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DESIGNING A PENTAHELIX-BASED DIGITAL KNOWLEDGE MANAGEMENT SYSTEM FOR RURAL ENTERPRISES: A PROTOTYPE FROM TOMINI BAY, INDONESIA

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ABSTRACT

Aim/Purpose	The research aimed to design, develop, and test a system that enabled reciprocal knowledge flows between government, academia, business, media, and community stakeholders.
Background	The research problem addressed in this study concerned the absence of an integrated, digital knowledge management (KM) system that could operationalize the Pentahelix framework to strengthen the management and governance of VOEs. Despite policy frameworks such as Government Regulation No. 11/2021, which formalized the operational mechanisms of Village-Owned Enterprises (VOEs) and emphasized entrepreneurship and community empowerment, challenges persisted in translating these frameworks into practice.
Methodology	Employing a research and development (R&D) approach with Agile Scrum, the study engaged eight VOE managers from four villages in the Tomini Bay region of Gorontalo Province to elicit requirements through interviews, observations, and questionnaires. The system was developed iteratively over four sprints and implemented functionalities such as user authentication, collaborative forums, a knowledge repository, and analytics dashboards. The platform design utilized Unified Modeling Language (UML) diagrams to model workflows, actor roles, and class structures. System testing applied black-box and white-box approaches, complemented by sprint reviews and user acceptance testing.
Contribution	This research contributed to the body of knowledge by offering both a conceptual framework and a tested prototype for digitally mediated multi-stakeholder collaboration in rural enterprise development.
Findings	The findings underscored that digital KM platforms, when anchored in multi-stakeholder frameworks, served as strategic enablers of rural development. Evaluation demonstrated high system reliability with 100% functional test pass rate and optimized query response times (reduced by 60-75%). User acceptance testing revealed strong adoption potential, with Perceived Usefulness (M = 6.2/7.0), Intention to Use (M = 6.0/7.0), and Overall Satisfaction (M = 5.9/7.0) scores indicating high levels of satisfaction. Task completion rates improved from 72% in Sprint 1 to 95% in Sprint 4. The integration of the platform with potential e-government and e-commerce systems suggested significant implications for participatory governance, market democratization, and rural economic empowerment.
Recommendations for Practitioners	Practically, by presenting a tested prototype developed using Agile Scrum methodology that served as a model for similar initiatives in developing countries.
Recommendations for Researchers	Theoretically, by extending the application of KM and Pentahelix frameworks to rural enterprise contexts.
Impact on Society	The platform's adaptability to diverse digital readiness contexts signaled its transferability to other rural regions, provided that localized adjustments were made.
Future Research	Future studies could explore the integration of automation, advanced analytics, and recommender systems while further evaluating the longitudinal impacts on business performance, collaboration intensity, and community well-being.

Keywords village-owned enterprises, knowledge management, Pentahelix model, digital knowledge management system, rural development, multi-stakeholder collaboration, Indonesia

INTRODUCTION

Digital transformation redefined the way organizations function, reshaping the dynamics of knowledge access, sharing, and utilization across sectors. This transition, often aligned with the principles of Society 5.0, emphasized a human-centered approach to technological advancement, positioning knowledge as a key asset for competitiveness and sustainability. Knowledge management (KM) has thus become indispensable not only for large-scale corporations but also for micro, small, and medium-sized enterprises (MSMEs) seeking to remain adaptive and resilient in an increasingly digitized global economy. In developing countries, rural enterprises and community-based organizations, such as village-owned enterprises (VOEs), faced significant challenges, as limited access to infrastructure, expertise, and resources presented both obstacles and opportunities for adopting digital knowledge platforms (Luo et al., 2023; Tang & Zhao, 2023).

The adoption of digital platforms was consistently shown to enhance productivity, foster innovation, and integrate rural economies into broader markets (W. Zhang, 2023). Moreover, the digitization of rural enterprises contributed to resilience by empowering communities with tools to adapt to shifting market conditions, mitigate external shocks, and enhance long-term sustainability (H. Zhang & Qian, 2024). Digital empowerment, particularly for marginalized groups, was linked to greater socio-economic participation, underscoring the transformative potential of rural digitalization. Nevertheless, while digital platforms were critical enablers, the uneven distribution of digital literacy, infrastructural inadequacies, and cultural resistance constrained the extent to which rural enterprises could harness these opportunities (Atmojo & Fridayani, 2023; Hall, 2023).

The central challenge facing VOEs lay in their ability to mobilize and integrate knowledge from diverse stakeholders, which was inherently dispersed across government agencies, universities, private businesses, media institutions, and the broader community. This aligned with the Pentahelix model, a widely recognized framework for multi-stakeholder collaboration in sustainable development. The model emphasized the role of government in providing policy and regulatory support, academia in research and knowledge dissemination, businesses in fostering partnerships, media in promoting awareness, and communities in contributing local wisdom and contextual insights (Carayannis & Morawska, 2022). While the model has been validated in various contexts as an effective mechanism for policy implementation and governance (Effendi et al., 2023; Taratori et al., 2021), its digital operationalization, particularly in rural enterprise ecosystems, has remained limited. Existing efforts have often addressed individual elements of the model but have fallen short of achieving comprehensive integration through digital platforms.

The research problem addressed in this study concerned the absence of an integrated, digital KM system that could operationalize the Pentahelix framework to strengthen the management and governance of VOEs. Despite policy frameworks such as Government Regulation No. 11/2021, which formalized the operational mechanisms of VOEs and emphasized entrepreneurship and community empowerment (Revida et al., 2023), challenges persisted in translating these frameworks into practice. Issues of fragmented knowledge, limited access to reliable technology, and gaps in digital literacy hindered the creation of collaborative platforms that effectively supported decision-making, enhanced transparency, and improved accountability in VOE operations (Siskawati et al., 2022).

General solutions proposed in the literature often highlighted the importance of digital literacy programs, infrastructural investments, and the creation of digital ecosystems to facilitate knowledge exchange (Wilson et al., 2022). Furthermore, multi-stakeholder partnerships were regarded as critical in ensuring that rural communities were not left behind in the digital era. For example, Barinta (2023)

demonstrated that rural entrepreneurs who leveraged cloud technologies and social media for real-time market insights significantly improved decision-making processes and competitiveness. Similarly, interventions that emphasized collaborative governance mechanisms were shown to strengthen rural entrepreneurship ecosystems by pooling resources and aligning stakeholder objectives (Kania et al., 2021).

Specific solutions explored in prior studies included the application of adaptive KM frameworks that integrated both formal and informal knowledge-sharing practices (Hirawati et al., 2021). Scholars have argued that such approaches are particularly relevant in rural contexts, where cultural practices, local wisdom, and informal networks play significant roles in shaping entrepreneurial outcomes (Hall, 2023). Digital platforms that combine structured repositories with interactive features, such as forums, dashboards, and tutorials, were identified as promising tools for addressing the unique challenges faced by community enterprises (Romanelli, 2023). Moreover, the use of Agile methodologies in platform development has gained traction, enabling iterative design processes that incorporate feedback from diverse stakeholders and enhance usability (Ambarini et al., 2023).

Despite these advances, a significant research gap remained. Studies focusing on the quintuple helix or Pentahelix frameworks often examined their conceptual potential without developing concrete, operationalized systems tailored to rural enterprises. Likewise, while KM was extensively studied in corporate and urban contexts, there was limited empirical research on its integration into VOE management through digital tools. This gap underscored the need for research that not only conceptualized but also developed and tested digital KM platforms designed for multi-stakeholder collaboration in rural settings. Addressing this gap was critical, given the central role of VOEs in promoting rural economic independence, enhancing social welfare, and supporting sustainable village development (Effendi et al., 2023; Kania et al., 2021).

This study sought to design and develop a prototype digital KM system that facilitated collaboration among Pentahelix stakeholders to strengthen VOE management. By integrating the principles of knowledge management with the Pentahelix model, the research aimed to provide a comprehensive platform that enhances decision-making, fosters innovation, and improves stakeholder engagement. This study addresses three critical questions: (1) How can the Pentahelix model be operationalized through a digital knowledge management platform to support multi-stakeholder collaboration in rural enterprise contexts? (2) What system features and architectural components effectively support knowledge exchange, curation, and retrieval among diverse stakeholder groups with varying technical capabilities? (3) To what extent does the developed platform meet the functional requirements of VOE managers and achieve user acceptance in terms of usefulness, ease of use, and intention to adopt?

To address these questions, this study employs a Research and Development (R&D) approach integrated with Agile Scrum methodology, engaging VOE managers from the Tomini Bay region in Gorontalo Province through iterative development cycles. The study contributed to both theoretical and practical knowledge: theoretically, by extending the application of KM and Pentahelix frameworks to rural enterprise contexts; and practically, by presenting a tested prototype that served as a model for similar initiatives in developing countries. The novelty of this study lies in its operationalization of the Pentahelix model through a digital platform specifically designed to address the challenges of rural enterprises. The scope of this work extended to the conceptualization, design, and initial testing of the system, with the potential for future scaling and integration into national and regional rural development strategies.

LITERATURE REVIEW

DIGITAL KNOWLEDGE MANAGEMENT FOR RURAL DEVELOPMENT AND COMMUNITY ENTERPRISES

Rural development initiatives increasingly recognize knowledge as a critical resource that underpinned the sustainability and competitiveness of community-based enterprises. Digital knowledge management (KM) systems played a central role in this recognition, serving as enablers of effective knowledge governance and innovation within local organizations, such as Village-Owned Enterprises (VOEs) (Sophia et al., 2025). Through digital platforms, the capture, codification, and dissemination of both indigenous knowledge and external best practices were enhanced, enabling rural entrepreneurs to address persistent information gaps that would otherwise have constrained their growth. By supporting better decision-making, these systems bridged the rural-urban knowledge divide and strengthened inclusive development strategies (C. Wang, 2025).

Empirical studies have emphasized the prevalence of "knowledge disconnections" experienced by rural micro-entrepreneurs, which often hinder operational efficiency and limit their integration into broader market systems. Research from India illustrated that ICT-enabled interventions mitigated these gaps by mobilizing indigenous knowledge and aligning it with market requirements (Parthiban et al., 2024). Such interventions, when delivered through digital KM platforms, enabled access to training resources, expert consultation, and market intelligence, thus supporting strategic planning and innovation (Fahmi & Savira, 2021). By leveraging off-the-shelf technologies, these platforms empowered rural communities with minimal resource investment, making them highly adaptable and sustainable solutions. This integration of local and external knowledge also catalyzed inclusive innovation, ensuring that rural economies were better positioned to respond to dynamic challenges and opportunities (Xie et al., 2024).

The digital transformation of rural enterprises was widely regarded as a fundamental strategy for overcoming systemic barriers that disproportionately disadvantaged rural communities. Persistent disparities in infrastructure and access to resources between urban and rural areas exacerbated the challenges confronting rural entrepreneurs (C. Wang, 2025; Xie et al., 2024). Digital KM systems played a crucial role in addressing these disparities by fostering entrepreneurial attitudes, building organizational capabilities, and reinforcing rural–urban interconnectedness (Fahmi & Savira, 2021). Logunova et al. (2020) further argued that digital platforms provided adaptable frameworks that enabled rural enterprises to expand their market presence, optimize operations, and reduce existing inequalities, thereby strengthening rural resilience.

In Indonesia, VOEs (locally known as BUMDes) increasingly adopted KM frameworks to improve governance and performance. The SECI (socialization, externalization, combination, internalization) model offers a structured approach to facilitating the flow of both tacit and explicit knowledge, thereby enhancing organizational capacity and transparency (Pribadi et al., 2023). Community service initiatives in Gorontalo Province demonstrated that integrating institutional strengthening, local potential mapping, and digital platforms significantly improved BUMDes management capacity, leading to the development of flagship local food products and increased community awareness (Katili et al., 2025). Sophia et al. (2025) demonstrated that digitizing VOEs' knowledge processes improved managerial efficiency, promoted financial accountability, and fostered stronger community empowerment outcomes. Such findings highlighted the importance of integrating KM frameworks within rural enterprises to ensure that local governance systems are both efficient and legitimate. Case studies further showed that digitalizing knowledge processes streamlined management, reduced redundancies, and enhanced accountability mechanisms (Pribadi et al., 2023; Putra et al., 2023). These outcomes aligned with broader observations that knowledge-sharing platforms contributed to improved governance by making community enterprises more efficient and participatory (Correani et al., 2020).

The literature also highlighted the role of digital KM in fostering continuous learning and innovation. By documenting and disseminating indigenous practices alongside external knowledge, KM systems created hybrid models of development that balanced modernization with cultural preservation (Correani et al., 2020). This dual capacity enabled rural enterprises to remain competitive in changing economic contexts while safeguarding local wisdom and identity. In this way, digital KM contributed not only to business performance but also to the preservation of cultural heritage as an asset in rural development.

Maximizing the benefits of digital KM required robust collaboration among diverse stakeholders. Studies underlined the importance of cooperative networks involving local governments, NGOs, private actors, and academic institutions in building the enabling ecosystems necessary for digital KM adoption (Dubey & Ranjan, 2024; Li et al., 2024). Such collaborative structures ensured that digital KM initiatives were embedded within broader rural development agendas rather than remaining as fragmented technological interventions. By pooling resources, expertise, and institutional support, multi-stakeholder networks amplified the effectiveness and sustainability of KM platforms.

Strategic clarity was another key factor in realizing the transformative potential of digital KM. Organizations needed to clearly define their transformation objectives to ensure alignment between digital adoption and governance improvements (K. Wang et al., 2022; Zhao, 2024). This clarity facilitated consistent decision-making and targeted improvements in transparency, accountability, and operational efficiency. By linking digital initiatives with explicit developmental goals, VOEs and other community enterprises reinforced their roles as catalysts of empowerment and local development.

Nevertheless, challenges persisted in embedding digital KM within rural contexts. Limited digital literacy, inadequate infrastructure, and cultural barriers to knowledge sharing often constrained the long-term effectiveness of these systems (C. Wang, 2025). Addressing such challenges required integrating technological interventions with capacity-building efforts and supportive policy frameworks tailored to rural contexts. Only by cultivating both the technical and institutional conditions for sustainability could digital KM initiatives achieve their full potential.

In synthesis, the literature establishes digital KM as a critical enabler for rural enterprise development (Sophia et al., 2025; C. Wang, 2025; W. Zhang, 2023), yet reveals three persistent gaps. First, while theoretical benefits are well-documented, empirical evidence of successful KM implementation in resource-constrained rural contexts remains limited, particularly in developing countries beyond India and China (Fahmi & Savira, 2021; Parthiban et al., 2024). Second, existing studies focus predominantly on individual KM components (e.g., knowledge capture or sharing) rather than integrated, multi-stakeholder systems (Correani et al., 2020; Dubey & Ranjan, 2024). Third, the literature emphasizes technological solutions but inadequately addresses the socio-cultural and institutional prerequisites for sustained adoption in communities with varying levels of digital readiness (Logunova et al., 2020; C. Wang, 2025). These gaps underscore the need for research that develops and validates holistic KM platforms designed explicitly for multi-actor collaboration in rural enterprise ecosystems.

Pentahelix Collaboration Model in Rural Enterprise Development

Multi-stakeholder collaboration was increasingly recognized as a cornerstone of sustainable rural enterprise development, particularly within the framework of Village-Owned Enterprises (VOEs) in Indonesia. The Pentahelix model emerged as a prominent framework for fostering this collaboration, incorporating five key stakeholder groups: government, academia, business, media, and local communities (Abdullah et al., 2024; Kania et al., 2021). Each actor contributed distinct resources, perspectives, and roles that, when integrated, created a synergistic ecosystem for rural innovation and enterprise sustainability. This five-helix approach expanded upon the earlier quadruple helix framework by explicitly incorporating media as a central actor, reflecting the increasing significance of communication and knowledge dissemination in contemporary development contexts (Hangui, 2024; Murphy et al., 2021).

In the Pentahelix model, the government functioned as both regulator and supporter, providing policy direction, legal frameworks, and resource allocation necessary to foster rural enterprise growth (Kania et al., 2021). Academia contributed by acting as a knowledge provider, delivering research insights, training, and capacity-building programs to enhance the skills of local entrepreneurs. Businesses served as enablers, offering technology, investment, and operational expertise to strengthen the viability of VOEs. Local communities acted as accelerators, driving grassroots initiatives, ensuring cultural relevance, and mobilizing collective participation in enterprise activities. Finally, the media played a role as an expander, amplifying visibility, disseminating success stories, and enhancing outreach to broader audiences (Abdullah et al., 2024). This complementary distribution of responsibilities illustrates the holistic nature of the Pentahelix framework, enabling rural enterprises to thrive.

Research has demonstrated that the effective implementation of the Pentahelix model significantly enhances the governance, efficiency, and sustainability of rural enterprises. For example, Effendi et al. (2023) reported that digital knowledge management processes implemented within VOEs had improved managerial efficiency, financial transparency, and community empowerment. These improvements were primarily attributed to the collaborative engagement of stakeholders, who provided resources, knowledge, and networks, resulting in tailored solutions to local challenges. Similarly, Olmedo and O'Shaughnessy (2022) argued that such partnerships were instrumental in stimulating rural entrepreneurship by pooling resources and fostering accountability, thereby addressing the socio-economic limitations that rural enterprises frequently encountered.

The inclusion of media within the Pentahelix model was particularly relevant in the digital age. Studies have highlighted that the media act as a catalyst for communication and public engagement, enabling the scaling of rural innovations through the dissemination of knowledge and best practices (Li et al., 2024). For example, in rural tourism development, media exposure was shown to increase visibility, attract external support, and boost community pride (Luca et al., 2021). In this way, the media expanded the reach of local initiatives and enhanced their competitiveness, making it a crucial component for sustaining the growth of rural enterprises in interconnected markets (Y. Chen et al., 2020).

Inclusive planning and co-creation were recurring themes in the literature on the Pentahelix framework. When stakeholders actively engaged in shared planning and decision-making, outcomes were often more innovative and better suited to local contexts (Aritenang, 2021; Kuneva & Hough, 2023). This collaborative process ensured that diverse perspectives were integrated into rural enterprise development, fostering not only innovation but also legitimacy and trust within local communities. Case studies have demonstrated that co-creation enhances the resilience of rural enterprises, with collective efforts resulting in improved service delivery, increased customer satisfaction, and strengthened community solidarity (Hirschey et al., 2023; Yuan et al., 2023).

Despite its promise, challenges persisted in operationalizing the Pentahelix model. Sumarna et al. (2025) emphasized that maintaining balanced and consistent engagement across all five stakeholders was often tricky, as priorities and capacities varied significantly. For instance, the role of media was sometimes underutilized, leading to limited dissemination of knowledge and reduced public awareness of rural enterprise successes (Abdullah et al., 2024). Furthermore, sustaining long-term trust and commitment among stakeholders requires strong governance mechanisms and structured platforms for dialogue, coordination, and continuous knowledge exchange. Without these mechanisms, collaborations risked becoming fragmented and unsustainable.

To overcome these challenges, scholars emphasized the importance of integrating digital technologies and knowledge management systems into Pentahelix collaborations. Digital platforms created structured spaces for real-time communication, resource sharing, and performance monitoring, thereby strengthening coordination across stakeholders (Effendi et al., 2023). Such technologies also enabled continuous capacity building and facilitated broader dissemination of knowledge, compensating for the limitations of traditional media engagement. By leveraging these tools, stakeholders can

more effectively align their goals, adapt to emerging challenges, and ensure the long-term sustainability of rural enterprises.

In summary, the Pentahelix literature validates multi-stakeholder collaboration as essential for rural enterprise development (Abdullah et al., 2024; Effendi et al., 2023; Kania et al., 2021), yet reveals critical implementation gaps. While conceptual frameworks are well-articulated (Hangui, 2024; Murphy et al., 2021), empirical evidence of successful digital operationalization remains sparse, particularly in developing country contexts (Sumarna et al., 2025). Existing studies document benefits but inadequately address coordination challenges, power asymmetries, and the practical mechanisms needed to sustain engagement across diverse actor groups with competing interests (Abdullah et al., 2024; Murphy et al., 2021). Moreover, the role of digital platforms in mediating Pentahelix interactions remains underexplored, with most research treating technology as a supplementary tool rather than as a core enabler of collaborative governance (Effendi et al., 2023; Li et al., 2024). This gap highlights the need for research that develops and validates integrated digital systems specifically designed to operationalize multi-stakeholder frameworks in rural settings.

Integrating Digital Technologies with Multi-Stakeholder Governance

The integration of digital technologies within multi-stakeholder frameworks, particularly the Pentahelix model, offered transformative potential for rural enterprise development. This framework emphasized collaboration among government, academia, business, media, and local communities, and when combined with digital platforms, it significantly enhanced communication, knowledge sharing, and coordination. Such integration was essential in addressing the "wicked" problems often associated with rural development, which demanded blending codified scientific knowledge with context-specific local knowledge (Olmedo & O'Shaughnessy, 2022; van Ewijk et al., 2024). By enabling the co-creation of solutions, digital platforms served as central hubs that fostered collaborative governance and innovation.

Digital knowledge platforms played a crucial role in bridging institutional silos and facilitating joint problem-solving. They embodied collaborative governance by facilitating real-time exchanges among stakeholders and created conditions for inclusive innovation (van Twuijver et al., 2020; N. Zhang et al., 2023). The literature on community-based enterprises emphasizes that such platforms mobilize local resources, enhance participation, and adapt to geographical and social contexts, thereby amplifying the effectiveness of external support (Olmedo & O'Shaughnessy, 2022). Moreover, empirical studies revealed that collaborative networks frequently produced more innovative and sustainable outcomes than isolated efforts, demonstrating the value of shared digital infrastructures (Effendi et al., 2023; Gwanyemba & Kilonzo, 2023).

Concrete examples illustrated how digital platforms operationalized these theoretical insights. The Next Generation Collaborative and Responsive Rural Community (NCoRe) platform in India exemplified how an e-platform connected rural producers, urban consumers, academia, logistics providers, and government agencies within a unified digital ecosystem (Bandyopadhyay et al., 2020; Basak & Bhaumik, 2023). NCoRe enabled stakeholders to exchange knowledge, coordinate logistics, and align business processes. By creating a shared space, it enhanced transparency and optimized the contributions of each actor, from providing training to offering materials and financial services (Ramanauskas et al., 2021). This collaborative infrastructure demonstrated how digital platforms bridged the rural-urban divide, facilitated knowledge integration, and strengthened enterprise networks (Romanelli, 2023).

Similar benefits were evident in digital governance initiatives such as the "smart village" platform in the Philippines, which integrated government services, educational resources, and economic support into a single system (Camba, 2024). This model illustrates how cross-sectoral digital platforms enhance service delivery, reduce costs, and promote accountability by enabling data-driven decision-making. Through integrated digital systems, governments and partners ensured that service provision

was more efficient and transparent, thereby reinforcing trust and legitimacy in rural development efforts.

Beyond connectivity, digital platforms contributed to collaborative governance by institutionalizing mechanisms for risk-sharing and resource pooling. Studies have highlighted that digital platforms reduce uncertainties and encourage stakeholders to leverage complementary strengths, resulting in more resilient rural enterprises (Monda et al., 2023). By integrating local and expert knowledge, such platforms promoted sustainable practices that were responsive to both ecological and economic needs (X. Chen et al., 2024; Kakisina, 2023). These digital ecosystems thus created hybrid spaces where indigenous practices and scientific expertise intersected, producing context-sensitive solutions to rural challenges (Davis et al., 2022).

Nevertheless, successful integration required careful attention to inclusivity and capacity building. Challenges related to digital literacy, infrastructure disparities, and role clarity needed to be addressed to ensure meaningful participation of all helix members (Y. Wang et al., 2021; Zhai et al., 2024). Equitable access to technology remained a fundamental condition for avoiding the exclusion of marginalized groups, while precise governance mechanisms were necessary to align stakeholder roles and expectations. Without these considerations, digital platforms risked reinforcing existing inequalities rather than alleviating them.

The literature on digital technology integration demonstrates its potential to enhance multi-stakeholder governance (Effendi et al., 2023; Olmedo & O'Shaughnessy, 2022; N. Zhang et al., 2023), but it also reveals significant implementation challenges. While case studies from India (Bandyopadhyay et al., 2020; Basak & Bhaumik, 2023) and the Philippines (Camba, 2024) provide proof of concept, generalizability to other developing country contexts – particularly those with weaker institutional capacity and infrastructure – remains uncertain. Existing research primarily focuses on platform functionality and connectivity (Ramanauskas et al., 2021; Romanelli, 2023), while inadequately addressing critical issues such as the digital divide, data governance, privacy concerns, and long-term financial sustainability (Y. Wang et al., 2021; Zhai et al., 2024). Furthermore, the literature lacks rigorous evaluation frameworks for assessing the actual impact of integrated digital systems on rural enterprise performance outcomes beyond anecdotal success stories (X. Chen et al., 2024; Monda et al., 2023). These gaps underscore the need for research that not only develops integrated platforms but also evaluates their effectiveness, scalability, and sustainability in resource-constrained rural settings. Building on the literature reviewed above, Table 1 synthesizes the key research gaps and articulates how this study addresses each gap through specific conceptual, methodological, and empirical contributions.

Table 1. Research gap synthesis and study contributions

Literature stream	Key findings	Identified gaps	This study's contribution
Digital KM for Rural Development	Digital KM enhances productivity, innovation, and market integration for rural enterprises (C. Wang, 2025; W. Zhang, 2023)	• Limited empirical evidence from developing countries beyond India/China • Focus on individual KM components rather than integrated systems • Inadequate attention to socio-cultural prerequisites for adoption	• Develops an integrated KM platform tested in the Indonesian rural context • Addresses multi-component KM system (capture, storage, sharing, application) • Incorporates stakeholder engagement and cultural considerations

Literature stream	Key findings	Identified gaps	This study's contribution
Pentahelix Collaboration	Multi-stakeholder collaboration strengthens rural enterprise governance and sustainability (Effendi et al., 2023; Kania et al., 2021)	• Conceptual frameworks are well-articulated but lack digital operationalization • Limited evidence on coordination mechanisms and power dynamics • Insufficient attention to digital platforms as core enablers	• Operationalizes Pentahelix model through functional digital platform • Implements explicit coordination mechanisms (forums, repositories, dashboards) • Tests the platform's effectiveness in facilitating multi-stakeholder collaboration
Digital Technology Integration	Digital platforms bridge institutional silos and enable collaborative governance (Effendi et al., 2023; N. Zhang et al., 2023)	• Limited generalizability beyond India/Philippines case studies • Inadequate attention to the digital divide and sustainability • Lack of rigorous impact evaluation frameworks	• Provides evidence from a new geographic context (Tomini Bay, Indonesia) • Addresses digital literacy and connectivity constraints in design • Employs systematic evaluation (functional testing, UAT, performance metrics)

METHODOLOGY

This study employed a research and development (R&D) approach, integrated with the Agile Scrum framework, to develop a digital knowledge management platform for VOEs. The R&D approach was selected due to its iterative, user-centered process, which enabled systematic exploration, prototype design, and refinement in addressing practical challenges in VOE management (Cui et al., 2021). In parallel, Agile Scrum offered an adaptable development structure that emphasized collaboration, rapid iteration, and responsiveness to evolving requirements. Scrum's incremental sprints and frequent feedback loops proved well-suited to socio-technical projects where user needs and stakeholder inputs evolved dynamically (Uriawan et al., 2024). Combining R&D with Scrum ensured a system design that was both theoretically grounded and practically viable, with development cycles continually guided by stakeholder feedback and iterative testing (Shee et al., 2022).

As a conceptual foundation, the research developed a model that integrated the Pentahelix stakeholders into reciprocal knowledge flows to guide system design. In this framework, VOE managers interact with five stakeholder groups – government, academia, business, media, and community – to exchange knowledge resources and insights. Each stakeholder served as a knowledge source (e.g., the government contributed regulatory information, academia provided training and research, business shared market and process knowledge, media enhanced visibility and digital literacy, and the community offered local wisdom). At the same time, VOEs provided feedback on practical experiences and needs to each stakeholder group. Rather than a one-way transfer, knowledge exchange was cyclical and mutually reinforcing, ensuring that local enterprise practices continually informed institutional support and vice versa (Astriyantika et al., 2025; Bourke, 2025; Yunas et al., 2023).

To maintain knowledge quality across these exchanges, the platform's design included governance mechanisms such as content categorization by source and relevance, validation processes (including editorial checks and peer review within stakeholder groups), and user feedback loops to flag accuracy

or context issues. These provisions aligned with best practices in collaborative knowledge management, which emphasized structured curation and periodic updates to ensure reliability and relevance (Kalibala et al., 2021; Miklošík et al., 2021; Olszewski, 2021). To visualize this integrated framework, Figure 1 illustrates the conceptual Pentahelix integration model developed in this study, highlighting the bidirectional knowledge flows between VOEs and each stakeholder, as well as the feedback points where VOE input re-enters the system to support continuous learning and improvement.

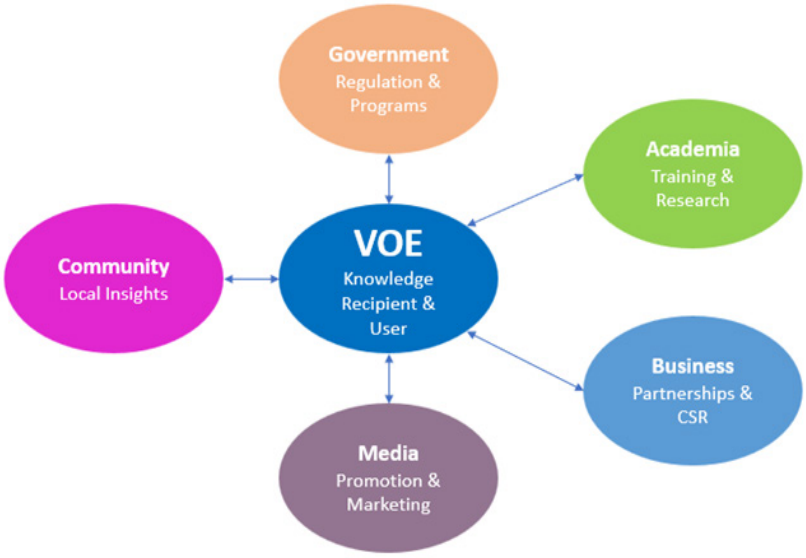

Figure 1. Conceptual model of pentahelix integration

SYSTEM IMPLEMENTATION

CASE STUDY AND REQUIREMENTS ELICITATION

The empirical context for this project was the coastal Tomini Bay region in Gorontalo Province, Indonesia. Within this region, four Village-Owned Enterprises (VOEs) – Tabongo Timur, Panggulo, Tamboo, and Moutong – were selected as case sites due to their active engagement in village economic development and their diverse operational contexts. To capture the needs and challenges of these VOEs, the study employed a triangulated requirements elicitation strategy. VOE managers participated in semi-structured interviews, provided direct observations of their business processes, and responded to structured questionnaires. This combination of qualitative and quantitative data collection provided a comprehensive understanding of the VOEs' operational environment. It also allowed for the identification of critical knowledge gaps in VOE operations and the mapping of stakeholder needs, which together informed the system's design requirements (Eiraldi et al., 2023; Slattery et al., 2020).

The requirements analysis revealed several recurring issues and needs across the case sites. VOE managers reported difficulties in accessing up-to-date regulatory information, limited market knowledge, and challenges in integrating technology into daily operations. Observation of existing workflows uncovered inefficiencies in record management and communication channels, underscoring the need for better knowledge-sharing tools. The questionnaire results further quantified user priorities, highlighting key desired system features. These included role-based user access (e.g., differentiating between VOE managers, government officials, academics, and others), interactive discussion forums to facilitate stakeholder communication, a searchable knowledge repository for documents and best practices, and performance dashboards to monitor enterprise outcomes.

By synthesizing insights from interviews, observations, and surveys, the development team constructed a product backlog that aligns with both the explicit requirements voiced by users and the latent needs gleaned from operational patterns. This ensured that the subsequent design and development steps remained grounded in actual VOE contexts and challenges.

Sampling Strategy. The four VOEs were purposively selected based on operational maturity (minimum two years of active business), stakeholder diversity (engagement with multiple Pentahelix actors), geographic distribution (Gorontalo and Bone Bolango regencies), sectoral variety (tourism, fisheries, agriculture, mixed enterprises), and management willingness to participate in iterative development. Eight managers (two per VOE) included both directors/chairpersons (strategic perspective) and village heads serving as supervisors (oversight perspective).

Data Triangulation. Requirements elicitation employed methodological triangulation combining interviews (n=8, 45-60 minutes each), direct observations during site visits, and questionnaires at sprint reviews. Interview coding yielded 127 discrete needs consolidated into 18 thematic categories, then synthesized into five Pentahelix-aligned requirement domains. Cross-validation strengthened confidence: for instance, "offline access" emerged in six interviews, was corroborated by observed connectivity issues (2-3 outages per visit), and was rated critically important (M=6.5/7.0) in Sprint 2 feedback.

Agile Development Process

System development was conducted using the Agile Scrum methodology, structured into four iterative sprints of approximately four weeks each. Based on the prioritized product backlog of 22 user stories derived from the requirements analysis, development progressed incrementally. Sprint 1 established foundational capabilities, including user registration, authentication, and basic VOE profile management. Sprint 2 implemented collaborative functions, including the discussion forum and document sharing modules. Sprint 3 focused on the knowledge repository, introducing content categorization and advanced search functions to support information retrieval. Sprint 4 developed an analytics dashboard for tracking user engagement and knowledge-sharing activities.

Daily stand-up meetings (also known as Scrum meetings) were held to coordinate the development team's tasks. At the end of each sprint, a review meeting was conducted, during which VOE managers evaluated the newly developed features. This iterative cycle (illustrated in Figure 2) ensured that development remained user-driven, allowing requirements to adapt through continuous stakeholder input and feedback. As shown in Figure 2, the development followed a cyclical Scrum process. Table 2 provides a comprehensive breakdown of each sprint, detailing the duration, focus area, and specific deliverables achieved during the approximately 19-week development period.

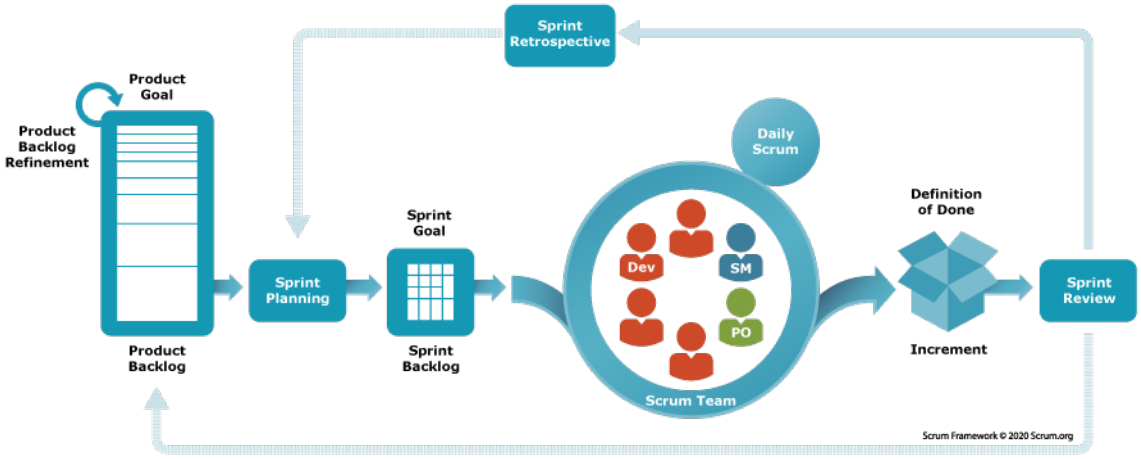

Figure 2. Stages of application development in the Scrum model

Table 2. Sprint timeline and key deliverables

Sprint	Duration	Focus area	Key deliverables
Sprint 0	2 weeks	Requirements & Planning	Interviews (n=8), product backlog, and architecture design
Sprint 1	4 weeks	Core Infrastructure	User authentication, basic dashboard, database schema
Sprint 2	4 weeks	Repository & Content	Knowledge repository, categorization, search functionality
Sprint 3	4 weeks	Collaboration Features	Discussion forum, Q&A module, user profiles & roles
Sprint 4	4 weeks	Analytics & Polish	Analytics dashboard, performance optimization, mobile responsiveness
Post-Sprint	1 week	Final Testing	Comprehensive testing, code review, and deployment preparation

Note: Total project duration approximately 19 weeks (4.5 months). Each sprint concluded with review sessions (stakeholder feedback) and retrospectives (process improvements).

Stakeholder Engagement. Stakeholder participation was staged across sprints: government representatives (n=2) engaged in Sprints 1-2 for regulatory content validation, academic partners (n=1) contributed in Sprint 2 for taxonomy review, business stakeholders (n=2) participated in Sprint 3 for market feature testing, and media partners (n=1) engaged in Sprint 4 for visibility evaluation. VOE managers (n = 8) participated continuously across all sprints as primary users, providing requirements, feedback, and validation throughout the development process.

System Architecture and Modeling

The system's architecture was designed in a layered fashion to integrate multiple knowledge sources while ensuring scalability and resilience. The final prototype comprised six layers: an Access Layer, providing users with a cross-device interface and handling authentication; a Client Layer, managing request/response processing with optimizations for intermittent rural internet connectivity; a Core Services Layer, encapsulating business logic for knowledge capture, curation, retrieval, and analysis; a Repository Layer, implementing a structured knowledge graph with domain-specific taxonomies and indexes to balance search precision and recall; a Data Storage Layer, for persistent storage of both structured database records and unstructured content; and a Knowledge Sources Layer, interfacing with external systems or stakeholder contributions (e.g., government open data and academic resources). This modular, layered design (Figure 3) separates system concerns across the stack, enabling targeted optimizations at each level and facilitating future integration with e-government portals or third-party services via well-defined APIs. Security and resilience were integrated throughout the architecture via secure authentication and authorization in the client and service layers, encryption of data in transit, and data replication and caching mechanisms to maintain performance during network interruptions.

To formally capture system requirements and behaviors, Unified Modeling Language (UML) diagrams were developed during the design phase. A Use Case model defined seven primary actor roles – VOE Manager, Government Officer, Academic, Business Partner, Media Contributor, Community Member, and System Administrator – and mapped their interactions with the system. Each role was linked to specific use cases aligned with its responsibilities within the Pentahelix framework. For example, Government Officers published regulatory documents, Academics uploaded training materials, and VOE Managers initiated discussions or queried the knowledge repository. This model helped delineate role-based access controls, ensuring that functionality aligned with stakeholder expectations, consistent with actor-centric design principles for multi-stakeholder platforms (Asqia,

2023; Diva & Priyadi, 2020). Figure 4 presents the use case diagram, showing the actors and their key use cases.

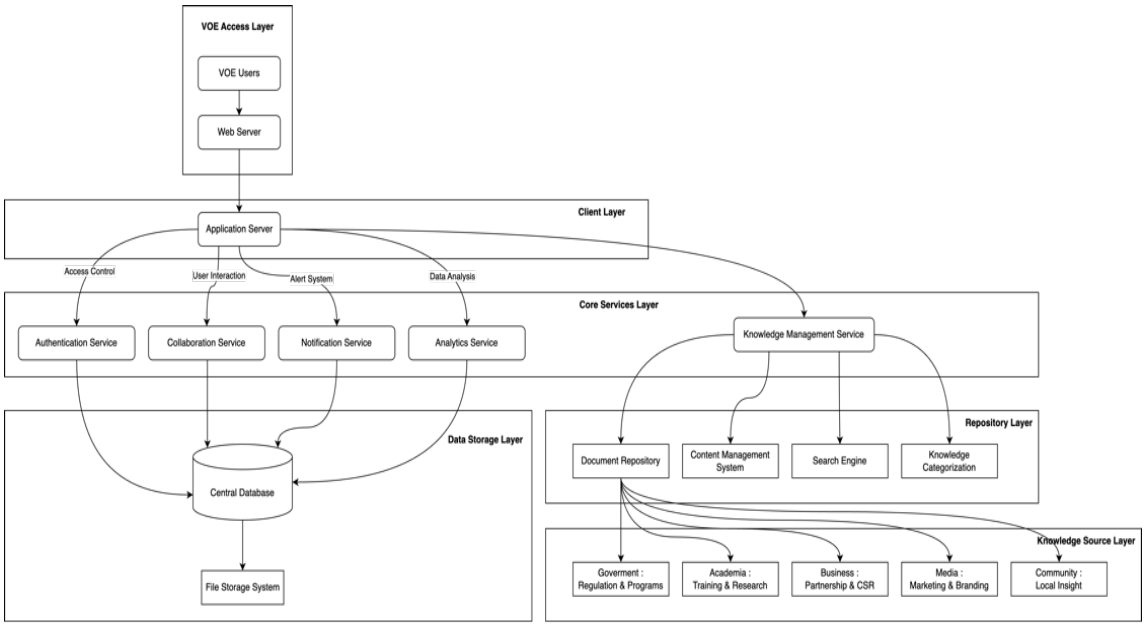

Figure 3. Pentahelix-based digital knowledge system architecture

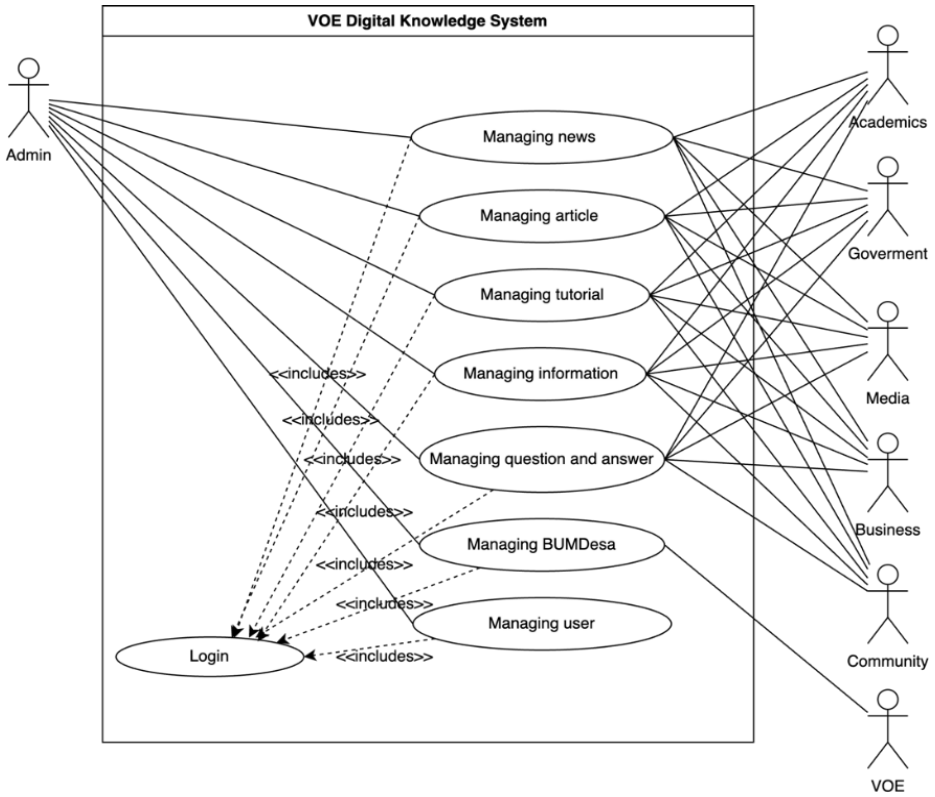

Figure 4. Use case diagram

For dynamic behavior, process-oriented models were created. An Activity Diagram and corresponding Sequence Diagram were used to design and verify critical workflows, with user authentication chosen as a representative example. The activity flowchart details each step from a user submitting login credentials to the system confirming the information and directing the user to the appropriate dashboard.

The sequence diagram mapped the interactions among interface components, controllers, and data stores during the login process, including handling of failed authentication and routing based on user roles. By explicitly modeling the authentication process (Figures 5a and 5b), the team ensured clarity in how security and session management were handled, aligning with recommendations in the design literature for transparent and secure user experiences in multi-actor systems (Shirole & Kumar, 2021; Song et al., 2021).

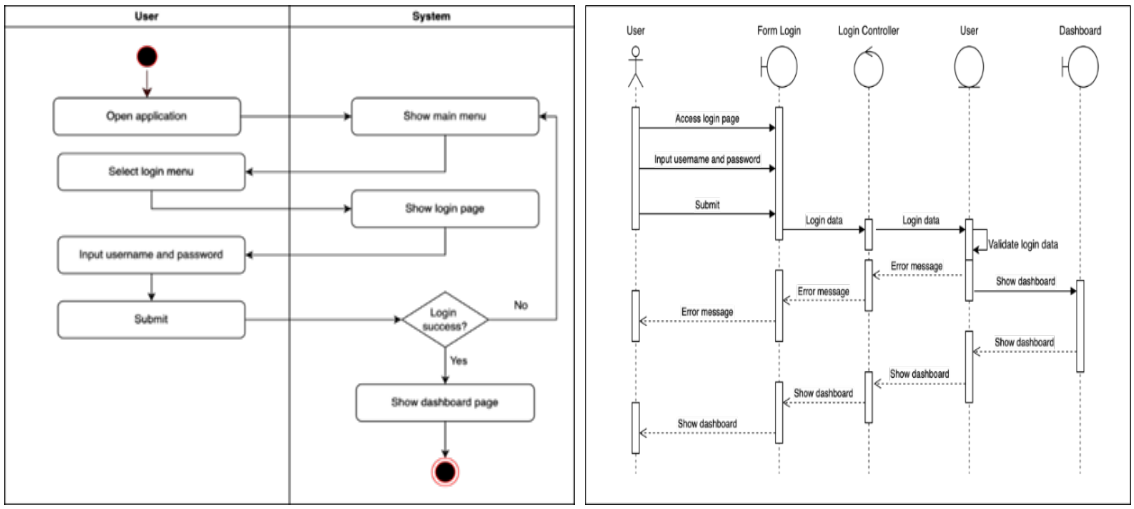

Figure 5. (a) The activity diagram, and (b) the corresponding sequence diagram

The structural design of the platform was represented through a Class Diagram that encapsulated the core data entities and their relationships. Ten primary classes were identified: User, Role, VOE (enterprise profile), Product, Article, News, Tutorial, Information (for announcements and regulations), Question, and Answer. These classes were interconnected to represent relationships between users, content, and organizational data; for example, linking VOE profiles to their associated products and connecting users to the content they contributed to or accessed. The class model (Figure 6) ensured a coherent schema for the knowledge repository and provided extension points for future features such as recommendation algorithms or advanced analytics. Following best practices for KM system design, the class structure was kept modular and normalized to support maintainability and scalability (Cabour et al., 2021; Kopp, 2022).

The UML modeling approach directly addresses Research Question 2 by formalizing the system's features and architectural components that support multi-stakeholder knowledge exchange. Use case diagrams operationalize Pentahelix stakeholder roles identified in RQ1, defining specific interactions each stakeholder type performs. Class diagrams establish the data architecture for categorizing, storing, and retrieving knowledge, while sequence diagrams illustrate the collaboration workflows central to the platform's knowledge management objectives.

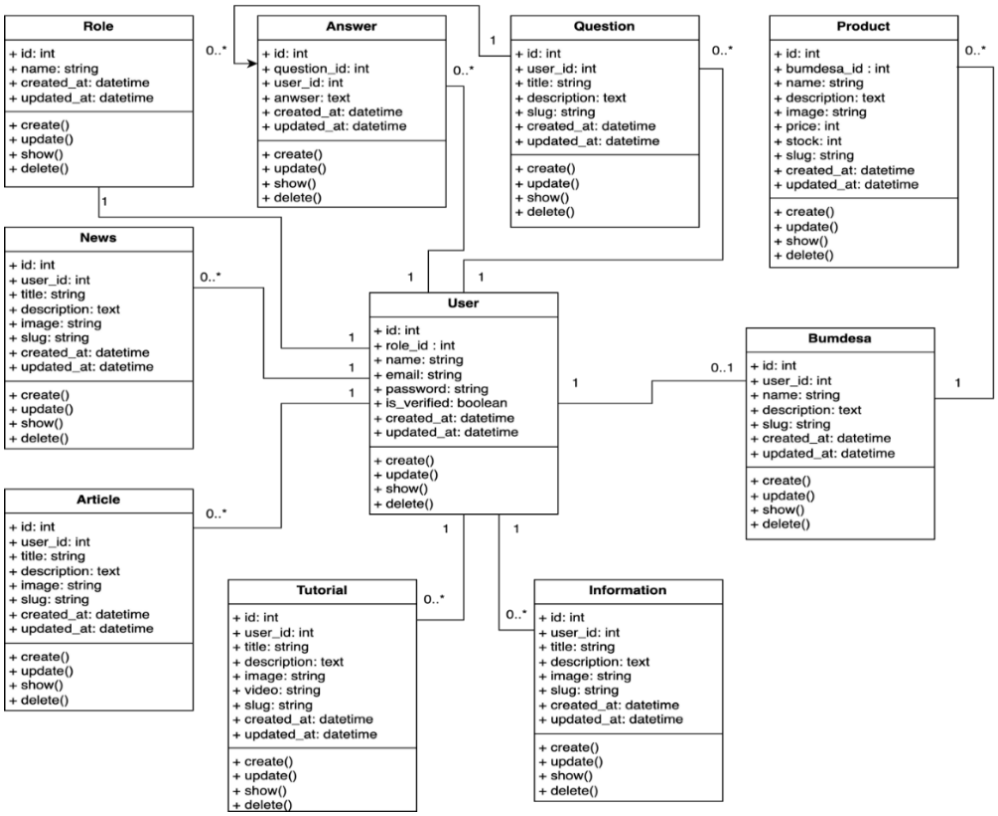

Figure 6. Class diagram

PROTOTYPE FEATURES AND USER INTERFACE

The implemented prototype was a web-based platform that consolidated the Pentahelix knowledge streams into a single accessible portal for VOEs. The landing dashboard featured a unified navigation menu providing direct access to stakeholder-specific sections. For example, the main menu (Figure 7) included entries for Government, Academia, Business, Media, and Community, each leading to a dedicated space with relevant content and tools. Within the Academic section, for instance, VOE managers could find training modules, research summaries, and tutorials tailored to rural enterprise development (Figure 8 provides a sample view of this section). A left-hand sidebar provided filtering options and quick links, allowing users to refine repository contents by type (e.g., articles, news, tutorials) or by tags and dates.

In addition to the knowledge repository and browsing features, the system included an interactive discussion forum where users across different helix groups could post questions, share experiences, and respond to ongoing conversations. Each VOE also had a profile management page where enterprise administrators could update their organizational information, list products or services, and highlight needs or success stories. These features were designed to encourage active participation and knowledge exchange, mirroring approaches in similar rural knowledge projects where cloud-hosted repositories and community forums improved scalability and engagement (Mukti et al., 2022; B. Zhang et al., 2021).

Significant attention was given to the user interface design to ensure accessibility for users with varying levels of digital literacy. The main pages of the application, such as the overall dashboard and the user registration page (shown in Figures 9a and 9b), feature a clean layout with high-contrast text and intuitive navigation cues. Key actions – such as searching the knowledge base, adding a new post, or

updating a profile – were made prominent and accompanied by brief on-screen instructions, or "microcopy," to guide users. These design choices were informed by usability principles and prior studies suggesting that simple, clear interfaces help sustain user engagement in diverse user groups (Hiryanto et al., 2024; Rose & Ghazali, 2023).

Moreover, the platform was built to be mobile-responsive, acknowledging that many rural users would access the system via smartphones. By ensuring the interface remained clear and functional across devices, the system maximized its potential reach and usefulness in the field.

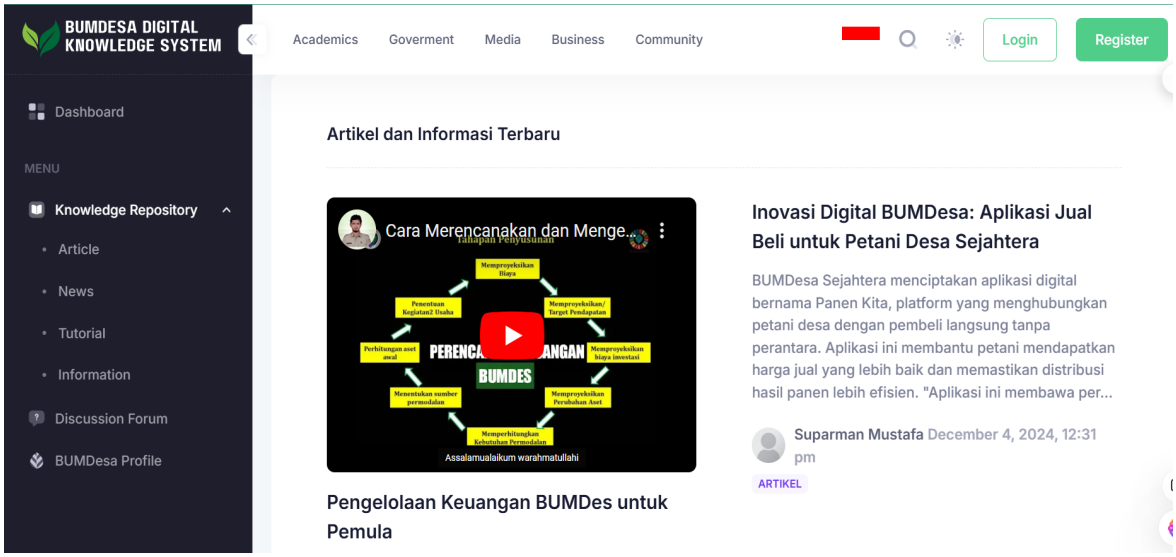

Figure 7. Main menu (dashboard)

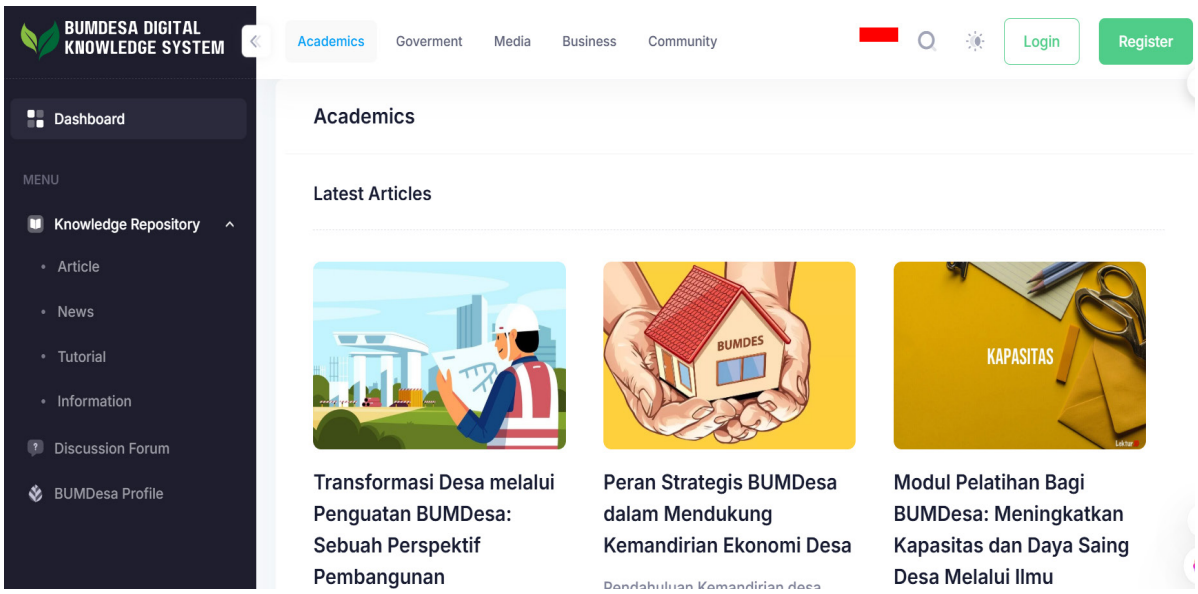

Figure 8. Academics menu

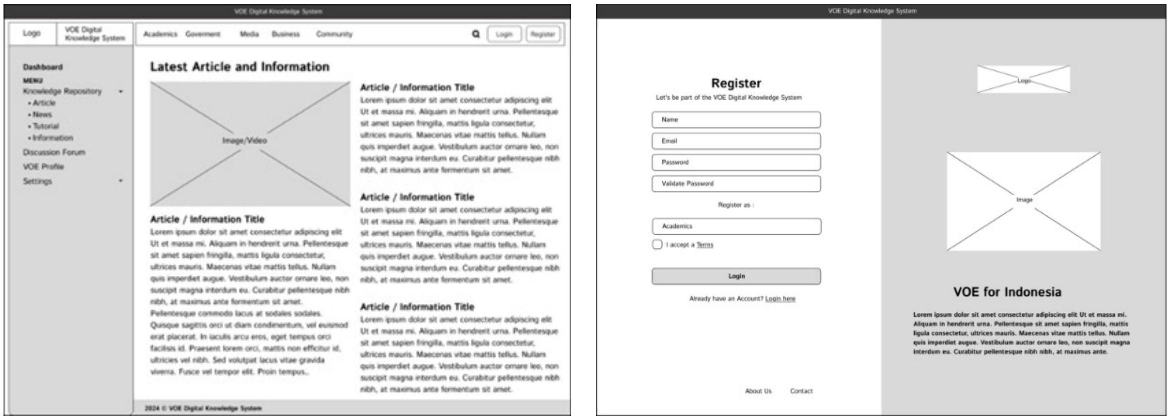

Figure 9. (a) Dashboard and (b) registration page interface design

EVALUATION

The evaluation of the digital knowledge management platform employed a multi-method approach combining technical verification, performance assessment, and user-centered validation to ensure functional reliability and alignment with VOE operational needs in rural deployment contexts.

EVALUATION METHODOLOGY

The evaluation framework integrated three complementary approaches: (1) formal software testing to verify functional correctness and code quality through black-box and white-box methods, (2) iterative user acceptance testing (UAT) embedded within Agile development to validate workflow alignment and usability, and (3) qualitative analysis of user feedback to understand contextual fit and adoption potential. This triangulated approach provided convergent evidence from developer, administrator, and end-user perspectives (Broekhuizen et al., 2021).

Evaluation activities were conducted iteratively across four sprint cycles rather than as terminal validation. At each sprint conclusion, newly implemented features underwent immediate testing and user review, enabling the rapid resolution of issues and ensuring that user feedback directly shaped subsequent development priorities (Trabucchi et al., 2024). This integration of evaluation within development proved essential for maintaining quality while preserving responsiveness to emerging user needs.

TESTING SETUP AND PROTOCOLS

Black-box functional testing

Black-box testing validated the external system's behavior against functional specifications derived from 22 user stories elicited during the requirements analysis. Test cases were systematically designed to cover primary user journeys, without examining the internal code structure, simulating realistic usage scenarios that VOE managers would encounter in their daily operations.

Test Environment: A staging server was used that mirrored the production configuration (PHP 8.1, MySQL 8.0, Apache 2.4). Testing was conducted on desktop browsers (Chrome, Firefox) and mobile devices (Android smartphones) to ensure cross-platform compatibility, reflecting the diverse access modes of rural users.

Test Case Development: Twenty representative test cases were documented across five critical modules: User Management (5 cases), Knowledge Repository (5 cases), Discussion Forum (3 cases), VOE Profile Management (4 cases), and Stakeholder Content Areas (3 cases). Each test case specified preconditions, input data (both valid and invalid), expected outcomes, and pass/fail criteria, ensuring systematic validation across all functional requirements.

Test Execution and Results: Two testing phases were conducted. Phase 1 (Sprint 3 conclusion) identified four moderate-severity usability issues: unclear error messages (2 cases), inconsistent date formatting (1 case), and missing input validation (1 case). Notably, no critical or high-severity defects (such as system crashes, data loss, or security vulnerabilities) were detected, indicating that the iterative process effectively prevented significant errors. All issues were resolved within one development week through targeted fixes. Phase 2 (Sprint 4 completion) confirmed a 100% pass rate across all documented test cases, validating complete issue resolution without regressions.

White-box structural testing

White-box testing examined internal code structure, logic flows, and implementation quality to complement behavioral validation. Cyclomatic complexity analysis assessed code maintainability, while static analysis verified security practices.

Complexity Analysis: Cyclomatic complexity evaluation of representative functions revealed well-structured code with manageable complexity. Figure 10 presents the control flow graph for the article submission function – a typical CRUD operation involving validation, conditional file handling, and database persistence.

Figure 10 illustrates decision points (orange diamonds), processing steps (blue rectangles), and terminal nodes (green rounded rectangles). The graph consists of 10 nodes, representing distinct computational steps, 11 directed edges representing control flow transitions, and one connected component. Cyclomatic complexity V(G)=3 indicates three linearly independent paths requiring test coverage: Path 1 (red) handles validation failure, Path 2 (blue) processes submissions without custom images using default placeholders, and Path 3 (green) handles complete submissions with custom image uploads. The complexity score V=3 falls well below the maintainability threshold (V≤10), indicating straightforward logic amenable to comprehensive testing and future modification. The complexity score V=3, calculated as $V(G) = E - N + 2P = 11 - 10 + 2(1) = 3$, indicated three independent paths: validation failure leading to form redisplay with errors, valid submission without a custom image using default image assignment, and valid submission with custom image processing. Broader sampling confirmed that 93% of functions maintained $V \leq 10$, with no functions exceeding $V = 15$, indicating a well-structured codebase conducive to maintenance and testing (McCabe, 1976).

Security Validation: Static analysis using PHPStan identified only low-severity issues (unused variables, redundant declarations, minor naming inconsistencies). Critically, no security vulnerabilities were detected: all database queries used parameterized prepared statements, preventing SQL injection, all user content was sanitized, preventing XSS attacks, authentication and authorization were properly enforced, and error messages did not expose sensitive system details. This clean security profile validated adherence to secure coding practices throughout implementation.

User acceptance testing

UAT engaged VOE managers directly in evaluating system fitness for operational deployment through facilitated workshops at the conclusion of each sprint, treating users as active co-evaluators whose experiential knowledge was essential for assessing practical utility.

Participant Profile: Eight VOE managers were recruited from four village enterprises in the Tomini Bay region based on specific criteria: active operation for a minimum of 2 years (ensuring mature operational understanding), willingness to participate across all sprints (sustained engagement), and internet access availability (technical feasibility). The four selected VOEs represented diverse contexts:

- **Tabongo Timur VOE** (Gorontalo Regency): Tourism and agricultural marketing
- **Panggulo VOE** (Bone Bolango Regency): Fisheries and local trade
- **Tamboo VOE** (Bone Bolango Regency): Agricultural processing
- **Moutong VOE** (Bone Bolango Regency): Mixed enterprises (retail, services, manufacturing)

From each VOE, two participants were engaged: the VOE Director/Chairperson (primary operator) and the Village Head, serving as the VOE supervisor, ensuring both operational and governance perspectives. Participants' self-reported digital literacy averaged 3.0/5.0 (moderate), with a range of 2-4, accurately reflecting rural VOE contexts where formal technology training is limited. Table 3 presents the complete demographic profile of the eight participants.

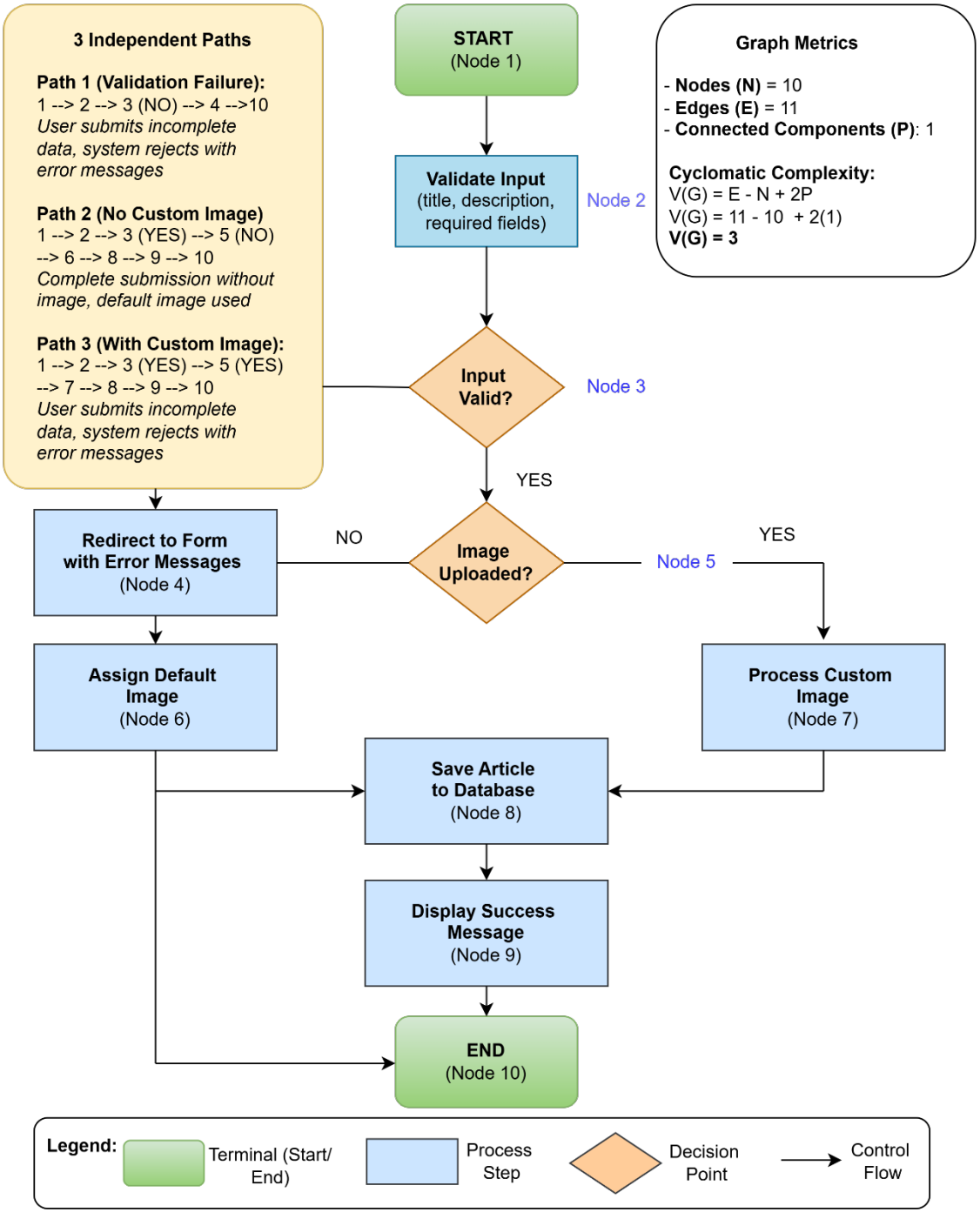

Figure 10. Control flow graph for the article submission function

Table 3. Participant demographics (N=8)

Characteristic	Category	n	%
Gender	Male	6	75%
	Female	2	25%
Age Group	30-39 years	2	25%
	40-49 years	4	50%
	50-59 years	2	25%
Education	High School	3	37.5%
	Diploma/Bachelor	5	62.5%
VOE Experience	2-3 years	3	37.5%
	4-5 years	3	37.5%
	6+ years	2	25%
Digital Literacy	Limited	4	50%
	Moderate	3	37.5%
	Advanced	1	12.5%

Participant demographics revealed a predominantly male sample (75%), reflecting broader patterns in village leadership in Indonesia. The age group clustered in the 40-49 range (50%), representing experienced mid-career managers. Education was split between high school (37.5%) and tertiary levels (62.5%). Digital literacy was generally limited to moderate levels (87.5%), reinforcing the importance of user-centered design that accommodates varying technical capabilities.

UAT protocol: Each 2-hour session followed a standardized protocol: (1) **Orientation** (15 min) introducing new features and establishing evaluation mindset, (2) **Hands-on Testing** (75 min) where participants performed scenario-based tasks using laptops or personal devices while facilitators observed without intervening, (3) **Structured Discussion** (20 min) eliciting pain points and improvement suggestions, and (4) **Questionnaire Completion** (10 min) measuring acceptance constructs on 7-point Likert scales.

User acceptance measurement. Participants provided quantitative ratings using 7-point Likert scales (1=strongly disagree, 7=strongly agree) measuring perceived usefulness ("This platform would improve my ability to access knowledge for VOE management"), ease of use ("I find it easy to navigate the platform"), and intention to adopt ("I intend to use this platform regularly"). Open-ended questions elicited feedback on functional features, encountered difficulties, and suggested improvements. All input was documented and reviewed in sprint retrospectives for iterative refinement.

Scenario-based tasks: Tasks exercised features within authentic workflows. Examples included: *Sprint 1* – "Register for account, verify email, complete VOE profile, explore dashboard"; *Sprint 2* – "Search for government funding program, save information, configure notifications"; *Sprint 3* – "Read forum question from peer, provide helpful response sharing insights"; *Sprint* – "Upload financial report, organize appropriately, verify retrieval and access sharing."

Feedback integration: All findings were reviewed within 48 hours in sprint retrospectives. Issues were prioritized by severity, with high-priority items added to the backlog for the next sprint. Figure 2 visualizes this iterative feedback integration cycle.

Figure 11, iterative user feedback integration cycle embedded within Agile Scrum development process. The cycle consists of five phases: (1) Sprint Development implementing prioritized features over 4 weeks, (2) UAT Session where 8 participants evaluate new features through 2-hour workshops, (3) Feedback Analysis categorizing issues by severity within 48 hours, (4) Sprint Retrospective reviewing lessons learned and updating the product backlog, and (5) Sprint Planning integrating high-

priority feedback into the next sprint. The dashed orange arrow represents the continuous feedback loop, demonstrating how user insights directly shape subsequent development cycles, enabling early defect detection, rapid issue resolution, and progressive refinement based on empirical evidence.

Concrete refinement examples: Sprint 2 feedback about confusing search results led to Sprint 3 interface redesign with content-type icons, stakeholder-domain color tags, and publication date stamps. Sprint 3 requests for advanced filtering drove the implementation of multi-criteria search with dropdown filters for domain, content type, and date range in Sprint 4. This tight feedback loop exemplified responsive, evidence-based development.

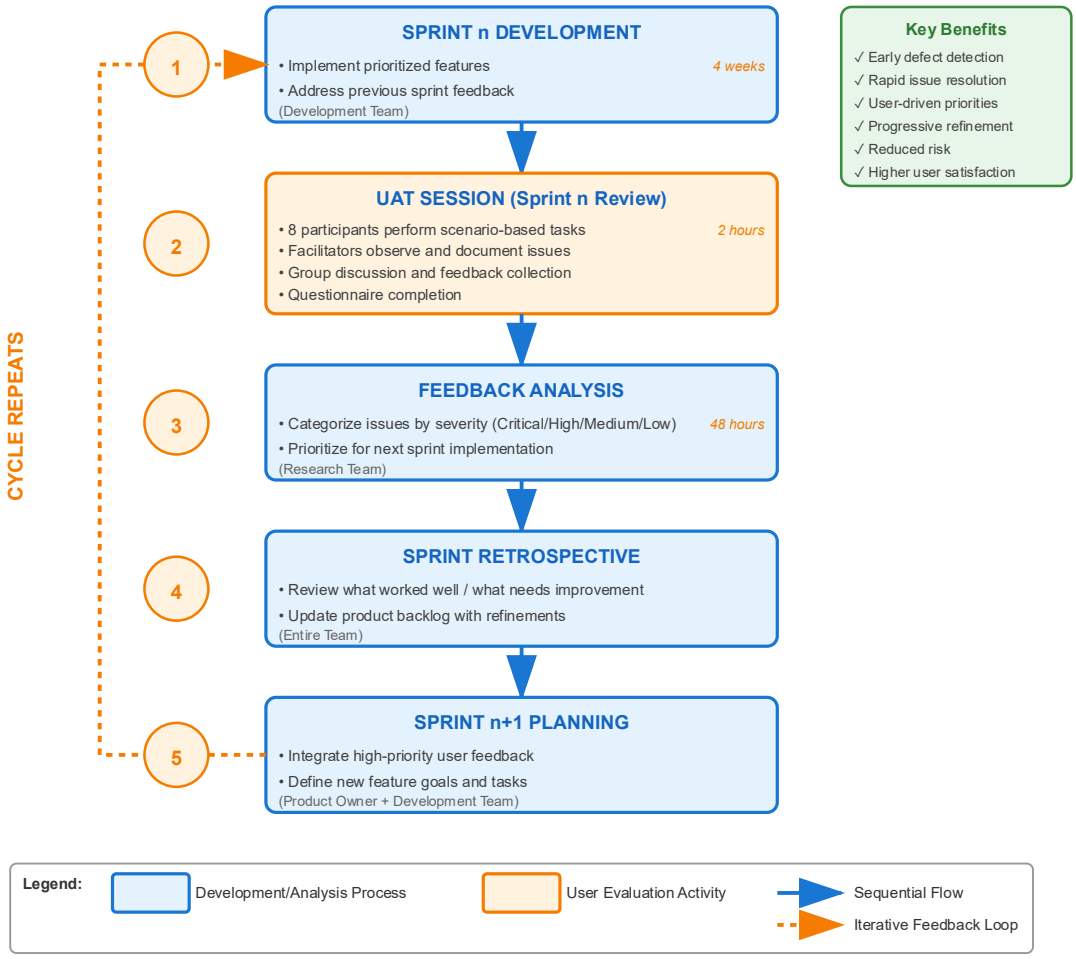

Figure 11. Iterative user feedback integration cycle

Evaluation Results

Functional testing outcomes

Black-box testing demonstrated high reliability, with progressive improvement across phases. Initial testing revealed four moderate-severity usability issues: inconsistent error messaging, variations in date format, and missing validation feedback, all of which impacted the user experience but did not compromise functionality or data integrity. All issues were resolved within one development cycle. Final testing confirmed a **100% pass rate**, with no critical defects detected throughout the development process. This progression validated the effectiveness of the Agile approach in detecting early defects and facilitating rapid remediation.

Code quality assessment

White-box testing confirmed technical quality conducive to long-term maintenance. Cyclomatic complexity analysis revealed that 93% of functions had a $V \leq 10$, indicating a manageable code structure. The exemplar article submission function (V=3, Figure 1) illustrated straightforward control flow typical throughout the system. Static analysis identified only low-severity issues with no security vulnerabilities, validating secure coding practices. Database query optimization, including the addition of composite indexes, reduced complex search execution time by 60-75% (from 800-1200ms to 200-350ms), significantly improving responsiveness.

User acceptance and satisfaction

UAT across four sprints yielded convergent evidence of strong user reception. Table 4 presents final evaluation satisfaction scores.

Table 4. User acceptance scores (sprint four final evaluation)

Construct	Mean score (1-7)	Std. dev.	Interpretation
Perceived Usefulness	6.2	0.7	Strongly positive - Highest rated
Intention to Use	6.0	0.8	Positive - Strong adoption intent
Overall Satisfaction	5.9	0.8	Positive - General approval
Perceived Ease of Use	5.8	0.9	Positive - Acceptable learning curve
Feature Completeness	5.6	1.0	Moderate positive - Enhancement opportunities

Note: n=8 participants, 7-point Likert scale (1=strongly disagree, 7=strongly agree, 4.0=neutral)

All constructs scored significantly above neutral (4.0), indicating positive perceptions. **Perceived Usefulness** (M=6.2) received the highest ratings, suggesting users strongly recognized platform value for addressing knowledge management needs – critical for platform adoption. **The Intention to Use (M = 6.0) score indicated genuine adoption intent rather than a** polite endorsement. The modest gap between Ease of Use (5.8) and Usefulness (6.2) suggested that users found the learning curve acceptable, given the perceived benefits.

Task Performance: By Sprint 4, objective completion rates were high: 100% successfully updated VOE profiles, 95% completed document searches without assistance, and 90% posted forum responses. Time-on-task measurements revealed learning effects, as document search time decreased from 4.2 minutes (Sprint 2) to 2.8 minutes (Sprint 4), a 33% reduction, demonstrating efficiency gains from interface refinements.

Qualitative Feedback Themes: Users consistently appreciated the Pentahelix stakeholder organization, noting that it aligned with their conceptualization of knowledge sources: "This makes it easy to know where to look – if I need funding, I check Government and Business sections." The discussion forum received an enthusiastic reception: "Finally, a place where we can learn from each other's experiences!" Multiple participants requested mobile apps with offline capability, highlighting rural connectivity constraints that inform future development priorities.

Figure 12 visualizes the progression of satisfaction and performance across sprints, demonstrating the cumulative benefit of iterative refinement. The figure shows progressive improvement in user satisfaction and task performance across four sprint cycles. The left panel shows overall satisfaction scores on a 7-point Likert scale, increasing from 5.1 (Sprint 1) to 5.9 (Sprint 4), representing a 16% improvement. The right panel displays task completion rates without assistance, rising from 72% (Sprint 1) to 95% (Sprint 4), representing a 32% improvement. Both metrics exhibit consistent upward trends, validating the effectiveness of iterative refinement. Key improvements per sprint—search functionality (Sprint 1→2), interface redesign with visual indicators (Sprint 2→3), and advanced filtering (Sprint 3→4)—yielded measurable user experience gains. The convergence toward

higher satisfaction and completion rates by Sprint 4 indicates cumulative refinements successfully addressed usability issues and aligned features with user needs and workflows.

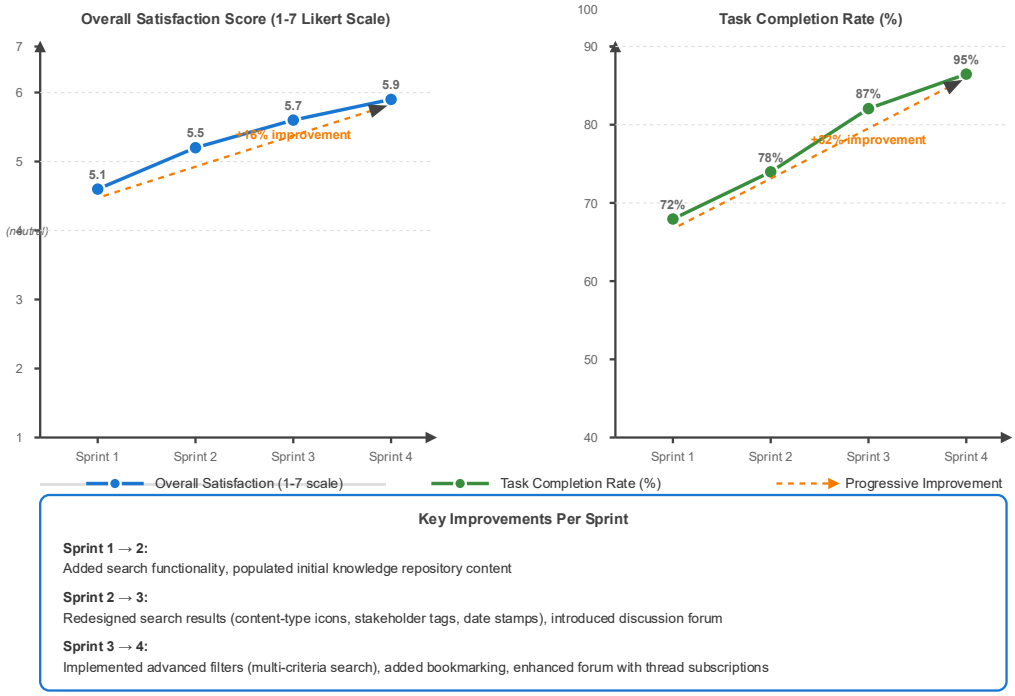

Figure 12. User engagement and satisfaction progression across sprints

Discussion of Evaluation Findings

The multi-method evaluation provided convergent evidence that the platform successfully achieved core objectives: functional reliability, technical quality, and alignment with VOE operational needs.

Technical validation: The 100% final pass rate with no critical defects validated functional reliability. White-box analysis confirmed maintainable code structure ($V \leq 10$) and secure implementation, essential for rural deployment with limited technical support. Database optimization transformed adequate features into responsive ones, underscoring the need for evaluation to assess quality attributes beyond correctness and accuracy.

User acceptance: Strong Perceived Usefulness (M=6.2) and Intention to Use (M=6.0) indicated high adoption potential – critical for rural digital interventions where acceptance cannot be assumed. The discussion forum's enthusiastic reception validated that knowledge co-creation and community building may prove as valuable as information access, as communities of practice are powerful mechanisms for organizational learning (Wenger, 1998).

Iterative refinement impact: The progression from Sprint 1's cautious interest to Sprint 4's intense satisfaction (+16%) and from 72% to 95% task completion (+32%) provided concrete evidence that continuous user involvement yielded superior outcomes compared to traditional approaches. Each sprint's feedback shaped subsequent development, creating a virtuous cycle where users felt heard while developers gained empirical guidance. This approach reduced risk by identifying and correcting problems incrementally when they were small and localized, thereby keeping correction costs low through early intervention (Boehm, 1981).

Contextual appropriateness: Participants represented actual target users – rural VOE managers with moderate digital literacy in resource-constrained environments. Their successful completion rates (90-100%) and positive satisfaction ratings validated the appropriateness of the design for this

context. However, recurring requests for offline capability highlight infrastructure constraints that the current web platform does not fully address, informing future priorities.

Pentahelix operationalization: The explicit stakeholder-organized content architecture proved effective in helping users understand and navigate the multi-actor ecosystem. Comments about knowing "where to look" and being prompted to think about "who else to talk to" suggest that the platform successfully operationalized the abstract Pentahelix concept into practical structures.

Limitations: The relatively small sample size (n = 8 from 4 VOEs) is suitable for formative evaluation but may limit generalizability. Evaluation occurred in facilitated sessions, which may have influenced behavior. Post-deployment field studies, which observe natural usage, would provide complementary ecological validity. Future research should examine actual adoption rates, the impact on VOE performance outcomes (including funding success, market access, and management practices), the evolution of the forum community, and scalability to additional contexts. Despite limitations, the evaluation provided robust evidence supporting the platform's functional reliability, technical quality, and user acceptance, offering reasonable confidence for pilot deployment and meeting the intended objectives of enhancing knowledge management and multi-stakeholder collaboration among VOEs in the Tomini Bay region.

Synthesis of findings. Evaluation demonstrates that the platform successfully meets design objectives across multiple dimensions. Technical quality metrics confirm maintainable code (93% functions with $V \leq 10$) and reliable functionality (100% test pass rate). Performance optimization reduced query times by 60-75%. User acceptance scores indicate substantial perceived value ($M = 6.2$, usefulness) and adoption intention ($M = 6.0$), both of which are significantly above neutral. Task completion improved from 72% (Sprint 1) to 95% (Sprint 4), validating the effectiveness of iterative refinement. Qualitative feedback highlights the successful operationalization of Pentahelix, while identifying ongoing needs for enhanced offline functionality and expanded training. These convergent findings establish the empirical foundation for discussing theoretical contributions and practical implications.

DISCUSSION

THEORETICAL IMPLICATIONS

The findings articulated how a Pentahelix-oriented digital knowledge management (KM) system translated conceptual collaboration models into operational capability for Village-Owned Enterprises (VOEs). The conceptual model (Figure 1) demonstrates that knowledge flows are not linear conduits but reciprocal cycles in which VOEs are both beneficiaries and contributors to a shared knowledge base. This reciprocity aligns with the multi-actor development literature, which shows that rural innovation ecosystems thrive when local practices and institutional expertise co-evolve through iterative exchange and mutual adjustment (Afandi et al., 2024; Wijaya et al., 2023). In the Tomini Bay context, VOEs utilized stakeholder-specific channels to align regulatory compliance, managerial learning, market exploration, and promotion with situated community insights, a pattern that mirrored broader evidence showing that stakeholder synergy strengthens local identity while widening economic opportunities (Hasanah et al., 2024; Sentanu et al., 2021). The bidirectionality of the flows further substantiated that Pentahelix collaboration was more than role aggregation; it was a governance modality that reorganized who produced, validated, and mobilized knowledge at the periphery, in alignment with observations in rural enterprise and ecotourism collaborations (Bourke, 2025; Yunas et al., 2023).

When viewed in light of the layered architecture (Figure 3), these relational dynamics became technically actionable. The separation into Access, Client, Core Services, Repository, Data Storage, and Knowledge Sources layers operationalized concerns noted in the KM and distributed-systems literature: resilience under intermittent connectivity, controlled surface area for security, and performance

tuning proximal to user interaction (Bainomugisha & Mwotil, 2021; Saboia et al., 2022). The Repository and Core Services layers held particular importance because they encoded the rules of knowledge curation, categorization, and retrieval that determined the precision–recall tradeoffs users experienced. Interoperability adapters designed for prospective integration with e-government and open-data services reflect lessons from health informatics and cultural heritage repositories, where standardized schemas and APIs extend cross-system functionality while preserving domain semantics (Ertürkmen et al., 2021; Tsipi et al., 2023). The empirical result was an architecture capable of supporting a gradual path from a prototype serving local needs to a platform that could federate with external systems as policy and capacity matured (Widiatmoko et al., 2023; Yao, 2024).

Comparing this prototype with analogous systems reveals both convergent strategies and distinctive contributions. The NCoRe platform in India (Bandyopadhyay et al., 2020; Basak & Bhaumik, 2023) similarly connects rural producers, urban consumers, and institutional actors through a unified digital ecosystem, demonstrating how e-platforms can bridge the rural-urban divide. However, NCoRe primarily emphasized supply-chain integration and market linkages. In contrast, this study's platform explicitly operationalizes multi-stakeholder knowledge governance through role-differentiated access, structured editorial workflows, and Pentahelix-aligned collaboration mechanisms. The "smart village" initiative in the Philippines (Camba, 2024) integrated government services, educational resources, and economic support into a single platform, echoing this study's vision of cross-sectoral integration. Yet the Philippine model relies heavily on centralized government provisioning. At the same time, this platform distributes knowledge production and validation across five stakeholder groups, thereby institutionalizing plural governance rather than hierarchical service delivery. Both international examples validate the technical feasibility of integrated rural digital platforms but operate within stronger infrastructure and institutional contexts. This study's contribution lies in demonstrating that a modular, stakeholder-governed KM platform can function effectively in resource-constrained settings with intermittent connectivity and variable digital literacy – conditions characteristic of many rural areas in developing countries.

Technical Implementation and Design Decisions

The system design decisions illustrated how the model's social complexity was transformed into implementable software. The use case model aligned actor responsibilities with least-privilege access and transparent editorial governance, thereby reducing the friction often reported when heterogeneous stakeholders converge on a single platform (Asqia, 2023; Diva & Priyadi, 2020). Focusing the activity and sequence diagrams on authentication addressed a ubiquitous cross-cutting concern – secure, comprehensible onboarding – whose failure could erode trust and reduce participation in rural deployments (Shirole & Kumar, 2021; Song et al., 2021). The resulting flow, which routed users to role-specific dashboards, reinforced the proposition that microcopy and visual affordances shaped early impressions and guided digital novices through complex tasks, a claim reinforced in human–computer interaction studies in mixed-literacy populations (Asri et al., 2024; Hiryanto et al., 2024; Rose & Ghazali, 2023).

The class model supported extensibility by separating content types (articles, news, tutorials, Q&A) from organizational entities (VOE, product), an approach endorsed in prior KM platform designs to enable analytics, recommendations, and governance policy enforcement without entangling content logic with identity management (Cabour et al., 2021; Kopp, 2022). Implementation outcomes indicated that these design choices resulted in a usable platform. Early field feedback indicated that VOE managers could locate regulatory circulars, training modules, and market guidance with fewer steps in the navigation. The forum provided a venue for problem-solving that did not require participants to be present synchronously. Such patterns aligned with reports that cloud-hosted, repository-centered systems scaled access while training and governance sustained adoption (Intezari et al., 2021; Mukti et al., 2022; B. Zhang et al., 2021). By embedding editorial and peer-validation mechanisms into the

content lifecycle, the system also addresses recurrent critiques of open KM initiatives, where unmoderated submissions can dilute quality. This risk is mitigated here through categorization, review cycles, and user feedback loops (Kalibala et al., 2021; Miklošík et al., 2021).

The verification strategy shed light on how the concept of 'fit-for-purpose' was assessed under rural constraints. The combination of black-box and white-box testing, supplemented by structured sprint reviews and user acceptance testing (UAT), closely mapped to recommendations for validating sociotechnical platforms where end-user perception and internal code quality jointly determined reliability and sustainability (de Souza et al., 2021; Sigalla et al., 2021; Trabucchi et al., 2024). In this study, functional coverage across registration, authentication, repository search, content submission and moderation, and forum use was further supported by performance checks that revealed latency improvements from caching and pagination. Beyond immediate functionality, the analysis of the prototype's role in the broader VOE ecosystem invited consideration of policy and market linkages. The architecture's prospective integration with e-government and e-commerce responded to arguments that public digital services and market platforms formed complementary infrastructures for rural empowerment: the former streamlined compliance and participation, the latter improved market reach and price discovery (Nam et al., 2024; Wa & Zhang, 2023).

Practical Implications

Aligning KM processes with these infrastructures helped reduce administrative overhead while amplifying the return on knowledge uptake, a synergy repeatedly emphasized in governance and public–private partnership literature (Widiatmoko et al., 2023; Yao, 2024). Yet realizing this complementarity placed demands on interoperability, consent management, and equitable data-sharing arrangements that needed to be embedded into APIs and governance policies from the outset, to prevent integration from reproducing asymmetries that disadvantaged rural producers. The trajectory from prototype to mature platform also depended on automating parts of the knowledge lifecycle and deepening analytics. Evidence from enterprise KM suggested that analytics could reveal bottlenecks in knowledge flows, identify high-value artifacts, and support predictive services; recommender systems could tailor discovery to user roles and histories, thereby increasing engagement and skill acquisition (Milano et al., 2020; Xu et al., 2021).

However, the ethics and political economy of automation in rural contexts should not be treated as afterthoughts. The same recommender engines that personalize learning could unintentionally restrict exposure or reinforce stakeholder biases unless they were designed with multi-perspective representation and transparency (Milano et al., 2020; Zhitomirsky-Geffet & Hajibayova, 2020). Food informatics research has highlighted similar tensions, advocating for design choices that align algorithmic optimization with sustainability and community benefit – lessons that translate well into rural enterprise platforms (Karpati et al., 2020). This study's class and repository structures created technical space for such features, but their implementation required explicit ethical frameworks, participatory model auditing, and governance mechanisms that prioritize community agency (Aryaningsih et al., 2021; Prikshat et al., 2022).

Considerations of privacy and security intensified when pooled knowledge blended personal, organizational, and community-generated content. Stakeholder concerns typically revolved around consent, confidentiality, secondary use, and the right to be forgotten, especially where power differentials and historical marginalization exacerbated risks (Tang & Zhao, 2023). The authentication and role-resolution design illustrated in Figure 4 laid a foundation for differential access control; however, long-term legitimacy depended on transparent data catalogs, precise provenance tracking, and consent dashboards that enabled contributors to manage visibility and revocation. Integrating such safeguards with government and commercial platforms added complexity but was essential to maintaining trust as the system scaled. The layered security posture – encompassing encryption in transit, authorization at service boundaries, and storage-level protections – addressed standard attack surfaces but required

complementing it with capacity-building efforts so that local operators could understand and implement effective data stewardship.

The question of impact, finally, extended beyond usage statistics to whether the platform changed patterns of collaboration, business performance, and community well-being over time. Longitudinal evaluation designs needed to track knowledge uptake through training and assessment, collaboration intensity through joint projects and social network analysis, and enterprise outcomes through revenue, profitability, and customer indicators, while also capturing community-level measures of inclusion and cultural vitality (Hasanah et al., 2024; Rahu & Suprayitno, 2021; Romero-Rodríguez et al., 2020; Yuniati et al., 2023). The results here – that VOE managers gained navigational clarity and access to a broader set of resources – were encouraging but not sufficient in isolation. Embedding instrumentation for these indicators into the platform could transform it into its own evaluation apparatus, providing regular, low-friction snapshots that guide adaptive governance and targeted support. Such embedded evaluation also strengthened arguments for diversified, durable funding through grants and public–private partnerships by demonstrating value with evidence rather than rhetoric (Fofuh & Awolusi, 2021; Jansen & Kalas, 2020).

Sustainability, Scalability, and Transferability

Long-term platform sustainability requires careful attention to four dimensions: financial, human resource, temporal, and governance. Annual operational costs are estimated at USD 1,200-1,500, comprising web hosting (USD 300-400), domain registration and SSL certificates (USD 150-200), security updates and software patches (USD 400-500), and periodic technical support (USD 350-400). Personnel requirements include a minimum of one part-time digital facilitator per 3-4 village cluster (approximately 10-15 hours per week), responsible for user support, content quality monitoring, and stakeholder coordination. Additionally, quarterly 2-day training workshops are provided for new users and feature updates. Timeline for achieving full stakeholder integration is estimated at 6-12 months post-deployment, with government and academic validation workflows requiring 3-4 months to establish, business and media content streams developing over 4-6 months, and community adoption reaching critical mass (>60% active monthly users) by 8-10 months. Governance structure should establish a multi-stakeholder oversight board with quarterly review cycles, representation from all five Pentahelix helices (government two seats, academia one seat, business two seats, community three seats, media one seat), rotating 2-year chairmanship, and transparent decision-making protocols for content policies, feature prioritization, and conflict resolution. These concrete requirements enable realistic planning for platform sustainability beyond pilot implementation.

Sustainability and transferability also depend on institutional arrangements as much as on code. Iterative engagement practices from Agile Scrum in this project aligned with broader findings that regular stakeholder contact increased ownership and accelerated problem resolution, particularly in volatile or resource-constrained settings (Aguirre et al., 2024; Castillo López et al., 2023).

To scale beyond Tomini Bay, the system required offline-first features and localized language and examples to accommodate uneven connectivity and heterogeneous literacies, in alignment with recommendations for rural digitization efforts (Ibrahim & Alenezi, 2024; Nguyen & Dang, 2024). Governance boards that included VOE representatives, government, academia, businesses, media, and community advocates helped institutionalize plural oversight, while API-level commitments to interoperability lowered barriers to integrating with regional initiatives. A culture of continuous learning—backed by feedback channels, issue trackers, and periodic retrospectives—helped keep the platform aligned with shifting needs and policies, consistent with evidence that adaptive learning processes mediated the relationship between KM investments and sustained impact (Holmes et al., 2023; Lillis et al., 2025; Vanderlinden et al., 2022).

CONCLUSION

This study demonstrated the feasibility and effectiveness of integrating the Pentahelix model with a digital knowledge management (KM) platform to strengthen the management and sustainability of Village-Owned Enterprises (VOEs). By operationalizing bi-directional knowledge flows among government, academia, business, media, and community stakeholders, the system fostered reciprocal learning and collaboration that directly enhanced VOE capacity. The layered system architecture and design models ensured scalability, security, and usability, while iterative development through Agile Scrum facilitated continuous stakeholder engagement. Testing outcomes confirmed the reliability of the platform, and early implementation highlighted its potential to improve access to regulatory, technical, and market knowledge. Significantly, the prototype not only facilitated knowledge access but also encouraged collaboration and innovation, positioning VOEs to expand their market reach and optimize local resources.

The findings underscored that digital KM platforms, when anchored in multi-stakeholder frameworks, served as strategic enablers of rural development. The integration of the platform with potential e-government and e-commerce systems suggested significant implications for participatory governance, market democratization, and rural economic empowerment. Ethical and governance considerations, particularly concerning privacy and data ownership, required robust frameworks to ensure equitable benefit-sharing and community trust. Furthermore, the platform's adaptability to diverse digital readiness contexts signaled its transferability to other rural regions, provided that localized adjustments were made. This research contributed to the body of knowledge by offering both a conceptual framework and a tested prototype for digitally mediated multi-stakeholder collaboration in rural enterprise development. Future studies could explore the integration of automation, advanced analytics, and recommender systems while further evaluating the longitudinal impacts on business performance, collaboration intensity, and community well-being.

For practitioners, implementation should begin with pilot programs in four villages, supported by a minimum of four weeks of digital literacy training before platform deployment. VOE managers should designate knowledge champions to facilitate peer support and organize bi-weekly knowledge-sharing sessions. Government agencies should establish multi-stakeholder governance boards with quarterly review cycles to ensure sustained coordination within the Pentahelix. Technology developers should prioritize offline-first capabilities and role-based access controls, ensuring platform functionality in resource-constrained rural settings with intermittent connectivity.

This study's limitations include the sample scope (eight VOE managers from four villages in the Tomini Bay region), limiting generalizability to other Indonesian contexts with different socio-economic conditions and institutional support systems. The four-month development timeframe precluded assessing long-term sustainability, post-deployment usage patterns, or measurable business performance impacts, such as revenue growth, customer base expansion, or operational efficiency improvements. Evaluation relied on prototype testing during development rather than extended field deployment with actual VOE operations.

Future research should prioritize longitudinal studies (12-24 months) measuring actual adoption rates, sustained usage patterns, and quantifiable business outcomes across different performance dimensions. A comparative effectiveness analysis examining platform performance across Indonesian regions, VOE sectors (tourism, fisheries, agriculture, and mixed), and enterprise scale levels would enhance generalizability. Research investigating the integration of new systems with existing government e-government infrastructure and national digital ecosystems merits attention. Scalability studies should examine how knowledge quality and stakeholder engagement can be maintained as platforms expand to larger enterprise networks.

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