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Farmers' Knowledge Gaps in Irrigation Modernization: A SECI Model Approach in the Krueng Aceh Region

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ABSTRACT

The modernization of irrigation systems requires farmers to manage knowledge effectively, adapt to technological changes, and participate actively in increasingly complex institutional arrangements. This study analyzed farmers' knowledge gaps (K-Gap) and the knowledge transformation process using the SECI model in the Krueng Aceh region. A descriptive mixed-methods approach was applied through interviews, observations, questionnaires, and documentation. Quantitative analysis using PLS-SEM assessed inter-variable relationships, while K-Gap and IPA identified priority knowledge areas. All constructs met validity and reliability requirements, with Composite Reliability values ranging from 0.835 to 0.982 and AVE values between 0.559 and 0.933. The conformity level of 99.32% indicated strong alignment between farmers' perceptions and expectations of institutional performance. K-Gap analysis showed that infrastructure had the highest knowledge gap (0.05), while water management had the lowest (0.02). The integrated results of IPA and SECI revealed strengths in the socialization and internalization stages, indicated by active participation, mutual cooperation, and consistent water distribution, while weaknesses were concentrated in the externalization and combination stages, particularly in documentation and knowledge integration. Therefore, strengthening SECI-based knowledge management is recommended, with emphasis on improved documentation, technical capacity building, and more effective support systems to ensure the sustainability of irrigation modernization in the Krueng Aceh.

1. INTRODUCTION

Modernizing irrigation systems is one of Indonesia's national strategic priorities to enhance water distribution efficiency, strengthen food security, and support sustainable agriculture (Asian Infrastructure Investment Bank, 2022; Kementerian Pertanian RI, 2024; World Bank, 2018). Irrigation modernization should be understood not merely as the upgrading of irrigation systems, but as a broader transformation of irrigation systems that includes physical infrastructure, institutional arrangements, participatory management, human resource readiness, and the use of emerging technologies. In the Krueng Aceh region, these modernization efforts are reflected in strengthened institutional collaboration, improved infrastructure performance, and enhanced water distribution practices. This research focuses not only on physical infrastructure upgrades but also on participatory management and human resource readiness.

Farmer readiness, in both knowledge and skills, is central to the success of irrigation modernization. Transformation depends not only on the performance of infrastructure but also on farmers' capacity to understand, accept, and adapt to innovation, given their critical role in water allocation and field-level operations (Kusumastuti *et al*., 2021). In this context, accurate and data-driven decisions are essential to ensure efficient and coordinated irrigation management and sustainable agricultural systems (Zhao *et al*., 2023).

However, most farmers' knowledge remains tacit, embedded in personal experience and rarely documented, thereby limiting transparency, collaboration, and (Hörner *et al*., 2022; Jalotjot & Tokuda, 2024; Flores López *et al*., 2020; Phu, 2023; Playán *et al*., 2018; Tumwebaze *et al*., 2022, 2025). Knowledge gaps are hindering innovation adoption in many developing regions, often due to limited information flow and insufficient mechanisms for knowledge transfer (Hörner *et al*., 2022; Phu, 2023; Playán *et al*., 2018).

Consequently, knowledge management (KM) becomes essential for strengthening farmers' social learning, accelerating knowledge transfer, and supporting data-driven decision-making (Tumwebaze *et al*., 2025). KM in agricultural organizations requires adaptive approaches that consider farmer heterogeneity and resource constraints (Buitendag & Hattingh, 2024; López-Meza *et al*., 2024). It shifts development agendas from resource-based to knowledge-based strategies, emphasizing continual learning and effective information management.

The SECI model proposed by Nonaka & Takeuchi (1995) offers a robust conceptual foundation for understanding processes of knowledge transformation. Through its four stages, socialization, externalization, combination, and internalization, the model explains how tacit knowledge is shared, articulated, integrated with formal references, and embedded into practice (Dalkir, 2005; Jalotjot & Tokuda, 2024; Tumwebaze *et al*., 2025). Erden *et al*. (2008) emphasize that the quality of group knowledge improves through trust, intensive communication, and collective action under conditions of uncertainty. Within this context, P3A/GP3A functions as a platform for collective knowledge creation, enabling farmers to exchange experiences, improvise, and build shared understanding. This aligns with Ayele & Wield (2005), who highlight that community-based knowledge-sharing mechanisms accelerate capacity building, strengthen innovation systems, and facilitate the adoption of new agricultural technologies.

Empirical studies demonstrate that SECI-based approaches enhance knowledge conversion, strengthen adaptability, and broaden collaborative learning systems within agricultural systems (Erden *et al*., 2008; Jalotjot & Tokuda, 2024). Institutional arrangements are equally critical, as emphasized by Chuang (2004), who noted that effective knowledge linkages between technical procedures and social practices are essential for sustaining knowledge transfer in community-based irrigation systems. Thus, integrating the SECI model into irrigation modernization can help bridge knowledge gaps, improve farmer readiness, and reinforce institutional capacity for sustainable water resource management.

This research aims to assess farmers' knowledge gaps and develop a SECI-based KM strategy to support water resource management in the modernization of irrigation systems in the Krueng Aceh region. Ultimately, farmers' knowledge represents a key asset for innovation, while collective learning through P3A and GP3A plays a critical role in transforming individual experiences into shared knowledge that sustains irrigation modernization.

2. MATERIALS AND METHODS

This study was conducted in 2025 in the Krueng Aceh Irrigation Area, Aceh Province, one of Indonesia's national pilot regions for irrigation modernization. Sampling was concentrated in the secondary channels of Blang Bintang and the DI Krueng Jreue area to capture variations in network conditions and farmer institutional arrangements. The site was selected due to its integration of technical and institutional components within a participatory modernization program. The study respondents included 53 respondents, including managers of the UPTD in Krueng Aceh region, farmers, and members of P3A/GP3A. Respondents were selected using purposive sampling based on their active involvement in irrigation management activities and farmer institutions.

A five-point Likert-scale questionnaire was developed based on Permen PUPR No. 12/2015, FAO Benchmarking Irrigation & Drainage, and the Rapid Appraisal Procedure (RAP) for assessing the Irrigation Management Performance Index (IKMI). The questionnaire collected data on five pillars of irrigation modernization, namely water availability, infrastructure, irrigation water management, institutions, and human resources. Data collection involved distributing questionnaires, conducting in-depth interviews, and engaging in participatory observation. A mixed-methods approach was employed, in which qualitative analysis mapped knowledge flows using the SECI model, while quantitative analysis evaluated importance and mastery using the Importance–Performance Analysis (IPA) and Knowledge Gap (K-Gap) frameworks (Martilla & James, 2010; Nonaka & Takeuchi, 1995; Playán *et al*., 2018).

Reliability and convergent validity were assessed using SmartPLS 3.3 (Hair *et al*., 2021a) to ensure construct consistency within the Partial Least Squares Structural Equation Modelling (PLS-SEM) framework. The selection of PLS-SEM is supported by studies of Farmer Producer Organizations (FPOs), which share participatory and collective resource-management characteristics with P3A/GP3A, and because PLS-SEM is robust for moderate sample sizes, non-normal data, and complex mediation structures (Veesam *et al*., 2025). The K-Gap analysis was performed by averaging importance and mastery scores to evaluate knowledge alignment and the role of KM in farmers' learning processes. Construct validity was examined through expert judgement, while reliability testing employed Cronbach's alpha and corrected item–total correlation following standard PLS-SEM procedures (Hair *et al*., 2014b; Tavakol & Dennick, 2011).

The SECI model served as the analytical framework for knowledge transformation: socialization captured tacit knowledge; externalization articulated it into indicators and documents; combination integrated it with formal references (Burt, 2002; Cornish, 2005; Kementerian PUPR, 2015); and internalization applied the recommendations in field practices (Buitendag & Hattingh, 2024; Nonaka & Takeuchi, 1995).

The knowledge gap obtained from the difference between the importance score and the mastery score, if positive, indicates the need for farmer capacity building. The resulting K-Gap value indicates the direction of improvement or development that needs to be undertaken. The gap analysis formula refers to (Setiarso *et al*., 2009):

The importance and mastery scores for each knowledge item were calculated based on the number of respondents selecting the Likert-scale options "A," "B," "C," "D," and "E". Each response option was assigned a weight or score ($x_{1,2,3,4,5}$), and the number of respondents selecting each option was denoted as ($K_{1,2,3,4,5}$) for importance and ($P_{1,2,3,4,5}$) for mastery. The total number of respondents is represented by R. The importance and mastery scores were calculated using Equations (1) and (2), and the knowledge gap (K-Gap) as shown in Equation (3).

$$NK_i = \frac{(K_1 \times 1) + (K_2 \times 2) + (K_3 \times 3) + (K_4 \times 4) + (K_5 \times 5)}{R} \tag{1}$$

$$NP_i = \frac{(P_1 \times 1) + (P_2 \times 2) + (P_3 \times 3) + (P_4 \times 4) + (P_5 \times 5)}{R} \tag{2}$$

$$K - Gap = NK_i - NP_i \tag{3}$$

2.1. Suitability Level

A method for measuring the level of suitability to determine the level of satisfaction with organizational performance and the extent of understanding possessed. The level of suitability is the result of comparing the perception/performance score with the expected/importance score. The conformity rate is calculated based on the respondent conformity level (Tki), the total perception/performance score of respondent *i* ($\sum X_i$), and the total expectation/importance score of respondent *i* ($\sum Y_i$), as expressed in Equation (4).

$$Tk_i = \frac{\sum X_i}{\sum Y_i} \times 100\% \tag{4}$$

2.2. Cartesian Diagram

The Cartesian diagram is used to identify and prioritize the attributes that require improvement. The quadrant analysis follows the procedure outlined by Supranto (2011), which compares the average importance and performance scores of each attribute with their overall mean values to determine their position within the four IPA (Importance-Performance Analysis) quadrants. The Cartesian diagram of the IPA model is presented in Figure 1.

The average importance and performance scores for each attribute were calculated based on the average performance score for attribute/statement *i* ($\overline{X}_i$), the average importance score for attribute/statement *i* ($\overline{Y}_i$), and the number of respondents (*n*), as expressed in Equations (5) and (6):

$$\overline{X}_i = \frac{\sum_{i=1}^{k} X_i}{n} \tag{5}$$

$$\bar{Y}_i = \frac{\sum_{i=1}^{k} Y_i}{n} \tag{6}$$

The average importance and performance scores for all attributes were calculated based on the overall average performance score across all attributes/statements i ($\bar{\bar{X}}_i$), the overall average importance score across all attributes/statements i ($\bar{\bar{Y}}_i$), and the total number of attributes or statements (k), as expressed in Equations (7) and (8):

$$\bar{\bar{X}}_i = \frac{\sum_{i=1}^{k} \bar{X}_i}{k} \tag{7}$$

$$\bar{\bar{Y}}_i = \frac{\sum_{i=1}^{k} \bar{Y}_i}{k} \tag{8}$$

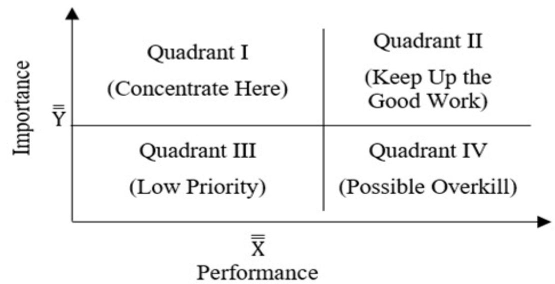

Figure 1. Cartesian diagram of the Importance–Performance Analysis (IPA) method (Rangkuti, 2003; Supranto, 2011)

3. RESULTS AND DISCUSSION

Based on the results of the measurement model analysis using the PLS-SEM method, the outer loading factor values were obtained for each indicator within its respective latent construct. These outer loading values were used to assess the convergent validity of each indicator in relation to its construct. The results of the outer loading factor measurements before and after the indicator testing in the indirect model are presented in Figure 2.

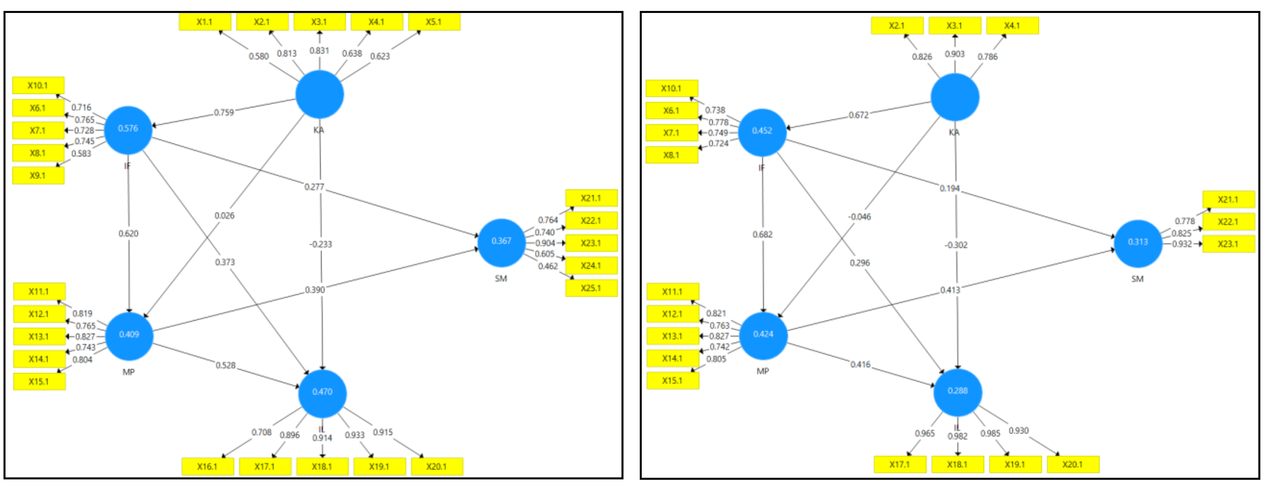

Figure 2. Outer loading factor measurement model (left) and after indicator testing on the indirect model (right)

Figure 2 illustrates the measurement model, showing the outer loading factors before and after the indicator refinement process. The refinement was conducted to improve construct validity and reliability by removing indicators with loading values below 0.5, particularly those under 0.4 (Benitez *et al*., 2020; Chin, 2009; Hair *et al*., 2019; Sarstedt *et al*., 2019). In general, acceptable loading values range from 0.6 to 0.7, although values between 0.5 and 0.6 may be allowed in early measurement development when validity and reliability criteria are still satisfied. Convergent validity is met when an indicator has a loading (λ) ≥ 0.5 (Chin, 1998). The assessment of the measurement model also includes reliability and validity testing, where a construct is considered reliable if Cronbach's α > 0.6, CR (composite reliability) > 0.6, and AVE (average variance extracted) > 0.5 (Chin, 1998; Hair, *et al*., 2014b; Lyberg *et al*., 2012).

3.1. Measurement Model (Outer Model)

Evaluation of the outer model showed that several indicators in the initial specification had loading values below the recommended threshold, particularly within the Infrastructure and Irrigation Water Management constructs. In accordance with the criteria suggested by (Chin, 1998, 2009) and (Hair *et al*., 2021b; Hair *et al*., 2014b), indicators with loadings < 0.70 were removed to ensure sufficient convergent validity. After refinement, only high-loading indicators remained, resulting in improved AVE and CR scores (Sun *et al*., 2018). This outcome is consistent with Veesam *et al*. (2025), who emphasize that reflective constructs achieve stronger reliability when dominated by indicators with substantial loadings. All constructs met the required thresholds for internal reliability and convergent validity (Leguina, 2015; Sarstedt *et al*., 2014). The Human Resources and Institutional constructs demonstrated the highest stability, with loading values exceeding 0.90, indicating that these dimensions constitute the most consistent contributors to irrigation modernization performance.

3.2. Relationships among Constructs (Inner Model)

The structural model analysis showed clearer inter-construct relationships after indicator refinement. Infrastructure exhibited a positive influence on Irrigation Water Management, while Water Availability also contributed significantly to water management performance. In contrast, the direct effects of Infrastructure and Water Availability on Human Resources weakened, suggesting that their influence is largely mediated through Irrigation Water Management. Institutional capacity further strengthened the link between water management and human resource development, consistent with the organizational learning principles of the SECI model (Nonaka & Takeuchi, 1995).

The simplified model produced lower but more precise R^2 values, 0.288 for Irrigation Water Management and 0.313 for Human Resources, indicating a more parsimonious and coherent model (Henseler *et al*., 2015, 2016; Hair *et al*., 2021a). Although these R^2 values are moderate, they remain acceptable in behavioral, social, and agricultural management studies, where endogenous constructs are often influenced by complex human, institutional, and contextual factors (Hair *et al*., 2014b; Henseler *et al*., 2016). In community-based irrigation systems, farmer capacity and water management performance are shaped not only by technical variables but also by collective behavior, institutional coordination, local knowledge, and adaptation to field conditions. Therefore, these R^2 values still indicate meaningful explanatory power and support a parsimonious and theoretically coherent model. These results align with integrated water resource management perspectives, which highlight the interdependence of technical, institutional, and human dimensions (Chin, 2009; Henseler *et al*., 2016). The results are summarized in Table 1.

Table 1. Coefficient of determination (R^2) for latent constructs

Criteria	Cronbach's α	ρA	Composite Reliability	Average Variance Extracted
Water Availability	0.789	0.796	0.877	0.705
Infrastructure	0.737	0.740	0.835	0.559
Irrigation Water Management	0.852	0.858	0.894	0.628
Institution	0.976	0.978	0.982	0.933
Human Resources	0.802	0.834	0.884	0.718

3.3. Internal Reliability Test (Cronbach's α and Composite Reliability)

Cronbach's α was used to assess the internal consistency of indicators within each construct. According to Hair *et al*. (2021b), values above 0.70 indicate satisfactory reliability, while the 0.60–0.70 range is acceptable for exploratory research. As shown in Table 1, all constructs meet this criterion, with Cronbach's α values ranging from 0.737 to 0.976. The institutional construct demonstrates the highest reliability (0.976), whereas Infrastructure has the lowest (0.737), although still within acceptable limits. Composite reliability further confirms internal consistency, with all constructs exceeding the recommended threshold of 0.70 (Hair *et al*., 2014b; Sarstedt *et al*., 2017), ranging from 0.835 to 0.982.

3.4. Convergent Validity Test (Average Variance Extracted/AVE and ρA)

Convergent validity was evaluated using the AVE, where values ≥ 0.50 indicate adequate representation of indicators by their latent constructs (Fornell & Larcker, 1981). Table 1 shows AVE values between 0.559 and 0.933, confirming that all constructs satisfy convergent validity criteria. These results are consistent with PLS-SEM validity standards (Hair *et al*., 2019; Sarstedt *et al*., 2019).

The ρA values (0.740–0.978) also support construct reliability, since values above 0.70 reflect stable relationships among indicators (Henseler *et al*., 2014). The highest rho_A values in the Institutional and Human Resources constructs highlight the strong role of social and institutional capacity in supporting irrigation modernization, whereas slightly lower values in Infrastructure indicate potential areas for strengthening technical indicators.

3.5. Knowledge Gap Analysis

The K-Gap analysis shows that the largest gap occurs in the Infrastructure aspect (0.05), while the smallest occurs in Water Management (0.02). This suggests that farmers recognize the importance of irrigation infrastructure but remain limited in their technical ability to operate and maintain it. These findings align with Arif *et al*. (2021), who emphasize the need to improve communication systems and technical documentation between irrigation agencies and farmers. Furthermore, the priority for strengthening water management capacity is consistent with Jayanti *et al*. (2021), who highlight the importance of synergy between land and water control at the farmer level to maintain irrigation efficiency. These results indicate that integrating technical improvements with KM strategies is essential for reducing gaps between theoretical understanding and field-level application. Figure 3 presents the K-Gap values for farmers in the Krueng Aceh region.

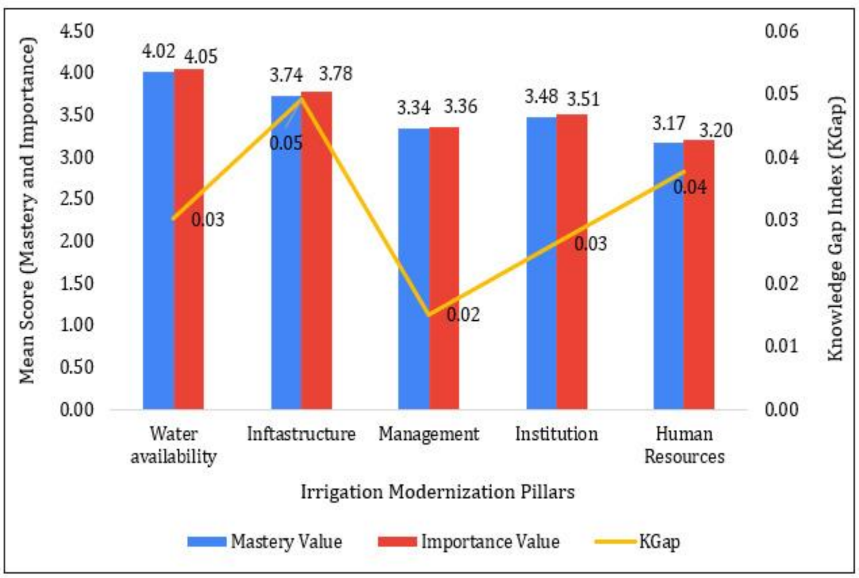

Figure 3. Value of farmers' knowledge gap in the Krueng Aceh Region

The K-Gap results shows that farmers in the Krueng Aceh are generally prepared for irrigation modernization, as indicated by the small gap values (0.02–0.05). However, variation across the irrigation pillars indicate the need for targeted capacity-building efforts aligned with field priorities. Infrastructure shows the highest K-Gap (0.05), suggesting that although farmers recognize the importance of irrigation facilities, their technical skills in operating and maintaining them remain limited. This highlights the need for practical training and participatory technology transfer, consistent with Jackson *et al*. (2015) and Nepal *et al*. (2024). The Human Resources construct (0.04) also indicates limited cognitive and managerial capacity, particularly in data-based decision-making, aligning with Jayanti *et al*. (2021), who emphasize the importance of technical understanding and collaboration in water institutions.

Institutional performance (K-Gap = 0.03) indicates that P3A/GP3A function adequately but still require improved coordination, transparency, and information management, supporting (Chuang, 2004) view of institutions as central to KM and innovation governance. Strengthening community-based knowledge-sharing platforms, as suggested by Ayele & Wield (2005), could enhance collaboration among irrigation actors.

Irrigation Water Management has the lowest K-Gap (0.02), indicating effective turn-sharing, field monitoring, and water regulation. This finding aligns with previous studies emphasizing the importance of participatory management and farmer involvement in modern irrigation systems (Kusumastuti *et al*., 2021; Rao *et al*., 2021; Suwanmaneepong *et al*., 2024; Wang & Wu, 2018; Wang & Zheng, 2010). Overall, the results indicate that capacity strengthening must integrate technical, institutional, and social learning dimensions. Combining SECI-based knowledge processes (Dalkir, 2005; Nonaka & Takeuchi, 1995) with multi-criteria decision frameworks can help reduce knowledge gaps and enhance readiness for sustainable irrigation modernization.

3.6. Importance–Performance Analysis

The Importance–Performance Analysis (IPA), introduced by Martilla & James (2010), was used to assess the alignment between farmers' expectations and perceptions of institutional performance. As shown in Figure 4, the suitability level is 99.32%, indicating high alignment and showing that most attributes fall within the good performance category.

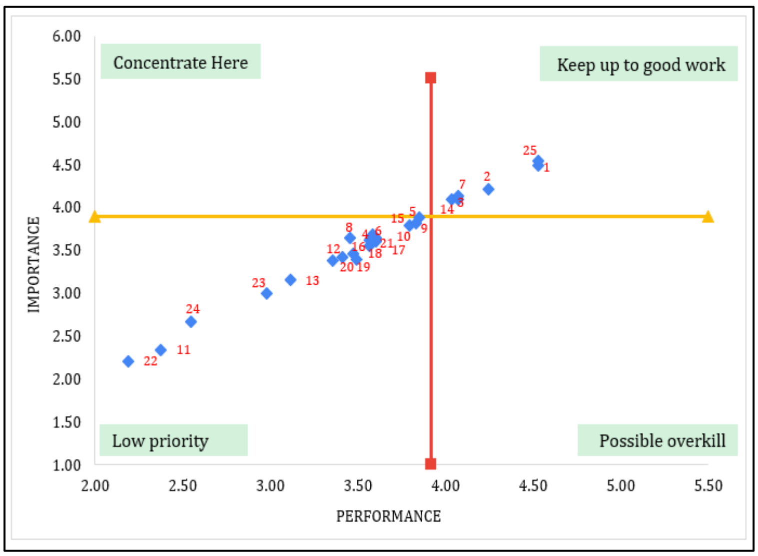

Figure 4. Importance–Performance Analysis (IPA) of farmers' perceptions in the Krueng Aceh

This suggests that irrigation institutions in the Krueng Aceh region already demonstrate adaptive capacity in supporting irrigation modernization. Integration of IPA with PLS-SEM (Hair *et al*., 2014b; Ringle & Sarstedt, 2016) strengthens causal interpretation, identifying latent constructs that influence institutional performance. While P3A/GP3A's main strength lies in social learning (Dalkir, 2005; Nonaka & Takeuchi, 1995), weaknesses remain in documentation and knowledge integration (Ministry of Water Resources, 2014; Ostrom, 1990; Playán *et al*., 2018). Strengthening SECI-based KM is therefore essential for sustainable irrigation governance.

In Quadrant I (Concentrate Here), attributes such as institutional coordination and technical documentation are highly important but perform below expectations. This reflects weaknesses in the externalization and combination stages of the SECI model (Dalkir, 2005; Nonaka & Takeuchi, 1995), indicating inadequate documentation and sharing of tacit knowledge. Oh (2001) and Sever (2015) emphasized that IPA interpretation should also consider social learning processes rather than relying solely on numerical performance. Quadrant II (Keep Up the Good Work) includes mutual aid, water distribution, and network maintenance, attributes with high importance and high performance. These represent strengths in the socialization and internalization, where knowledge is reinforced through shared experience (Nonaka & Takeuchi, 1995; Polanyi, 1966). Quadrant III (Low Priority) includes administrative reporting and record-keeping which, despite lower priority, are vital for accountability. Improvements can focus on integrating institutional data and regulation-based documentation (Ministry of Water Resources, 2014; Kementerian PUPR, 2015), supporting evidence-based policymaking (Abalo *et al*., 2007; Bacon, 2003). Quadrant IV (Possible Overkill) contains attributes with low importance but high performance, such as repetitive reporting. Resources may be reallocated toward participatory learning or technical training (Matzler *et al*., 2003).

3.7. SECI Process and Results Interpretation

The SECI process in the Krueng Aceh irrigation community shows a progressive and adaptive transformation of farmers' knowledge.

3.7.1. Socialization (Tacit → Tacit)

Farmers share experiences through discussions, P3A/GP3A meetings, and field interactions. Tacit knowledge such as water rotation and cropping patterns is informally exchanged and still undocumented. Senior farmers serve as key sources of traditional knowledge, while younger farmers are more open to innovation. This stage reflects collective learning and forms the foundation of knowledge transformation.

3.7.2. Externalization (Tacit → Explicit)

Farmers' tacit knowledge was converted into explicit forms, such as discussion notes, simple guidelines, questionnaires, and local Standard Operating Procedures (SOPs), through Likert-scale surveys, in-depth interviews, and participant observation. This externalization process enabled the systematic identification of irrigation needs, technology-adoption barriers, and key knowledge gaps, particularly in institutional administration and water distribution. Insights gathered from questionnaires, interviews, and observations were further distilled into clear knowledge-gap indicators, demonstrating the effective transformation of tacit field experience into explicit and integrable information.

3.7.3. Combination (Explicit → Explicit)

Explicit knowledge from farmers was integrated with formal references, including Permen PUPR No. 12/2015, FAO Benchmarking Irrigation & Drainage, the RAP method, primary data, relevant literature, and IKMI indicators. This integration produced a structured knowledge framework that identifies priority areas essential for strengthening farmers' preparedness for irrigation modernization. The analysis indicates that modernization-oriented water distribution is the most important aspect, followed by the need to reinforce P3A/GP3A institutional management and improve administrative capacity. This combination stage represents a systematic consolidation of diverse explicit knowledge sources into a coherent framework, thereby supporting more accurate and informed decision-making in the modernization of irrigation systems.

3.7.4. Internalization (Explicit → Tacit)

The recommendations were re-internalized by farmers through training, mentoring, and field practice. Farmers began applying data-driven water rotation and simple digital record-keeping, allowing new knowledge to be embedded in daily routines and used directly in decision-making. This internalization strengthened farmers' understanding of irrigation modernization; however, continued support is needed for the knowledge to become habitual. This stage sustains community learning and develops key competencies such as need-based irrigation scheduling and readiness to adopt modern approaches. Such continued support may include periodic technical training on irrigation scheduling and infrastructure maintenance, routine mentoring by irrigation officers or P3A/GP3A leaders, and regular institutional monitoring to ensure consistent implementation of water management practices. In addition, structured feedback mechanisms, such as farmer meetings or evaluation forums, can help farmers reflect on operational challenges and share practical solutions. These efforts reinforce repeated learning cycles and gradually embed explicit knowledge into farmers' daily irrigation management routines.

The SECI cycle in this study demonstrates that farmers' knowledge transforms progressively and adaptively. From experience sharing (socialization) to the application of new practices in the field (internalization), each stage reflects dynamic knowledge conversion that reinforces organizational learning within P3A/GP3A institutions. Overall, the SECI cycle illustrates how farmers' tacit experience evolves into explicit, systematized, and re-internalized knowledge. The integration of these four stages strengthens organizational learning and supports the transition toward data-driven and sustainable irrigation management (Dalkir, 2005; Ministry of Water Resources, 2014; Nonaka & Takeuchi, 1995; Ostrom, 1990), as summarized in Table 2.

Table 2. SECI knowledge conversion cycle based on the research findings

SECI stages	Process	Form of Activity	Main Results
Socialization (Tacit → Tacit)	Farmers share their experiences, engage in group discussions, and interact within P3A/GP3A.	Informal discussions, experience sharing, field observations.	Shared knowledge is still tacit and informal.
Externalization (Tacit → Explicit)	Tacit knowledge is translated into questionnaires, interviews, and IKMI notes.	The Likert questionnaire, in-depth interviews, and documentation of discussion.	Needs and knowledge gaps have been identified.
Combination (Explicit → Explicit)	Merging explicit farmer data with regulations (PUPR, FAO, RAP).	Document analysis, a combination of primary and secondary data.	The priority of knowledge aspects is determined (water distribution, institutions, administration).
Internalization (Explicit → Tacit)	Applying the analysis results through training, mentoring, and field practice.	The implementation of simulation, data-driven irrigation practices, and the adoption of simple technologies is essential.	Internalization of knowledge and increased understanding of the concept of modernization.

The research results indicate that farmers' knowledge of modern irrigation is generally adequate to support modernization efforts. This is evident from the small K-Gap value (0.02–0.05), reflecting the difference between expected and actual levels of knowledge demonstrated by farmers. However, significant gaps remain, particularly in infrastructure skills, human resource capacity, and knowledge documentation and integration. This suggests that farmers' knowledge is evolving dynamically. This process can be explained by the SECI model, which includes Socialization (sharing tacit knowledge through social interaction), Externalization (articulating tacit knowledge into explicit concepts), Combination (systematizing concepts into a knowledge system), and Internalization (absorbing explicit knowledge into tacit understanding), as a framework for creating and sharing knowledge.

In the socialization stage, knowledge is formed through informal discussions, group interactions, and field activities, although it is not yet documented. In the externalization stage, this tacit knowledge is converted into explicit forms, such as Likert-scale responses, in-depth interviews, and IKMI records, allowing the identification of farmers' needs and knowledge gaps related to irrigation modernization. The combination stage integrates this explicit knowledge with formal regulatory references, including the Ministry of Public Works and Housing guidelines, FAO benchmarking, and the RAP method, to determine priority knowledge domains such as modernization-oriented water distribution, institutional strengthening, and administrative capacity improvement. In the internalization stage, recommendations are applied through training, mentoring, and field practice, embedding explicit knowledge into farmers' daily activities and increasing their readiness for modernization. The SECI cycle enhances institutional knowledge capital and supports the sustainability of community-based irrigation institutions.

4. CONCLUSIONS

The PLS-SEM results confirm that all constructs, Water Availability, Infrastructure, Irrigation Water Management, Institutions, and Human Resources, meet the required validity and reliability criteria, with irrigation water management acting as a key mediating factor linking infrastructure and water availability to farmer capacity. The K-Gap values (0.02–0.05) indicate that farmers are generally prepared for irrigation modernization, although gaps remain infrastructure-related skills and managerial competencies. The IPA analysis shows a high suitability level (99.32%), with coordination and documentation identified as priority areas for improvement.

The SECI model effectively captures the transformation of farmers' knowledge through socialization, externalization, combination, and internalization, thereby reinforcing institutional learning and enhancing readiness for modernization. Strengthening SECI-based knowledge management remains essential, particularly by improving documentation practices, providing targeted technical and managerial training, and enhancing institutional coordination within P3A/GP3A to support sustainable irrigation modernization in the Krueng Aceh region.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
DSJ	✓	✓	✓		✓	✓	✓	✓	✓	✓				
FT	✓						✓	✓		✓				

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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