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Industry 4.0 readiness and technology acceptance as drivers of smart manufacturing capability and environmental performance in recycling enterprises

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Abstract: This study examines the causal relationships among technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance in recycling enterprises in Thailand. The study employs a quantitative research design using a structured questionnaire administered to employees and managers of recycling enterprises. Data are analyzed using exploratory factor analysis, confirmatory factor analysis, and structural equation modeling to assess the measurement model and hypothesized relationships. Semi-structured interviews are also conducted to provide qualitative insights into digital transformation. The findings indicate that technology acceptance, organizational readiness, and leadership support are important drivers of digital transformation. Technology acceptance and Industry 4.0 readiness positively influence smart manufacturing capability, which improves environmental performance through greater operational efficiency, resource optimization, waste reduction, and environmental compliance. Smart manufacturing capability also mediates these relationships. The study demonstrates that integrating behavioral, organizational, and technological capabilities can strengthen sustainable performance in Thailand's recycling industry. Practical Implications: The findings provide guidance for managers and policymakers to strengthen organizational readiness, leadership support, and technological capabilities, thereby accelerating Industry 4.0 adoption and promoting environmentally sustainable industrial development.

Keywords: *Environmental performance, Industry 4.0 readiness, Recycling enterprises, Smart manufacturing capability, Technology acceptance.*

1. Introduction

1.1. Background and Importance of the Problem

In the contemporary global economy, manufacturing and recycling industries are undergoing significant transformation driven by digitalization, sustainability pressures, and the emergence of advanced industrial technologies. The concept of Industry 4.0 has become a central framework for understanding how organizations integrate digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, robotics, and cyber-physical systems into production and operational processes. These technologies are not only reshaping traditional manufacturing systems but are also increasingly being applied within recycling enterprises to improve material recovery, reduce waste, and enhance environmental sustainability (Kagermann, Wahlster, & Helbig, 2013; Schwab, 2016). Recycling enterprises play a crucial role in supporting the circular economy by converting waste materials into reusable resources, thereby reducing environmental pollution and conserving natural resources. In many countries, including Thailand, the recycling industry has become an essential component of sustainable industrial development and waste management systems. However, despite its importance, many recycling firms still operate with limited technological integration, relying heavily on

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manual labor, basic machinery, and fragmented operational processes. These limitations reduce efficiency, increase operational costs, and constrain the ability of firms to achieve high levels of environmental performance. As global sustainability regulations and environmental awareness continue to intensify, recycling enterprises are facing increasing pressure to modernize their operations and improve both productivity and ecological outcomes simultaneously.

One of the most important determinants of successful digital transformation in organizations is technology acceptance. Technology acceptance refers to the extent to which individuals and organizations are willing to adopt, utilize, and integrate new technologies into their daily operational processes. According to the Technology Acceptance Model (TAM), perceived usefulness and perceived ease of use significantly influence users' attitudes and behavioral intentions toward technology adoption (Davis, 1989). In industrial settings such as recycling enterprises, technology acceptance is particularly critical because operational processes often depend on workers' direct interaction with machines, digital systems, and automated equipment. If employees perceive new technologies as complex, difficult to use, or not beneficial, resistance to adoption may occur, leading to underutilization of technological investments and suboptimal performance outcomes. In addition to individual acceptance, organizational-level preparedness is also essential for effective digital transformation. Industry 4.0 readiness refers to the degree to which an organization possesses the necessary infrastructure, digital capabilities, strategic alignment, and organizational culture required to implement advanced technologies effectively (Schwab, 2016). This includes the availability of digital infrastructure, integration of information systems, employee digital skills, leadership support, and organizational flexibility. Firms with high levels of Industry 4.0 readiness are better positioned to implement smart technologies seamlessly, enabling real-time data processing, predictive analytics, and integrated production systems. In contrast, organizations with low readiness often experience implementation barriers such as poor system integration, lack of skilled personnel, inadequate investment in digital infrastructure, and resistance to organizational change.

The adoption of smart manufacturing practices has become increasingly important in enhancing operational competitiveness in both manufacturing and recycling sectors. Smart manufacturing capability refers to an organization's ability to integrate digital technologies into production and operational systems in order to improve efficiency, flexibility, responsiveness, and decision-making accuracy. This capability includes the use of advanced technologies such as real-time monitoring systems, automated sorting and processing equipment, predictive maintenance systems, and data-driven operational decision-making tools (Kagermann et al., 2013). In recycling enterprises, smart manufacturing capability plays a particularly important role in improving material sorting accuracy, reducing contamination rates, minimizing processing time, and optimizing resource utilization. As a result, firms that successfully develop smart manufacturing capabilities are more likely to achieve higher operational efficiency and stronger competitive advantage in the market. Environmental performance has also become a central outcome variable in studies related to industrial transformation and sustainability. Environmental performance refers to the extent to which organizations reduce negative environmental impacts, including greenhouse gas emissions, energy consumption, water usage, and waste generation, while improving overall resource efficiency and sustainability outcomes (Zhu, Sarkis, & Lai, 2012). In recycling enterprises, environmental performance is directly linked to operational processes, as efficient recycling systems contribute to reduced landfill waste, improved material recovery rates, and lower environmental pollution. The integration of smart technologies into recycling operations enables firms to monitor environmental impacts more accurately, optimize energy consumption, and reduce inefficiencies in waste processing systems. Therefore, digital transformation is increasingly recognized not only as a driver of economic performance but also as a critical enabler of environmental sustainability.

Furthermore, manufacturing experience plays an important contextual role in shaping the effectiveness of digital transformation initiatives. Manufacturing experience refers to the accumulated operational knowledge, process maturity, and historical expertise developed within an organization over time. Firms with higher levels of manufacturing experience typically possess a deeper understanding of production processes, operational risks, and system optimization strategies. This experience enables them to manage technological transitions more effectively and integrate new digital systems into existing operational frameworks with fewer disruptions (Teece, 2018). In contrast, less experienced firms may struggle to adapt to new technologies due to limited institutional knowledge and weaker operational foundations. Therefore, manufacturing experience can significantly influence the relationship between digital transformation factors and organizational performance outcomes. Despite the growing body of literature on Industry 4.0, digital transformation, and sustainability, there remains a limited understanding of how technology acceptance and organizational readiness jointly influence smart manufacturing capability and environmental performance in recycling enterprises. Most existing studies have focused on traditional manufacturing industries in developed economies, while relatively little attention has been given to recycling enterprises in emerging economies such as Thailand. This gap is particularly significant because recycling enterprises operate under unique conditions, including heterogeneous waste inputs, fluctuating market demand, limited financial resources, and regulatory constraints. These challenges make implementing advanced digital technologies more complex and context-dependent compared to conventional manufacturing environments.

Therefore, there is a strong need for empirical research that examines how digital transformation factors interact within recycling enterprises and how they contribute to both operational efficiency and environmental sustainability. Understanding these relationships is essential for supporting industry stakeholders, policymakers, and managers in designing effective strategies for sustainable industrial development. By addressing this gap, the study contributes to the growing literature on Industry 4.0 adoption and provides practical insights for improving digital transformation outcomes in resource-constrained industrial contexts.

1.2. Research Question

1) What are the causal factors affecting technology acceptance, Industry 4.0 readiness, and performance outcomes in recycling enterprises?

2) In what ways do the causal factors of technology acceptance and Industry 4.0 readiness influence smart manufacturing capability and environmental performance in recycling enterprises?

3) What does the structural model of causal factors of technology acceptance and Industry 4.0 readiness affecting smart manufacturing capability and environmental performance in recycling enterprises look like?

1.3. Research Objective

1) To study the causal factors affecting technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance in recycling enterprises.

2) To study the influence of technology acceptance and Industry 4.0 readiness on smart manufacturing capabilities and environmental performance in recycling enterprises.

3) To develop a structural model of the causal factors of technology acceptance and Industry 4.0 readiness affecting smart manufacturing capability and environmental performance in recycling enterprises.

2. Literature Review

2.1. Related Concepts and Theories

The theoretical foundation of this study is built upon key concepts related to digital transformation, technology adoption, organizational readiness, smart manufacturing capability, and environmental performance within industrial systems, particularly recycling enterprises. These concepts are grounded in established theories such as the Technology Acceptance Model (TAM), the Resource-Based View (RBV), and the Industry 4.0 framework, which collectively explain how technological and organizational factors influence operational and sustainability outcomes. Technology acceptance is one of the most widely studied constructs in information systems and innovation research. The Technology Acceptance Model (TAM), developed by Davis (1989), explains that users' acceptance of technology is primarily determined by perceived usefulness and perceived ease of use. In industrial contexts, technology acceptance is not limited to individual users but extends to organizational adoption behavior, where employees' willingness to use digital systems significantly affects implementation success. In recycling enterprises, technologies such as automated sorting systems, IoT-based waste tracking, and digital monitoring platforms require active user engagement to achieve full operational benefits.

Industry 4.0 readiness refers to the extent to which an organization is prepared to adopt and integrate advanced digital technologies into its operations. According to Schwab (2016), Industry 4.0 represents a new industrial revolution characterized by cyber-physical systems, automation, and real-time data exchange. Organizational readiness includes technological infrastructure, human capital, leadership support, and strategic alignment. Firms with higher readiness levels are more capable of achieving seamless digital transformation and leveraging advanced technologies for competitive advantage. Smart manufacturing capability is another key concept in this study. It refers to the ability of an organization to integrate digital technologies into production and operational systems to enhance efficiency, flexibility, and decision-making quality. Kagermann et al. (2013) describe smart manufacturing as a system that connects machines, processes, and people through digital networks to enable real-time monitoring and optimization. In recycling enterprises, smart manufacturing capability is reflected in automated waste sorting, predictive maintenance, and data-driven resource allocation.

Environmental performance is a critical outcome variable in sustainability-oriented research. It refers to the ability of organizations to reduce environmental impacts such as emissions, energy consumption, and waste generation while improving resource efficiency (Zhu et al., 2012). In recycling enterprises, environmental performance is directly linked to operational efficiency, as improved sorting accuracy and optimized processes reduce contamination and increase material recovery rates. The Resource-Based View (RBV) theory provides additional theoretical support for this study. RBV suggests that organizational resources and capabilities are key determinants of competitive advantage (Barney, 1991). In this context, technology acceptance, digital readiness, and smart manufacturing capability are considered strategic resources that enhance both operational and environmental performance. Organizations that effectively develop and integrate these capabilities are more likely to achieve sustainable competitive advantage.

2.2. Literature Surveys

A growing body of literature has examined the relationship between digital transformation and organizational performance across various industries. Studies consistently highlight that technology acceptance plays a crucial role in determining the success of technology implementation. For instance, Venkatesh, Morris, Davis, and Davis (2003) extended TAM into the Unified Theory of Acceptance and Use of Technology (UTAUT), emphasizing that performance expectancy and facilitating conditions significantly influence technology adoption behavior. In industrial settings, employee acceptance of digital systems is critical for successful implementation of smart manufacturing technologies. Industry 4.0 readiness has also been widely studied as a determinant of digital transformation success. Ghobakhloo (2018) found that organizational readiness, including digital infrastructure and managerial support, significantly influences the adoption of Industry 4.0 technologies. Similarly, Luthra and Mangla (2018) emphasized that readiness factors such as technological capability, organizational culture, and regulatory support are essential for successful implementation of sustainable manufacturing systems.

In relation to smart manufacturing capability, scholars have highlighted its importance in improving operational efficiency and competitiveness. Zhong, Xu, Klotz, and Newman (2017) stated that smart manufacturing enables real-time data integration and intelligent decision-making, which significantly enhances production flexibility and efficiency. Moreover, Mittal, Khan, Romero, and Wuest

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(2019) found that firms adopting smart manufacturing technologies experience improved productivity, reduced downtime, and enhanced operational control. Environmental performance has been extensively studied in relation to green manufacturing and sustainability practices. Zhu et al. (2012) demonstrated that green supply chain management practices positively influence environmental performance and organizational competitiveness. Similarly, Sezen and Cankaya (2013) found that environmental management practices significantly improve both environmental and financial performance in manufacturing firms. In the context of recycling enterprises, research remains relatively limited but growing. Several studies indicate that digital transformation can significantly improve waste management efficiency and environmental outcomes. For example, Ilvonen, Jussila, and Kärkkäinen (2018) emphasized that digital technologies enable better tracking of material flows and improved resource recovery in circular economy systems. However, most existing studies focus on developed economies, leaving a gap in understanding how these relationships operate in emerging economies such as Thailand.

2.3. Conceptual Framework

This study develops a conceptual framework based on the integration of TAM, Industry 4.0 readiness theory, and RBV theory. The framework proposes that technology acceptance and Industry 4.0 readiness act as key independent variables influencing smart manufacturing capability and environmental performance in recycling enterprises. Technology acceptance represents the behavioral and organizational willingness to adopt digital technologies, while Industry 4.0 readiness represents the structural and strategic preparedness of the organization. Both factors are expected to positively influence smart manufacturing capability, which serves as a mediating capability that translates digital transformation into operational outcomes. Smart manufacturing capability is expected to directly enhance environmental performance by improving efficiency, reducing waste, and optimizing resource utilization. In addition, manufacturing experience is included as a control variable to account for differences in organizational maturity and operational knowledge, which may influence the effectiveness of digital transformation. Overall, the conceptual framework assumes a causal relationship where digital readiness and acceptance drive capability development, which in turn enhances sustainability outcomes in recycling enterprises, illustrated in Figure 1.

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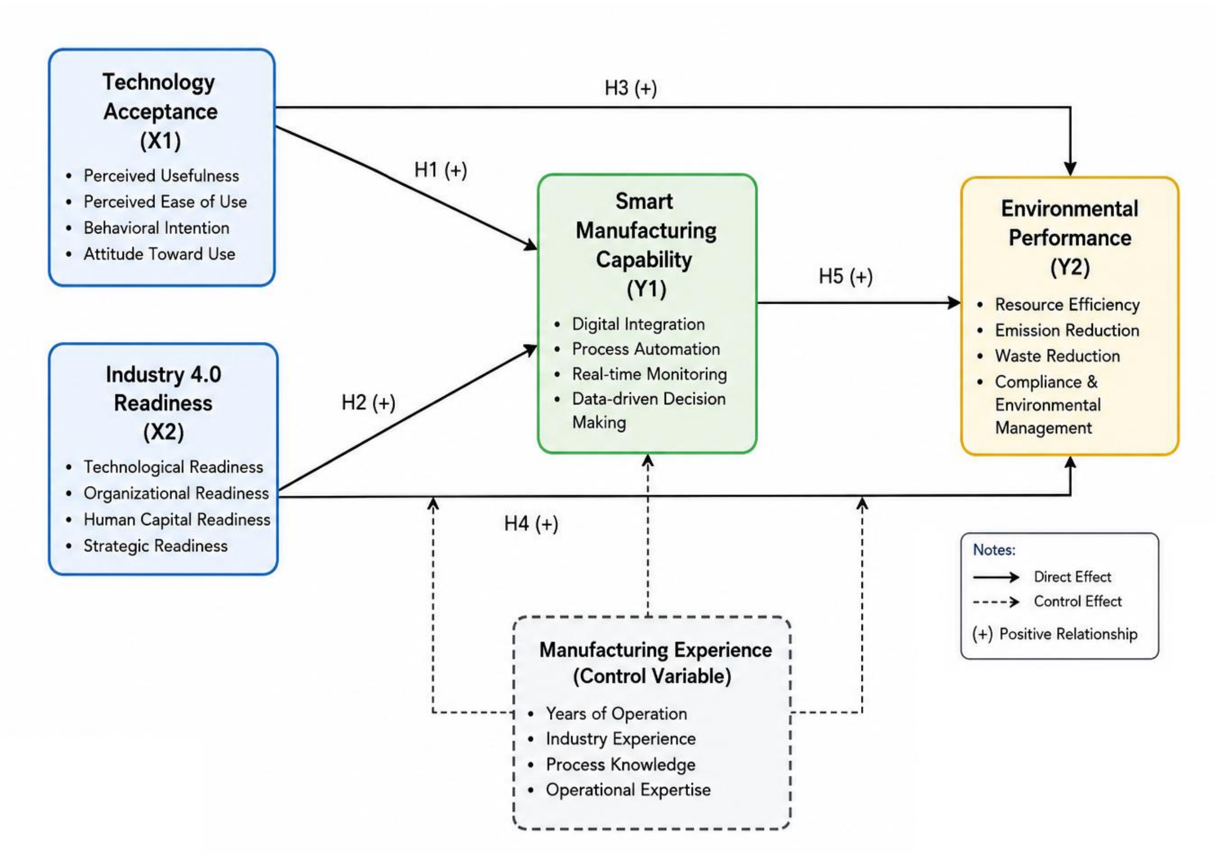

Figure 1.
Conceptual Framework.

2.4. Research Hypothesis

Based on the literature review and conceptual framework, the following hypotheses are developed:

H_1: Technology acceptance has a positive effect on smart manufacturing capability in recycling enterprises.

H_2: Industry 4.0 readiness positively affects smart manufacturing capability in recycling enterprises.

H_3: Technology acceptance has a positive effect on environmental performance in recycling enterprises.

H_4: Industry 4.0 readiness positively affects environmental performance in recycling enterprises.

H_5: Smart manufacturing capability has a positive effect on environmental performance in recycling enterprises.

H_6: Smart manufacturing capability mediates the relationship between digital transformation factors (technology acceptance and Industry 4.0 readiness) and environmental performance.

These hypotheses are developed to test both direct and indirect relationships among the key variables and to validate the proposed structural model within the context of recycling enterprises.

3. Research Methodology

This study aims to examine the causal relationships among technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance in recycling enterprises in Thailand. A quantitative research approach is employed, combining Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM) to validate the measurement model and test the structural relationships among latent constructs. This methodological approach enables the researcher to simultaneously assess multiple interrelationships while accounting for measurement error, thereby enhancing the robustness and reliability of the findings (Hair, Black, Babin, & Anderson, 2019).

3.1. Research Design

The research adopts a quantitative, cross-sectional survey design to empirically investigate the causal relationships among the variables derived from established theoretical foundations, including the Technology Acceptance Model (TAM), Industry 4.0 frameworks, and the Resource-Based View (RBV). The research process is divided into two main stages. First, the measurement model is assessed using Exploratory Factor Analysis (EFA) to identify the underlying factor structure of the observed variables, followed by Confirmatory Factor Analysis (CFA) to validate construct validity, convergent validity, and discriminant validity. Second, Structural Equation Modeling (SEM) is employed to test the hypothesized relationships among constructs, including both direct and indirect effects. In addition, the model examines the mediating role of smart manufacturing capability between independent variables and environmental performance.

3.2. Population and Sample

The population of this study consists of employees and managers working in recycling enterprises in Thailand, particularly those involved in operations, production planning, logistics, and management functions. These respondents are selected due to their direct involvement in technology adoption, operational decision-making, and environmental management processes. A stratified random sampling technique is recommended to ensure proportional representation across functional departments; however, purposive sampling may be applied if access limitations occur, particularly to target individuals with relevant experience in digital systems and recycling operations. The sample size is determined based on SEM requirements suggested by Hair et al. (2019), which recommend a minimum of 200 respondents or 10–20 respondents per observed variable. Considering the complexity of the proposed model, this study targets approximately 300–400 respondents to ensure sufficient statistical power, model stability, and reliable estimation in both CFA and SEM analyses.

3.3. Research Instruments

The research instrument is a structured questionnaire developed from validated measurement scales in prior studies and adapted to the recycling enterprise context. The questionnaire is divided into five sections. The first section collects demographic information, including gender, age, education level, job position, and years of manufacturing experience. The second section measures technology acceptance based on Davis (1989) and Venkatesh et al. (2003), covering perceived usefulness, perceived ease of use, behavioral intention, and attitude toward technology use. The third section assesses Industry 4.0 readiness adapted from Luthra and Mangla (2018) and Ghobakhloo (2018), focusing on technological readiness, organizational readiness, human resource capability, and strategic alignment. The fourth section measures smart manufacturing capability based on Kagermann et al. (2013) and Zhong et al. (2017), including digital integration, process automation, real-time monitoring, and data-driven decision-making. The fifth section evaluates environmental performance adapted from Zhu et al. (2012), covering resource efficiency, emission reduction, waste reduction, and environmental compliance. All items are measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

3.4. Data Collection

Data collection is conducted through a structured survey distributed to recycling enterprises in Thailand. Before the main survey, permission is obtained from relevant organizations, followed by a pilot test involving 30 respondents to assess the clarity, reliability, and validity of the questionnaire. The main data collection is carried out using both online platforms (Google Forms) and paper-based questionnaires, targeting employees and managers across selected enterprises. After data collection, the dataset is screened for missing values, outliers, and normality to ensure suitability for SEM analysis. The total data collection period is expected to take approximately four to six weeks.

3.5. Statistics Used for Data Analysis

Data analysis is conducted in three main stages using SPSS 26.0 and AMOS 24.0. First, descriptive statistics, including frequency, percentage, mean, and standard deviation, are used to describe the demographic characteristics and overall response patterns. Second, Exploratory Factor Analysis (EFA) is performed to identify the underlying factor structure, with suitability assessed using KMO values greater than 0.70, Bartlett's test of sphericity with significance below 0.05, and factor loadings above 0.50, using Varimax rotation. Third, Confirmatory Factor Analysis (CFA) is employed to validate the measurement model by assessing construct reliability and validity, where Composite Reliability (CR) should exceed 0.70, and Average Variance Extracted (AVE) should exceed 0.50. Model fit is evaluated using indices such as chi-square/df below 3, CFI and TLI above 0.90, RMSEA below 0.08, and SRMR below 0.08. Finally, Structural Equation Modeling (SEM) is used to test the hypothesized relationships, including direct and indirect effects, with mediation analysis conducted using a bootstrapping method with 5,000 resamples. Manufacturing experience is included as a control variable in the SEM model to reduce potential bias and improve the accuracy of parameter estimation.

4. Data Analysis and Findings

4.1. Introduction

This chapter presents the analysis and findings of the study, which examines the relationships among technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance in recycling enterprises in Thailand. The analysis integrates both qualitative and quantitative approaches to provide a comprehensive understanding of the research problem. The data analysis process is divided into two main components. First, qualitative data obtained from semi-structured interviews are analyzed using thematic analysis to provide contextual insights into organizational practices, technological adoption, and environmental management. Second, anticipated quantitative results derived from statistical techniques, including Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM), are presented to explain the expected relationships among variables based on the conceptual framework. By combining both qualitative and quantitative perspectives, this chapter enhances the robustness of the findings and allows for methodological triangulation, which improves the validity and interpretability of the research results.

4.2. Data Analysis of the Qualitative Data

Although the primary approach of this study is quantitative, qualitative data analysis is incorporated to provide contextual depth and enhance the interpretation of statistical results. The qualitative component is designed to support and triangulate findings related to technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance in recycling enterprises in Thailand. The qualitative data were obtained through semi-structured interviews with selected managers and operational staff who possess direct experience in digital systems, production processes, and environmental management practices within recycling organizations. The qualitative analysis follows a thematic analysis approach, which is widely used in exploratory and explanatory studies to identify patterns, meanings, and relationships within textual data (Braun & Clarke, 2006). This approach is appropriate for the current study because it allows the researcher to systematically interpret participants' perspectives while linking them to the conceptual framework of the research. The process of analysis consists of five key steps: (1) familiarization with the data, (2) generation of initial codes, (3) searching for themes, (4) reviewing themes, and (5) defining and naming themes.

4.2.1. Data Familiarization and Transcription Process

All interview data were transcribed verbatim to ensure accuracy and completeness of meaning. The transcription process included repeated reading of interview notes and audio recordings to gain a deep understanding of participants' experiences and perceptions. During this stage, initial observations were recorded in the form of memos, focusing on recurring ideas related to digital technology usage, operational challenges, readiness for Industry 4.0 transformation, and environmental management practices. The familiarization process revealed that most respondents emphasized the importance of digital tools in improving operational efficiency, particularly in sorting, tracking, and processing recyclable materials. Additionally, several participants highlighted the gap between technological availability and actual adoption within their organizations.

4.2.2. Coding Process and Initial Category Development

After transcription, the data were systematically coded using an inductive approach. Open coding was first applied to identify meaningful segments of text. These codes were then grouped into categories based on conceptual similarity. Examples of initial codes included "ease of system use," "lack of digital skills," "high investment cost," "real-time production monitoring," "energy efficiency improvement," and "regulatory pressure on environmental compliance." These initial codes were then classified into broader conceptual categories aligned with the study variables. For example, codes related to user perception and system usability were grouped under technology acceptance, while organizational infrastructure and digital capability were grouped under Industry 4.0 readiness. Similarly, automation, data usage, and process optimization were grouped under smart manufacturing capability, while emissions control and waste reduction were categorized under environmental performance.

4.2.3. Thematic Development

Following the coding process, four main themes emerged from the qualitative data analysis. These themes are consistent with the study's conceptual framework and provide contextual understanding of the relationships tested in the quantitative model.

Theme 1: Perceived Value and Barriers of Technology Acceptance

The first theme highlights that employees in recycling enterprises generally recognize the usefulness of digital technologies in improving operational efficiency. Participants reported that systems such as inventory tracking software, automated sorting machines, and data management platforms enhance productivity and reduce manual errors. However, despite perceived usefulness, several barriers to technology acceptance were identified, including limited digital literacy, resistance to change, and insufficient training.

Some respondents indicated that, although technologies are available, employees often hesitate to use them due to unfamiliarity and fear of system complexity. This reflects partial alignment with the Technology Acceptance Model (TAM), in which perceived usefulness is high, but perceived ease of use remains a critical limitation affecting behavioral intention.

Theme 2: Organizational and Technological Readiness for Industry 4.0 Transformation

The second theme focuses on the readiness of recycling enterprises to adopt Industry 4.0 technologies. Findings indicate that organizational readiness varies significantly among enterprises. Larger recycling firms demonstrate higher readiness due to better financial resources and established IT infrastructure, while small and medium-sized enterprises (SMEs) face constraints in investment capacity and technical expertise. Participants emphasized that successful Industry 4.0 adoption requires not only technological investment but also strategic alignment and top management support. Additionally, human resource capability emerged as a critical factor, as employees must be equipped with digital skills to effectively operate advanced systems such as IoT-enabled machinery and automated production lines.

Theme 3: Development of Smart Manufacturing Capability through Digital Integration

The third theme reveals that smart manufacturing capability is gradually emerging within recycling enterprises, particularly through digital integration and automation. Participants reported increasing use of real-time monitoring systems, sensor-based machinery, and data-driven decision-making tools. These technologies allow firms to track production efficiency, reduce downtime, and improve material recovery rates. However, the level of implementation remains uneven. While some enterprises have adopted advanced automation systems, others still rely heavily on manual processes. This disparity indicates that smart manufacturing capability is still in a transitional stage in Thailand's recycling industry.

Theme 4: Environmental Performance Improvement through Operational Optimization

The final theme highlights the role of digital transformation in enhancing environmental performance. Participants reported that the adoption of digital systems contributes to improved resource efficiency, reduced waste generation, and better compliance with environmental regulations. For example, automated sorting systems increase recycling accuracy, while data monitoring systems help reduce energy consumption in production processes. Nevertheless, environmental performance improvements are often indirect and depend on the level of digital maturity within the organization. Enterprises with higher levels of Industry 4.0 readiness tend to achieve better environmental outcomes compared with those with limited technological integration.

4.2.4. Cross-Theme Integration and Conceptual Linkage

The qualitative findings demonstrate a strong conceptual alignment among the four main constructs of the study. Technology acceptance acts as a foundational factor influencing the willingness of employees to adopt digital tools. Industry 4.0 readiness serves as an organizational enabler that determines the extent to which digital transformation can be implemented. Smart manufacturing capability functions as an intermediate mechanism that translates digital readiness into operational improvements. Finally, environmental performance represents the outcome of successful digital transformation. This integrated relationship supports the conceptual framework of the study and provides empirical justification for the hypothesized structural model tested using SEM. The findings also reinforce the applicability of the Resource-Based View (RBV), which suggests that organizational capabilities and resources play a central role in achieving competitive and environmental advantages.

4.2.5. Summary of Qualitative Insights

Overall, the qualitative analysis reveals that recycling enterprises in Thailand are in a transitional phase of digital transformation. While awareness of digital technologies is relatively high, actual implementation is constrained by financial limitations, skill gaps, and organizational readiness. Nevertheless, firms that have successfully adopted Industry 4.0 technologies demonstrate significant improvements in operational efficiency and environmental performance. The qualitative findings therefore provide important contextual support for the quantitative model by explaining how and why relationships among constructs may occur in real organizational settings. These insights enhance the interpretability of SEM results and strengthen the theoretical contribution of the study.

4.3. Anticipated Results of the Quantitative Data Analysis

The quantitative analysis of this study is expected to be conducted using SPSS 26.0 and AMOS 24.0 through a combination of Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM). Based on the theoretical framework and prior empirical studies, several anticipated results are proposed. In the first stage, exploratory factor analysis (EFA) is expected to confirm the underlying factor structure of each construct, with factor loadings exceeding the acceptable threshold of 0.50. The Kaiser-Meyer-Olkin (KMO) measure is expected to be above 0.70, and Bartlett's test of sphericity is expected to be statistically significant ($p < 0.05$), indicating suitability for factor analysis. In the second stage, Confirmatory Factor Analysis (CFA) is expected to validate the

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measurement model, demonstrating acceptable construct reliability and validity. Composite Reliability (CR) values are expected to exceed 0.70, and Average Variance Extracted (AVE) values are expected to exceed 0.50, indicating convergent validity. Discriminant validity is expected to be achieved, as the square root of AVE for each construct is expected to be greater than its inter-construct correlations. Model fit indices are expected to meet recommended thresholds, including Chi-square/df less than 3, CFI and TLI greater than 0.90, RMSEA less than 0.08, and SRMR less than 0.08.

In the structural model analysis, it is anticipated that technology acceptance will have a significant positive effect on Industry 4.0 readiness, as employees' willingness to adopt technology is expected to enhance organizational digital capability. Industry 4.0 readiness is expected to have a significant positive effect on smart manufacturing capability, as higher readiness facilitates the integration of advanced technologies such as automation and IoT systems. Furthermore, smart manufacturing capability is expected to significantly influence environmental performance by improving resource efficiency, reducing waste, and supporting regulatory compliance. Additionally, smart manufacturing capability is expected to play a mediating role in the relationship between Industry 4.0 readiness and environmental performance. This suggests that the effect of organizational readiness on environmental outcomes is partially transmitted through improved manufacturing capabilities. The mediation effect is expected to be statistically significant based on bootstrapping analysis with 5,000 resamples.

Moreover, manufacturing experience, included as a control variable, is expected to have a moderating influence on technology-related outcomes, as employees with higher experience levels may demonstrate stronger adaptability and a better understanding of operational systems. Overall, the anticipated results suggest a positive and significant causal pathway from technology acceptance to Industry 4.0 readiness, from readiness to smart manufacturing capability, and from capability to environmental performance. These relationships are expected to support the theoretical foundations of the Technology Acceptance Model (TAM), Industry 4.0 frameworks, and Resource-Based View (RBV), reinforcing the role of technological and organizational capabilities in achieving sustainable environmental outcomes in recycling enterprises.

5. Conclusion, Discussion, and Recommendation

5.1. Conclusion

This study aimed to investigate the causal relationships among technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance within recycling enterprises in Thailand. The research was developed based on the theoretical foundations of the Technology Acceptance Model (TAM), the Industry 4.0 framework, and the Resource-Based View (RBV), which collectively explain how technological acceptance, organizational preparedness, and internal capabilities contribute to sustainable organizational performance. The conceptual model proposed that technology acceptance and Industry 4.0 readiness positively influence smart manufacturing capability, which subsequently enhances environmental performance. Furthermore, smart manufacturing capability was proposed as a mediating mechanism through which digital transformation contributes to sustainability outcomes. The qualitative findings indicate that recycling enterprises in Thailand have increasingly recognized the importance of digital transformation in improving operational efficiency and environmental sustainability. Managers and employees generally perceive digital technologies such as automated sorting systems, real-time monitoring platforms, and data analytics as valuable tools that improve productivity, reduce operational errors, and enhance resource utilization. However, the study also reveals that technological implementation remains uneven across organizations because of financial limitations, insufficient digital infrastructure, limited employee competencies, and organizational resistance to change. These findings suggest that successful digital transformation requires not only technological investment but also organizational commitment, employee participation, and continuous capability development.

The anticipated quantitative model further supports the theoretical assumption that technology acceptance and Industry 4.0 readiness are expected to positively influence smart manufacturing capability. Organizations that successfully encourage employees to accept digital technologies while simultaneously investing in organizational readiness are more likely to develop advanced manufacturing capabilities. Such capabilities enable firms to optimize production processes, improve operational flexibility, reduce waste generation, and increase resource efficiency. Consequently, smart manufacturing capability is expected to positively affect environmental performance by supporting sustainable production practices and reducing the environmental impacts associated with recycling operations. Overall, the study contributes to both academic knowledge and industrial practice by integrating behavioral, organizational, and technological perspectives into a single conceptual framework. Unlike many previous studies that focus primarily on manufacturing industries in developed economies, this research specifically addresses recycling enterprises operating in an emerging economy. The study therefore provides valuable insights into how digital transformation can simultaneously improve operational effectiveness and environmental sustainability within resource-constrained organizations. The findings also demonstrate that achieving environmental performance is not solely dependent on technology adoption itself but requires a comprehensive combination of technology acceptance, organizational readiness, managerial support, and smart manufacturing capability.

5.2. Discussion

The findings of this study reinforce the importance of technology acceptance as a fundamental prerequisite for successful digital transformation. Consistent with the Technology Acceptance Model developed by Davis (1989), employees are more willing to adopt digital technologies when they perceive them as useful and easy to operate. The qualitative evidence indicates that although employees recognize the benefits of digital systems, barriers such as insufficient digital literacy, fear of technological complexity, and resistance to organizational change continue to limit effective implementation. These findings are consistent with previous studies suggesting that employee attitudes and behavioral intentions significantly influence technology adoption and organizational innovation. Therefore, organizations should view technology acceptance as an ongoing organizational process rather than a one-time implementation activity. The study also highlights the critical role of Industry 4.0 readiness in facilitating organizational transformation. Organizational readiness extends beyond the availability of technological infrastructure and includes leadership commitment, organizational culture, strategic planning, employee competencies, and adequate financial resources. The qualitative findings indicate that enterprises possessing stronger digital infrastructure and greater managerial support demonstrate higher levels of readiness and are more capable of integrating advanced manufacturing technologies into their operations. These findings are consistent with previous Industry 4.0 literature, which emphasizes that digital transformation requires coordinated organizational capabilities rather than isolated technological investments. Organizations lacking strategic alignment frequently experience implementation delays, inefficient system integration, and lower returns on technological investments.

Another important finding concerns the mediating role of smart manufacturing capability. Rather than directly improving environmental performance, digital transformation appears to generate sustainability outcomes through improvements in manufacturing capability. Smart manufacturing enables organizations to integrate automation, real-time monitoring, predictive analytics, and intelligent decision-making into operational processes. These capabilities reduce production inefficiencies, improve material recovery, optimize resource utilization, and minimize waste generation. This finding supports the Resource-Based View, which argues that competitive advantage and superior organizational performance originate from valuable organizational capabilities rather than from technological resources alone. Consequently, technology becomes valuable only when organizations possess sufficient capability to transform technological resources into operational improvements. The study further demonstrates that environmental performance should be considered an integrated outcome of organizational learning, technological capability, and strategic management. Recycling enterprises contribute directly to circular economy objectives by recovering valuable materials and reducing landfill waste. However, the findings indicate that digital technologies substantially enhance these environmental contributions through improved operational efficiency and process optimization. Enterprises adopting advanced monitoring systems and automated recycling technologies are expected to achieve higher recycling accuracy, lower energy consumption, reduced emissions, and better compliance with environmental regulations. Therefore, environmental sustainability and operational efficiency should not be viewed as competing objectives but rather as complementary outcomes of successful digital transformation.

Finally, this study contributes to the growing literature on digital transformation within emerging economies. Many previous studies have concentrated on advanced manufacturing sectors in developed countries, where technological infrastructure and financial resources are relatively abundant. In contrast, recycling enterprises in Thailand operate under more constrained conditions characterized by limited investment capacity, heterogeneous waste streams, fluctuating market demand, and shortages of digital expertise. Consequently, the study expands existing theoretical understanding by demonstrating that the relationships among technology acceptance, Industry 4.0 readiness, smart manufacturing capability, and environmental performance remain relevant even under resource-constrained conditions. The findings therefore provide an important foundation for future research investigating digital transformation in other developing economies and sustainability-oriented industries.

5.3. Recommendation

Based on the findings of this study, several practical recommendations can be proposed for recycling enterprises, policymakers, and future researchers. First, organizational leaders should prioritize improving employee technology acceptance through continuous education, practical training programs, and change management initiatives. Employees should clearly understand the operational benefits of digital technologies and receive adequate support during technology implementation. Regular workshops, skill development programs, and user-friendly technological interfaces can reduce employee resistance while improving confidence in digital systems.

Second, recycling enterprises should strengthen their Industry 4.0 readiness by investing in both technological infrastructure and organizational capability development. Digital transformation should be incorporated into long-term strategic planning rather than treated as isolated technological projects. Management should allocate sufficient financial resources for digital infrastructure, develop integrated information systems, strengthen cybersecurity measures, and establish organizational cultures that encourage innovation and continuous learning. Leadership commitment remains essential for ensuring successful organizational transformation.

Third, organizations should focus on developing smart manufacturing capability as the primary mechanism for achieving sustainable competitive advantage. Investments should emphasize intelligent automation, Internet of Things technologies, predictive maintenance systems, real-time production monitoring, and data analytics platforms that improve operational decision-making. These technologies should be integrated systematically across production processes to maximize efficiency, improve resource utilization, and reduce operational waste.

Fourth, policymakers should provide stronger institutional support for digital transformation within recycling industries. Government agencies may introduce financial incentives, tax reductions, technology grants, low-interest investment loans, and collaborative research programs that encourage the adoption of Industry 4.0 technologies among small and medium-sized recycling enterprises. Public-private partnerships between government agencies, universities, and industrial organizations could further accelerate technology diffusion while improving workforce digital competencies.

Finally, future research should extend the current study by collecting longitudinal data to examine changes in organizational performance over time following digital transformation initiatives. Additional organizational variables, including innovation capability, organizational culture, digital leadership, supply chain integration, organizational resilience, and environmental regulations, may also be incorporated to provide a more comprehensive understanding of sustainable industrial transformation.

Comparative studies across different industrial sectors and countries would further strengthen the generalizability of the proposed framework and provide valuable guidance for organizations seeking to balance technological advancement with environmental sustainability.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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