Appropriate Technology as a Mediator between Knowledge Integration Capability and Circular Economy: Evidence from Resource-Constrained Wood-Processing SMEs in Thailand

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Abstract

This study presents an integrated framework combining the knowledge-based view (KBV) and resource mobilization theory, positioning Appropriate Technology (ATech) as a mediating mechanism that explains how Knowledge Integration Capability (KIC) translates into Circular Economy (CE) outcomes. Unlike prior studies emphasizing high-tech and capital-intensive solutions, this research demonstrates how local knowledge integration enables sustainability through cost-effective ATech adoption in resource-constrained SMEs. Using PLS-SEM with bootstrapping, this study analyzed data from an attempted census of wood-processing SMEs in Surat Thani, Thailand (n = 82), collected in early 2024. The results confirmed that measurement validity, reliability, and model fit met accepted thresholds. The findings show that (1) KIC significantly enhances ATech adoption via effective integration of internal and external knowledge; (2) ATech positively influences CE through sustainable design, collaborative development, and local resource use; and (3) partial mediation occurs, as KIC affects CE both directly and indirectly through ATech. The study extends the KIC concept beyond competitive advantage to sustainability and shows that SMEs can leverage KIC to identify fit-for-purpose technologies, while policymakers can promote capability-building and ATech access programs.

Keywords: 1) Knowledge Integration Capability 2) Appropriate Technology 3) Circular Economy 4) Sustainability 5) SMEs

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Introduction

Knowledge networks have emerged as critical catalysts for organizational transformation. They represent one of the primary mechanisms for fostering collaborative partnerships and facilitating knowledge exchange and creation (Wilke and Pyka, 2024, pp. 1428-1429). Although knowledge management approaches are widely adopted to promote sustainable development (Georgakellos, Agoraki and Fousteris, 2024, p. 2), organizations in emerging economies still struggle to integrate environmental management knowledge with their capabilities and local contexts (Dei, 2024, pp. 113-114). The wood processing industry exemplifies this challenge by generating substantial waste and contributing to air pollution through PM2.5 emissions. These emissions impact respiratory health for workers and communities (Zhou, et al., 2023, pp. 14-15).

Surat Thani Province plays a vital role in Thailand's wood-processing industry, a key contributor to the provincial economy. However, the sector also poses environmental challenges from dust and wood waste. The provincial industrial development plan (2023–2027) addresses these issues by promoting eco-industrial development and circular economy (CE) practices to enhance production efficiency and environmental performance (Provincial Industry Office, Surat Thani, 2022, pp. 1-2). These provincial initiatives are consistent with Thailand's national Bio-Circular-Green (BCG) Economy policy. The policy serves as a strategic model for sustainable growth that enhances resource efficiency and reduces environmental impact (Surat Thani Provincial Office, 2021, pp. 184-186). Rooted in the Sufficiency Economy Philosophy and aligned with the Sustainable Development Goals (SDGs), the BCG policy develops a competitive advantage through science, technology, and innovation (Ministry of Higher Education, Science, Research and Innovation, 2019, p. 11). This study aligns with the BCG agenda by providing empirical insights into how SMEs in the wood-processing industry—particularly in Surat Thani Province—can operationalize these national goals through knowledge integration and appropriate technology (ATech) adoption to achieve circular and sustainable outcomes.

Existing literature reveals three critical research gaps in understanding how resource-constrained SMEs can achieve environmental goals. First, while knowledge management and CE research exist as separate domains, limited studies have examined their intersection, particularly how KIC influences CE in resource-limited contexts. Second, although scholars acknowledge the importance of cost-effective solutions for SMEs, current research predominantly emphasizes high-tech and capital-intensive innovations for CE implementation (Hassler, Krusell and Olovsson, 2022, pp. 15-16). This leaves a theoretical void regarding the role of ATech as a mediating mechanism between knowledge capabilities and environmental practices. Third, despite growing recognition of emerging economies' environmental challenges, empirical evidence remains scarce on how organizations in these contexts can strategically leverage knowledge integration to achieve circularity without substantial financial investments.

This research investigates how local organizations in the Thai wood processing industry can strategically harness their knowledge integration capability to advance CE practices. We focus particularly on SMEs with constrained financial resources. The study specifically examines: (1) the influence of KIC on ATech development, (2) the impact of ATech on CE implementation, and (3) the mediating role of ATech in the relationship between KIC and CE practices. By focusing on Surat Thani province, which exemplifies the challenges of balancing economic growth with environmental conservation in emerging economies, this study addresses the identified theoretical gaps in how KIC influences sustainable technological development through a CE lens.

To address these gaps and contribute to the understanding of sustainable development in resource-constrained environments, this study poses the following research question: How does KIC influence CE practices in resource-constrained wood-processing SMEs, and what is the mediating role of ATech in this relationship?

This study aims to examine the influences among KIC, ATech, and CE in wood-processing SMEs within resource-constrained contexts. It offers three significant contributions that directly address the identified gaps. First, it presents a novel theoretical framework that bridges knowledge management and environmental management literatures by integrating KBV with resource mobilization theory. This integration explains how organizations can leverage knowledge for environmental goals rather than solely competitive advantage. Second, we introduce ATech as a critical mediating mechanism that enables the translation of knowledge capabilities into sustainable practices. This provides an alternative pathway for resource-constrained organizations to achieve circularity. Third, the study provides practical insights for policymakers and SMEs by demonstrating that environmental goals can be achieved through strategic knowledge integration and cost-effective technology development. This offers a viable alternative to expensive innovation investments. The findings contribute to understanding knowledge integration mechanisms in sustainable technological development and offer actionable guidelines for promoting environmental stewardship in resource-constrained environments.

Literature Reviews

This study presents a novel theoretical framework that integrates KBV with resource mobilization theory to explain the conceptual framework. While the KBV highlights knowledge as a key strategic resource, it provides limited guidance on how firms reconfigure such knowledge under dynamic conditions. Resource mobilization theory explains how organizations collect and utilize limited human, financial, and social capital to support their activities. The integration of these theories offers a comprehensive lens for examining how KIC enables the development of ATech solutions that facilitate CE implementation in SMEs facing resource constraints.

Knowledge Integration Capability

Knowledge-based theory establishes that knowledge is an important strategic resource for value creation. Unlike traditional resources, knowledge has the distinctive property of increasing rather than diminishing with use (Usman Shehzad, et al., 2022, pp. 1078-1079). Under the Resource-Based View (RBV), organizations can leverage their resources and capabilities to gain competitive advantage and establish a sustainable market position (Varadarajan, 2023, p. 2). KIC represents an organization's ability to acquire knowledge from external sources and efficiently combine it with existing knowledge to create new knowledge (Liu, 2021, p. 769). This capability qualifies as a VRIN resource because its inherent social complexity—emerging from organizational culture, interpersonal relationships, and trust-based interactions—makes it valuable, rare, inimitable, and non-substitutable.

Drawing from Caccamo, Pittino and Tell's (2022, pp. 4-11) systematic review and RBV, KIC encompasses three sub-capabilities. First, open innovation capability emphasizes collaboration and knowledge sharing between an organization and ecosystem entities, including government agencies, universities, research institutes, industry peers, and communities (Wu, Han and Zhou, 2021, pp. 1-2). Second, cross-functional KIC refers to combining knowledge from different departments and interdisciplinary perspectives for decision-making and goal achievement. This capability focuses on collaboration, coordination, and communication (D'Souza, Bement and Cory, 2022, pp. 118-119). Third, team KIC involves effectively gathering, sharing, and utilizing knowledge resources within teams to handle situations efficiently (Ye and Chen, 2021, pp. 2138-2139).

KIC development occurs at three organizational levels. The micro level emphasizes interpersonal relationships within teams. The meso level addresses systematic processes across organizational units and knowledge networks. The macro level focuses on organizational culture transformation (Krajcsák and Bakacsi, 2024, pp. 641-643). The expected outcomes include product and process innovation development, operational efficiency improvement, and competitive advantage creation. KIC serves as a foundation for developing ATech by providing the knowledge integration mechanisms necessary for local collaboration and technology adaptation. Furthermore, KIC directly influences CE practices by enhancing organizations' ability to absorb and integrate environmental management knowledge from knowledge networks while efficiently disseminating it internally.

Appropriate Technology

ATech is grounded in resource mobilization theory, which explains the process of collecting and leveraging human, financial, and social capital to support organizational activities (Patnaik and Bhowmick, 2019, p. 18). ATech refers to technology tailored to meet the social and economic needs of a region at a specific time and place (Willoughby, 2019, pp. 45-46). The connection between resource mobilization theory and ATech involves four key aspects. These include building local networks for knowledge exchange, leveraging local support policies, managing limited resources efficiently throughout the entire lifecycle while maintaining cost-effectiveness and performance, and building acceptance through local social, economic, and environmental development.

Adaptation from Patnaik and Bhowmick's (2022, pp. 133-134) an exploratory factor analysis (EFA), ATech comprises three key elements. First, sustainable design reflects the balance between cost and efficiency, considering high productivity, durability, job creation, user-friendliness, environmental preservation, and optimal resource utilization (Park and Ohm, 2015, pp. 76-77). Second, collaborative development involves creating appropriate options through community engagement and local networks, including support from government agencies, educational institutions, and business sectors (Ulsrud, Rohracher and Muchunku, 2018, p. 95). Third, local resource utilization promotes the use of local raw materials and personnel to drive the local economy, create jobs, generate sustainable income, and foster relationships and cooperation among the local population while reducing costs.

ATech development relies heavily on knowledge management mechanisms. These include local knowledge identification, knowledge sharing through networks and learning centers, knowledge integration through practice, and knowledge transfer to local communities (Georgakellos, Agoraki and Fousteris, 2024, pp. 5-6). This creates a direct linkage with KIC, as ATech development requires effective integration of internal and external knowledge. ATech serves as a mediating mechanism between knowledge integration and CE implementation by providing cost-effective technological solutions that address environmental challenges while considering local resource constraints. The technology focuses on adapting and improving existing methods rather than creating entirely new innovations, making it suitable for resource-constrained environments.

Circular Economy

The CE framework represents a paradigm shift from linear economic systems that follow a take-make-use-dispose pattern. Instead, it promotes a closed-loop cycle economy that increases opportunities to use limited resources, reduces waste, and creates new value (Zhang, et al., 2021, p. 1). CE aligns with SDG-12.5, which aims to substantially reduce waste generation through prevention, reduction, recycling, and reuse (UN General Assembly, 2017, p. 16). The framework emphasizes circulating products and materials, eliminating or reducing waste and pollution for environmental restoration, and promoting sustainable economic development (Hernández-Arzaba, et al., 2022, pp. 1-2).

This study adopts the 6R mechanism based on Barnabè and Nazir's (2022, pp. 450-451) research, which offers a streamlined yet comprehensive approach particularly suited for SMEs in the wood-processing industry. The six mechanisms include: reduce, which minimizes resource use, emissions, and waste in production and product utilization; reuse, which involves utilizing products, parts, or resources again without reprocessing; recycling, which converts waste materials into new materials or products; remanufacturing, which entails reprocessing or repairing used products to restore components to their original condition; redesign, which focuses on improving product design to better utilize components, materials, and resources; and recover, which involves post-use collection of products to reclaim raw materials for reuse.

CE implementation requires collaboration from multiple stakeholders. Internally, executives and employees must recognize the importance and actively promote environmental initiatives. Externally, cooperation is needed among government agencies, educational institutions, businesses, and communities (Ting, et al., 2024, pp. 1-2; Li and Huang, 2023, pp. 34-37). The framework directly connects to KIC as organizations must absorb and integrate environmental management knowledge to implement CE principles effectively. ATech serves as an enabler for CE implementation by providing cost-effective technological solutions that reduce complexity and increase business profitability while addressing environmental, economic, and social sustainability requirements. The linkage between KIC and CE occurs through the quintuple helix model of collaboration, where knowledge integration among various stakeholders synthesizes and builds organizational knowledge capital for sustainable development.

Hypothesis development

Knowledge-based theory and resource mobilization theory provide the foundation for the relationship between KIC and ATech. KIC serves as a "soft" element that enables the acquisition of local wisdom integration and knowledge-to-practice translation, which influences the development of ATech as a "hard" element (Seyfang and Smith, 2007, pp. 588-589). KIC, particularly through open innovation capabilities, supports organizations in environmental assessment to identify valuable knowledge and technology while conducting parallel research and development (Cordero and Ferreira, 2019, pp. 64-65). Cross-functional and team KIC enhance internal organizational integration through collaborative problem-solving, value creation, and communication. This leads to practical knowledge application and technology development (Acharya, et al., 2022, p. 1; Liu, 2021, pp. 769-770). However, most prior studies have focused on high-technology or radical innovation contexts, providing limited evidence on how KIC fosters ATech development within resource-constrained SMEs. Addressing this gap, this study highlights KIC as a mechanism that transforms integrated knowledge into feasible technological solutions for sustainability. Therefore, this study proposes:

Hypothesis 1 (H1): Knowledge integration capability has a positive effect on appropriate technology.

Resource mobilization theory and design-led repair and reuse (DLRR) framework support the relationship between ATech and CE. ATech reduces technological complexity and increases business profitability while addressing environmental, economic, and social sustainability challenges consistent with CE principles (D'Urzo and Campagnaro, 2023, p. 7; Patnaik and Bhowmick, 2019, pp. 18-19). SMEs face significant financial barriers in implementing CE principles due to high costs of strong processes and cutting-edge technologies (De Vass, et al., 2022, p. 606). ATech provides a cost-effective alternative that enables resource-constrained organizations to implement CE practices through sustainable design, collaborative development, and local resource utilization. This study extends existing literature by emphasizing the adoption of low-cost, context-ATech as practical enablers of CE development. Therefore, this study proposes:

Hypothesis 2 (H2): Appropriate technology has a positive effect on circular economy.

The quintuple helix model of collaboration provides the theoretical foundation for the relationship between KIC and CE. This model emphasizes knowledge integration among government agencies, educational institutions, industrial sectors, environmental agencies, and society to synthesize and build organizational knowledge capital (Eizenberg and Jabareen, 2017, pp. 7-8). SMEs in the wood-processing industry lack knowledge and practical implementation of circularity principles, particularly in utilizing byproducts for business opportunities (de Oliveira, França and Rangel, 2018, pp. 205-207; Chu and Kumar, 2020, p. 1). By developing KIC, organizations can enhance knowledge transfer with networks, combine absorbed knowledge with existing expertise, disseminate knowledge internally, and apply it through product development, process improvement, and management practices while incorporating CE principles (Hernández-Arzaba, et al., 2022, pp. 4-5). Additionally, ATech serves as a mediating variable in this relationship by providing the technological mechanism through which knowledge integration translates into CE implementation. Existing research has not adequately addressed the role of knowledge integration in CE development in resource-limited SMEs. This study advances the literature by investigating ATech as a key mechanism for translating knowledge into practice for circularity outcomes. Therefore, this study proposes:

Hypothesis 3 (H3): Knowledge integration capability has a positive effect on circular economy, and appropriate technology mediates this relationship.

Methods

Sample and Data Collection

This causal research study focused on small and medium enterprises (SMEs) in the wood-processing industry in Surat Thani, Thailand. This Province has been prioritized under the national Bio-Circular-Green (BCG) strategy for its potential to transform agricultural and rubberwood residues into value-added bio-based products. The strategic orientation toward bio-industry and sustainable resource use provides an ideal setting to examine how KIC and ATech drive CE practices among resource-constrained SMEs. The study employed an attempted census approach, targeting all 185 registered wood-processing SMEs in Surat Thani, using company data (names, addresses, and contact information) obtained from the Department of Industrial Works as of December 2023. A total of 82 valid responses were received, representing a realized sample with a response rate of 44.32%.

Sample size calculation was conducted using the inverse square root and gamma-exponential methods (Kock and Hadaya, 2018, pp. 233-237). With a minimum path coefficient of 0.439 at 95% statistical power and 0.05 significance level, the required minimum sample sizes were 57 and 39 samples respectively. This calculation was performed to verify that the collected data would be sufficient for PLS-SEM analysis rather than for sampling purposes, given the census approach.

The survey was conducted between January and February 2024, distributing questionnaires via both postal mail and email with follow-up protocols implemented every two weeks for two rounds. Questionnaires were sent directly to chief executive officers (CEOs) or technicians who had been informed about the research via telephone, as these individuals possess profound understanding of the production processes and organizational capabilities relevant to the study constructs. A systematic follow-up protocol was implemented, with reminder contacts made at two-week intervals to non-responding companies to maximize response rates while maintaining data quality.

Although the achieved response rate was acceptable for SME studies, potential non-response bias was assessed by comparing early and late respondents. Specifically, the first 30 and final 30 responses were statistically compared, and no significant differences were found across key indicators, confirming the absence of non-response bias. Notably, no missing or incomplete data were identified in the collected responses; however, representativeness may still be limited due to the partial response rate. Further comparison with non-responding firms was not possible due to the lack of detailed firm-level data in the public database. This limitation is acknowledged in interpreting the results.

Measurement Instruments

The research instrument was a structured questionnaire that underwent rigorous content validity verification by five experts from diverse fields—two in knowledge management, one in engineering, one in sustainability management, and one in business development. Content validity was assessed using the Index of Item-Objective Congruence (IOC) method, with a minimum acceptance criterion of 0.5 (Turner and Carlson, 2003, p. 169). Items with an IOC score of 0.5 or higher were considered acceptable for inclusion in the final questionnaire, ensuring theoretical alignment and practical relevance.

A pilot test was conducted with thirty para processing companies in Surat Thani province to examine reliability using Cronbach's alpha coefficient, with a threshold value of 0.8 indicating acceptable reliability. The analysis revealed that all constructs demonstrated alpha coefficients above the threshold, confirming the instrument's reliability. Consequently, no questionnaire modifications were necessary for the main data collection phase.

The questionnaire comprised four sections: Section 1 covered company and respondent information; and Sections 2-4 contained the main research constructs corresponding to each variable under study. All construct items were measured on a 5-point Likert scale, with scores ranging from 1 (strongly disagree) to 5 (strongly agree).

The constructs were adapted from established literature to ensure theoretical grounding and measurement validity. KIC indicators were developed by reviewing Caccamo, Pittino and Tell's (2022, p. 7) work. ATech indicators were improved from Patnaik and Bhowmick's (2022, p. 134) work. CE indicators were adapted from Barnabè and Nazir's (2022, p. 452) work.

Data Analysis

This study utilized Partial Least Squares Structural Equation Modeling (PLS-SEM) through SmartPLS version 4.1.1.2, selected because the research model focuses on mediation analysis and prediction-oriented relationships among latent constructs, and the sample contained fewer than 200 observations (Guenther, et al., 2023, pp. 131-132).

Data quality assessment included examination of missing data, outliers, and normality tests. No issues were identified in these areas, confirming data suitability for structural equation modeling.

The analysis proceeded in two stages following established PLS-SEM procedures. First, evaluation of the reflective measurement model was conducted by examining factor loadings, internal consistency reliability, convergent validity, and discriminant validity. Second, assessment of the structural model was performed by evaluating multicollinearity issues, in-sample prediction, out-of-sample predictive power, and goodness of fit test.

Path analysis was conducted to examine direct relationships among constructs, while mediation analysis was performed to assess the mediating role of ATech in the relationships between other variables. All analyses employed bootstrapping with 5,000 sub-samples to determine the significance of path coefficients. Hypothesis testing was conducted by examining the direction and statistical significance of path coefficients.

Results and discussion

Sample Characteristics

The final sample comprised 82 respondents from wood-processing SMEs in Surat Thani, Thailand. Chief executive officers (CEOs) represented the majority of respondents (58.54%), while technicians accounted for 41.46%.

Regarding business operations, pressed wood production constituted the largest segment at 51.22%, followed by biomass pellets at 17.07%. Wood sawing and planning operations, along with furniture production, each represented 12.20% of the sample, while particle board production from rubber wood comprised 7.31%.

In terms of operational tenure, companies with less than 10 years of experience represented 39.02% of the sample. Organizations operating between 10 to 20 years constituted 29.27%, while companies with more than 20 years of operation accounted for 31.71% of the sample.

Measurement Model Assessment

Before assessing the measurement model, potential common method bias (CMB) was examined. The full collinearity test was applied to assess CMB. The variance inflation factors (VIFs) of all latent constructs ranged from 1.780 to 4.932 (Table 1). Several indicators slightly exceeded the conservative threshold of 3.3; however, Kock (2015, pp. 8-9) noted that when factor-based PLS-SEM algorithms are used, VIF values up to 5.0 can be considered acceptable because these algorithms account for measurement error. Therefore, CMB was not regarded as a critical issue in this study.

The reflective measurement model assessment (Table 1) demonstrated satisfactory reliability and validity. All outer loadings exceeded the 0.700 threshold, indicating adequate item reliability. Internal consistency was confirmed through multiple measures: Cronbach's alpha, rho_A, and composite reliability (rho_c) all surpassed the acceptable criterion of 0.7.

Convergent validity was established with Average Variance Extracted (AVE) values exceeding 0.50 for all constructs. Discriminant validity was confirmed using the Heterotrait-Monotrait (HTMT) criterion, with all ratios below the conservative threshold of 0.85. These results collectively demonstrate that the measurement model meets established quality criteria (Hair, et al., 2024, p. 93), providing a solid foundation for structural model analysis.

Table 1 Assessing the reflective measurement and VIF.

Constructs/ Indicators	Outer loading	Alpha	rho_A	rho_c	AVE	HTMT	VIF
KIC		0.880***	0.888***	0.927***	0.808***	ATech=0.845 CE=0.837	
KIC_1	0.832***						1.892
KIC_2	0.945***						4.363
KIC_3	0.916***						3.575
ATech		0.865***	0.880***	0.917***	0.788***	CE=0.846	
ATech_1	0.921***						2.801
ATech_2	0.830***						1.818
ATech_3	0.909***						2.731
CE		0.916***	0.934***	0.935***	0.709***		
CE_1	0.902***						3.760
CE_2	0.785***						1.945
CE_3	0.909***						4.621
CE_4	0.925***						4.932
CE_5	0.702***						1.780
CE_6	0.805***						2.270

Note: *** $p < 0.001$, one-tailed test; Alpha = Cronbach's Alpha; rho_A = Construct Reliability Coefficient; rho_c = Composite Reliability; AVE = Average Variance Extracted; HTMT = Heterotrait–Monotrait Ratio; VIF = Variance Inflation Factor.

Structural Model Assessment

The structural model evaluation revealed no multicollinearity concerns, as all Variance Inflation Factor (VIF) values remained below the critical threshold of 5.0 (Guenther, et al., 2023, p. 134) (Table 1). This confirms that the predictor variables are sufficiently distinct and do not exhibit problematic overlap.

The model's explanatory power, assessed through R^2 and adjusted R^2 values (Table 2), demonstrated moderate predictive capability for all endogenous constructs. Out-of-sample predictive power was evaluated using PLSpredict procedures, comparing Root Mean Square Error (RMSE) between the PLS-SEM model and a naïve benchmark. Results indicated high predictive power for ATech and medium predictive power for CE. All $Q^2_{predict}$ values were positive, confirming that the model performs better than the naïve benchmark (Shmueli, et al., 2019, pp. 2328-2330).

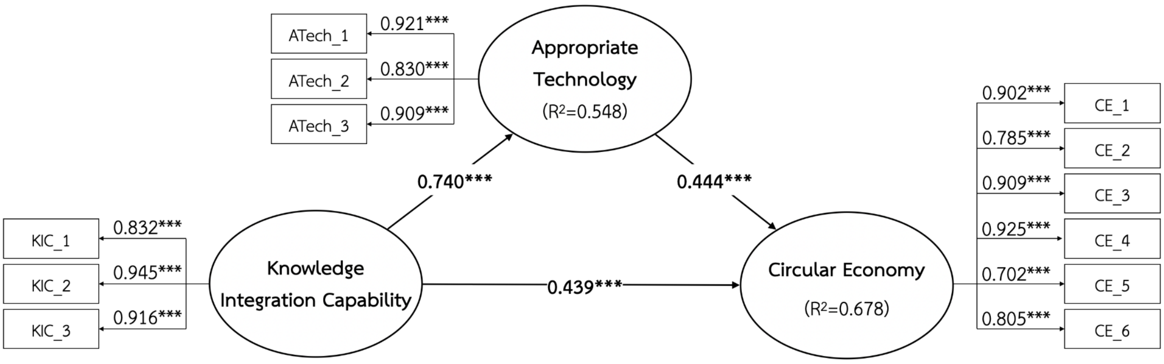
Overall model fit was assessed using the Standardized Root Mean Square Residual (SRMR), which yielded a value of 0.068. This falls well below the acceptable threshold of 0.08 (Hair, et al., 2022, p. 113), indicating good model fit. The significance of these fit indices was confirmed through bootstrap validation with 5,000 subsamples. One-tailed significance testing was applied because all hypotheses were directional, predicting positive relationships among constructs, consistent with prior theoretical expectations (Hair, et al., 2022, pp. 259-260).

These comprehensive assessments demonstrate that the structural model is robust and suitable for hypothesis testing. The model exhibits both adequate explanatory power and reliable predictive validity, supporting confidence in the theoretical relationships proposed in this study.

Table 2 Assessing the structural model.

Constructs/ Indicators	R^2	Adjusted R^2	$Q^2_{Predict}$	PLSpredict	
				RMSE (PLS-SEM)	RMSE (LM)
ATech	0.548 (Moderate)	0.542 (Moderate)		High predictive power (All indicators of PLS-SEM are less than LM)	
ATech_1			0.501	0.475	0.486
ATech_2			0.298	0.651	0.663
ATech_3			0.425	0.546	0.561
CE	0.678 (Moderate)	0.670 (Moderate)		Medium predictive power (The number of indicators PLS-SEM less than LM equals PLS-SEM greater than LM)	
CE_1			0.550	0.484	0.494
CE_2			0.453	0.478	0.476
CE_3			0.509	0.519	0.516
CE_4			0.434	0.555	0.552

Constructs/ Indicators	R^2	Adjusted R^2	$Q^2_{Predict}$	PLSpredict	
				RMSE (PLS-SEM)	RMSE (LM)
CE_5			0.149	0.596	0.600
CE_6			0.259	0.620	0.639



Note: *** p<0.001, one-tailed test. (bootstrapping, 5,000 subsamples); Values next to the observed indicators represent outer loadings. Values on the arrows between latent constructs represent standardized path coefficients. Values in parentheses inside circles indicate R^2 for endogenous constructs.

Figure 1 Results of the structural model.

Path Analysis

The analysis of relationships among constructs, as presented in Figure 1 and Table 3, revealed that all direct effects between constructs were positive and statistically significant. In particular, KIC significantly influenced ATech (Beta = 0.740, $p < 0.001$), supporting H1, which strongly indicated that firms with stronger KIC were more capable of developing and adopting ATech. In addition, ATech significantly influenced CE (Beta = 0.444, $p < 0.001$), supporting H2, which indicated that ATech adoption facilitated CE approaches among resource-constrained SMEs. Furthermore, KIC directly influenced CE (Beta = 0.439, $p < 0.001$), supporting H3, which indicated that an organization's KIC enhanced sustainable performance through knowledge-to-practice support. The f^2 values indicate that KIC exerts a large and significant effect on ATech (f^2 = 1.213, $p < 0.05$), while both ATech → CE (f^2 = 0.278, $p > 0.05$) and KIC → CE (f^2 = 0.270, $p > 0.05$) show moderate yet nonsignificant effect sizes. This suggests that the primary influence of KIC on CE occurs indirectly through ATech rather than directly. The indirect effect was significant (Beta = 0.329, $p < 0.001$), confirming that ATech acts as an important transmission mechanism translating KIC into CE outcomes. The mediation analysis examining the role of ATech demonstrated a complementary (partial mediation) pattern. This finding validates that both direct and indirect pathways simultaneously contribute to achieving sustainability. All effects, including direct, indirect, and total effects, achieved statistical significance, confirming the robust mediating role of technology adoption in transforming knowledge integration capabilities into CE outcomes.

Table 3 Structural model and hypothesis results.

Hypotheses	Influences	Results	Direct effects	Indirect effects	Total effects
H1	KIC → ATech	Supported	0.740*** (f^2 = 1.213*)	-	0.740***
H2	ATech → CE	Supported	0.444*** (f^2 = 0.278)	-	0.444***
H3	KIC → CE	Supported	0.439*** (f^2 = 0.270)	0.329***	0.768***

Note: *** $p < 0.001$, * $p < 0.05$, one-tailed test.

Conclusion and Discussion

This study enhances understanding and provides empirical evidence regarding the knowledge integration processes for developing ATech and circular economy practices, while addressing the established research questions. The researchers offer insights on theoretical and practical contributions in the following discussion.

Theoretical Contributions

This research bridges a crucial gap between knowledge management theory and sustainability practices by presenting a comprehensive framework within resource-constrained contexts. The theoretical contributions can be summarized in five key areas that advance our understanding of KIC and environmental sustainability.

First, this study advances theory integration by synthesizing distinct theoretical perspectives including KBV, RBV, resource mobilization theory, and environmental management theory. Our integration creates a novel theoretical bridge through the knowledge management-technology-sustainability framework, which distinguishes itself from existing literature through its unique theoretical foundations and conceptual underpinnings. This framework demonstrates how organizational knowledge can simultaneously build competitive advantage and sustainability performance.

Second, by examining the knowledge integration process through an organizational capability lens via RBV, this study introduces a new perspective on KIC development. This perspective demonstrates that KIC can be developed into a VRIN resource, rather than being merely one of many knowledge management processes. Through this lens, organizations can systematically develop, measure, and institutionalize knowledge integration capabilities within their organizational culture, establishing KIC as a distinct organizational capability that warrants further theoretical investigation and development (Varadarajan, 2023, pp. 2-3).

Third, this study extends KBV beyond its traditional focus on competitive advantage through knowledge resources to encompass sustainability development support. The findings align with KBV, which positions knowledge as a strategically significant resource for competitive advantage (Rana and Youn, 2024, p. 534). Our framework demonstrates how knowledge integration processes can simultaneously create competitive advantages and environmental benefits, challenging the conventional view that these objectives are mutually exclusive.

Fourth, the findings confirm that sustainable competitive advantage can be achieved through local knowledge integration. By applying appropriate technologies developed from local knowledge, organizations can enhance their operational efficiency and develop environmental management outcomes, even under resource constraints. This finding supports previous empirical evidence showing the link between knowledge integration and technological and innovation outcomes (Cordero and Ferreira, 2019, p. 65; Liu, 2021, p. 2) and confirms that effective knowledge management processes—knowledge acquisition, integration, and creation—are the cornerstone of technological progress (Yin et al., 2024, p. 2756).

Fifth, this study validates resource mobilization theory's assertion that goal achievement depends on acquiring and utilizing essential resources. We extend this theory by demonstrating how intangible knowledge resources can be effectively combined with tangible technological resources to achieve sustainability goals in resource-constrained contexts. These contributions collectively advance theoretical understanding of how organizations can leverage KIC to achieve environmental sustainability despite resource constraints.

Practical Contributions

This research demonstrates that KIC supports the development of ATech and CE practices to enhance environmental sustainability through 6R activities (Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture). The practical implications provide actionable guidance for organizations seeking to leverage knowledge integration for sustainability outcomes.

To strengthen KIC, organizations should follow three key steps. First, develop comprehensive knowledge management processes by identifying experts (tacit knowledge) and knowledge sources (explicit knowledge), designing and implementing activities to facilitate knowledge transfer and learning cross-functionally and within teams, and promoting knowledge integration and application in areas such as new product design and process improvement. Organizations can leverage information technology to support these processes, thereby enhancing the efficiency of knowledge management processes in terms of speed of knowledge exchange and distribution and the effectiveness of knowledge application.

Second, participate in collaborative networks with government agencies, educational institutions, businesses, environmental units, and communities. This creates opportunities for knowledge transfer and absorption, expanding vision, and integrating external knowledge with existing knowledge to keep pace with rapidly changing business environments. While building such networks, organizations should be prepared to address trust issues, intellectual property concerns, and potential conflicts of interest.

Third, develop KIC as a core organizational capability with VRIN characteristics. Organizations must systematically and continuously incorporate this capability into their organizational culture, align it with organizational strategies and goals, and regularly monitor and evaluate its performance. Through the lens of the SECI model, KIC accelerates the transformation between explicit and tacit knowledge through socialization, externalization, combination, and internalization processes (Nonaka and Takeuchi, 2020, pp. 59-63). This supports research findings that KM plays a critical role in CE development by leveraging internal knowledge resources and enhancing organizational learning capabilities (Ul-Durar, et al., 2023, p. 2235). Similarly, effective KM supports CE implementation by enabling organizations to create innovation, share best practices, and optimize resource utilization (Van Luu and Chromjaková, 2024, pp. 12567-12568). This aligns with research emphasizing knowledge as a key factor in implementing CE practices through improved resource efficiency and waste reduction (Zwiers, Jaeger-Erben and Hofmann, 2020, p. 122). Success can be measured through Key Performance Indicators (KPIs) such as speed of knowledge management processes, diversity of knowledge acquired from collaborative networks, number of new ideas generated from internal and external knowledge integration, application of knowledge to improve operations or performance, and employee participation in knowledge management activities.

Organizational knowledge can be leveraged to develop ATech and enhance environmental sustainability through CE practices via three approaches. First, organizations should design technology with sustainability in mind, considering environmental (waste, pollution, resource reduction), economic (efficiency, cost, durability), and social (community problem-solving, job creation) dimensions. This approach, which differs from traditional technology development that primarily focuses on efficiency, takes into account the broader impacts of technology on society, environment, and economy. The findings align with research on integrating technological and social strategies to support sustainable management (Adisa, Oyedeji and Porras, 2024, p. 2) and support the DLRR framework for applying the ATech concept to reduce technological complexity and create higher-quality processes and products from circular manufacturing activities (D'Urzo and Campagnaro, 2023, p. 1). This is consistent with approaches to leveraging technology for resource efficiency under CE principles (Neri, et al., 2023, pp. 4700-4701).

Concrete examples from the wood-processing industry include dust management technology that converts wood dust into bio-pellets or charcoal briquettes for fuel and water treatment applications, while also transforming it into agricultural materials such as soil conditioners and growing media. This aligns with sustainable design principles that emphasize efficiency and cost considerations while incorporating 6R principles into the design process. Additionally, sawing technology adapted for rubber wood's specific characteristics has resulted in approximately 50-70% reduction in wood waste through specially designed saw blades and wood-holding systems.

Second, organizations should collaborate with local sectors to foster mutual understanding and knowledge exchange. This can involve participating in community forums, joining knowledge networks, cooperating with educational institutions for technology development, and partnering with government agencies through knowledge transfer activities and memorandums of understanding. The effectiveness of these collaborations may vary depending on factors such as industry type, organizational size, inter-organizational relationships, and government support policies.

Third, organizations should consider utilizing local raw materials and personnel to stimulate the local economy and potentially reduce the cost of building ATech (Patnaik and Bhowmick, 2022, p.126). Integrating local businesses into the supply chain facilitates resource exchange and income distribution within the community. However, cost considerations may depend on local conditions and readiness, requiring organizations to assess the cost-effectiveness on a case-by-case basis.

The long-term implications of ATech adoption require consideration of moderating factors including organizational environmental and sustainability awareness, government support policies regarding technical assistance and knowledge transfer, business environment affecting network collaboration, entrepreneur-community relationships, local resource availability and supply chain systems, and organizational technology acceptance. These factors align with research identifying key CE implementation challenges including high development costs, knowledge and technological limitations, policy and incentive issues, organizational acceptance, continuity barriers, and leadership vision (De Vass, et al., 2022, pp. 604-605).

Government agencies play a crucial role in building environmental sustainability awareness and providing support through active public relations, education, collaboration building, establishing cooperation networks for best practice exchange, setting up expert consulting centers, creating tax incentives, and implementing environmental regulations. By adopting these approaches, organizations can create a virtuous cycle where improved sustainability practices lead to increased efficiency, reduced waste, and enhanced community relations, ultimately resulting in long-term economic benefits and a stronger competitive position in the market.

In the context of Thai SMEs, particularly the wood processing industry in Surat Thani Province, the study findings can support the country's BCG economic policy and the province's regional development strategy. These strategies aim to drive the bio-industry by adding value to resources from agricultural and wood waste, while maintaining environmental sustainability and quality of life. They also confirm that the sustainability achievement of Thai SMEs is a process that integrates economic, social, and environmental dimensions within the local development ecosystem.

Limitations and future research

The present study has five key limitations. Firstly, the cross-sectional design prevents capturing long-term changes in variables over time. Secondly, the research methodology was limited to quantitative approaches, lacking qualitative insights that could provide deeper understanding of the phenomena.

Thirdly, the sample size was relatively small (82 respondents) due to companies' reluctance to share corporate information. Furthermore, since the overall response rate was 44.32% and firm-level information for non-respondents was unavailable for comparison, the representativeness of the findings may be limited. Fourthly, data collection from single respondents per organization may have introduced single respondent bias. Finally, contextual differences may limit the generalizability of findings across different settings.

Future research opportunities emerge from these limitations. We recommend six key research directions. Firstly, conducting longitudinal studies to track the evolution of relationships between variables over time. Secondly, expanding research to different industries and geographical areas to validate the model and enable comparative analysis. Thirdly, examining moderating factors such as government policies, organizational culture, and location-specific characteristics to enhance understanding of contextual influences. Fourthly, for KIC, synthesizing development processes and analyzing both enabling factors and barriers to development. Fifthly, regarding ATech, investigating long-term environmental, economic, and social impacts through comprehensive impact assessment studies. Finally, future studies could extend this framework into the strategic management domain by exploring how knowledge integration and appropriate technology interact with dynamic capabilities, strategic alignment, and innovation governance, thereby clarifying their roles as strategic levers for sustainability-oriented competitiveness.

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Appendix. Finalized Measurement Items

Knowledge Integration Capability (Caccamo, Pittino & Tell, 2022)

KIC_1: In our company, we exchange and share knowledge effectively with external partners such as government agencies, universities, and communities.

KIC_2: In our company, departments coordinate and communicate to integrate knowledge for problem-solving and decision-making.

KIC_3: In our company, teams share and apply knowledge collaboratively in their work.

Appropriate Technology (Patnaik & Bhowmick, 2022)

ATech_1: In our company, we design or adapt technology with consideration for cost efficiency, productivity, and environmental sustainability.

ATech_2: In our company, we co-develop technology or equipment in collaboration with government agencies, universities, or other companies.

ATech_3: In our company, we use local materials and labor when developing or improving technology and equipment.

Circular Economy (Barnabè & Nazir, 2022)

CE_1: In our company, we reduce waste in production processes.

CE_2: In our company, we reduce emissions that harm the environment.

CE_3: In our company, we reuse materials and resources in production.

CE_4: In our company, we support recycling and material-recovery activities.

CE_5: In our company, we repair or remanufacture products for reuse.

CE_6: In our company, we redesign new products to utilize components from used or discarded products.