of PWMS improvement and that this effectiveness in the systems must be complemented by regulations, collaboration and conscious consumer practices.

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During the preparation of this manuscript, the author's used AI tool name, e.g., ChatGPT and Claude solely to improve the language, grammar, and clarity of the text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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