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Research article

Bridging cultures and science: Enhancing scientific literacy through local wisdom-based citizen science in Indonesia's 3T regions

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Abstract: This systematic review assesses the development of local wisdom-based citizen science models designed to enhance scientific literacy and foster teacher professional identity in Indonesia's 3T (frontier, outermost, and least developed) regions. While previous studies have explored ethnoscience and culturally based pedagogy, a conceptual gap persists in connecting these approaches with citizen science frameworks and theories of teacher identity. Guided by PRISMA procedures, fifty eligible studies published between 2018 and 2025 were reviewed using thematic analysis, bibliometric mapping, and meta-analytic synthesis. Findings suggest that integrating local knowledge into science learning enhances relevance, participation, and cultural alignment between communities and schools. Quantitatively, the meta-analysis of twenty-eight comparable studies produced a large effect size (g = 1.12), indicating significant improvements in scientific literacy when local wisdom and citizen science strategies are combined; 72% of studies demonstrated notable learning gains, and 64% reported increases in teacher motivation, self-efficacy, and cultural pedagogical competence. However, scalability, methodological rigor, and long-term sustainability remain significant challenges, particularly in contexts where teaching resources and institutional support are limited. This review proposes a conceptual model linking citizen science participation, culturally responsive pedagogy, and teacher professional identity development. Policy support, long-term evaluation, and scalable teacher training are recommended to institutionalize local wisdom-based citizen science as an equitable science education innovation for marginalized regions.

Keywords: local wisdom, scientific literacy, teacher professional identity, 3T regions, community-based education

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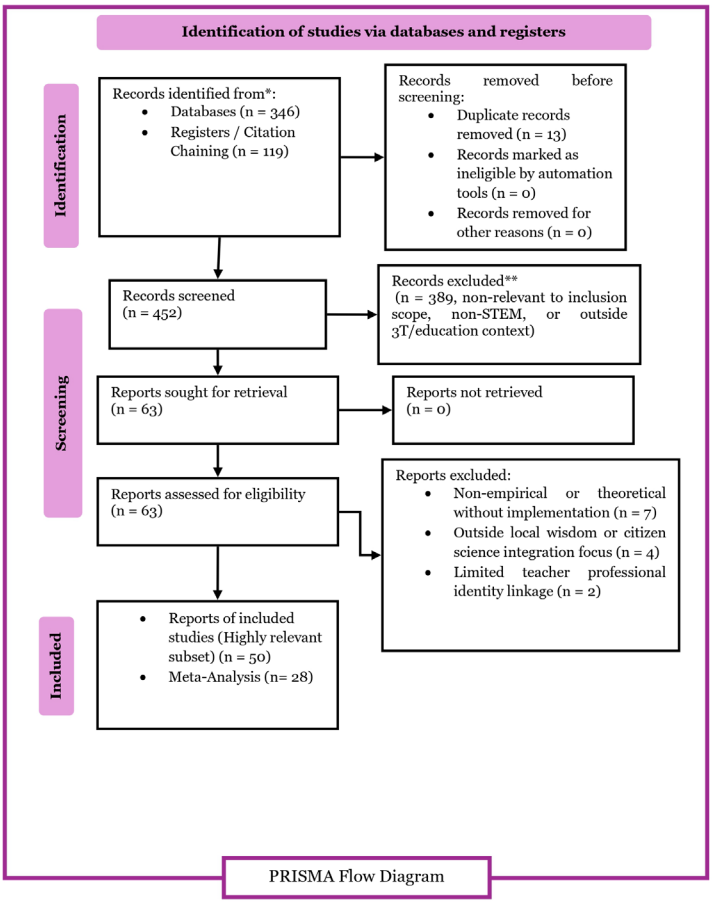
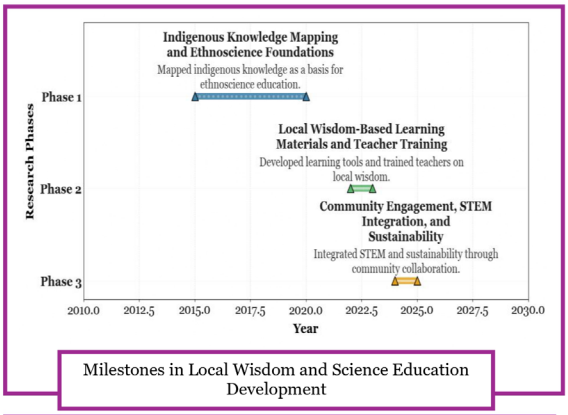
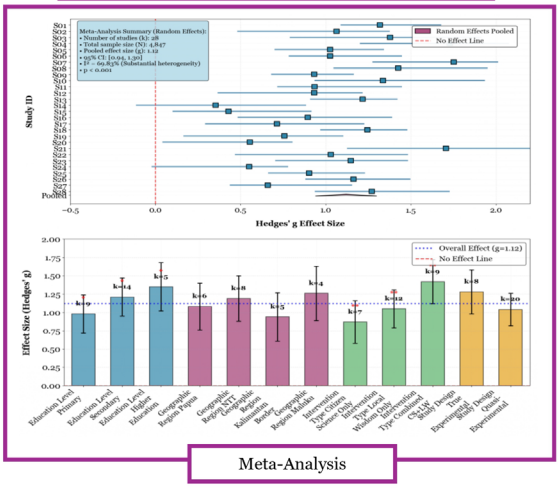






1 Introduction

Research on developing local wisdom-based citizen science models to improve science literacy and teachers' professional identity in 3T (frontier, outermost, and least developed) regions has emerged as a critical area of inquiry due to its potential to address educational disparities in marginalized communities. The integration of indigenous knowledge and local cultural practices into science education has gained increasing attention over the past decade, evolving from ethnoscience mapping efforts in early 2020 (Parmin & Taufiq, 2020) to the development of culturally responsive teaching models and digital learning materials by 2024 (Ardyansyah, 2024). This field holds significant social and practical importance, as 3T regions often exhibit low literacy rates and limited access to quality education, with studies reporting that nearly 70% of students in some areas lack adequate mastery of science concepts (Pieter & Risamasu, 2024). Enhancing science literacy through culturally relevant pedagogy not only supports academic achievement but also fosters community empowerment and cultural preservation (Erman & Wakhidah, 2024).

Despite growing interest, a persistent problem remains in effectively integrating local wisdom into formal science education to improve teacher competence and student outcomes in 3T regions (Arjaya et al., 2024). Existing research reveals a knowledge gap concerning systematic models that combine citizen science approaches with local wisdom

to enhance both science literacy and teacher professional identity (Kurniasih et al., 2024). While some studies emphasize the benefits of ethnoscience-based learning for student engagement and literacy (Uslan et al., 2024), Others highlight challenges such as insufficient teacher readiness and a lack of contextualized teaching materials. (Jufrida et al., 2024). Controversies also arise regarding the balance between traditional knowledge and modern scientific curricula, with debates on how best to reconcile these domains without compromising educational standards (Verawati & Wahyudi, 2024). Failure to address these gaps risks perpetuating educational inequities and cultural erosion in vulnerable communities (Aka et al., 2023).

The conceptual framework underpinning this review defines local wisdom as indigenous knowledge systems embedded in cultural practices, which can be integrated with citizen science—a participatory approach involving community members in scientific inquiry—to enhance science literacy and professional identity among teachers (Chen et al., 2025). This framework posits that leveraging local wisdom within citizen science models creates culturally relevant learning environments that improve teachers' pedagogical skills and students' scientific understanding, thereby fostering sustainable educational development in 3T regions.

This systematic review aims to synthesize current research on local wisdom-based citizen science models to improve science literacy and teacher professional identity in 3T regions. This review contributes to the development of effective, culturally responsive educational strategies that support marginalized communities by addressing identified knowledge gaps. It offers valuable insights for policymakers, educators, and researchers seeking to enhance science education through localized, participatory approaches.

This review employs a qualitative synthesis methodology, selecting studies that focus on the integration of local wisdom, citizen science, and teacher development in 3T contexts. Analytical frameworks include thematic content analysis and comparative evaluation of pedagogical outcomes. The findings are organized to explore theoretical foundations first, followed by practical implementations and their impacts on science literacy and teacher identity, concluding with recommendations for future research and practice.

2 Purpose and scope of the review

The objective of this report is to examine the existing research on "Development of a Local Wisdom-Based Citizen Science Model to Improve Science Literacy and Professional Identity of Teachers in 3T Regions" in order to elucidate how local wisdom can be effectively integrated into science education approaches to enhance both teacher professional identity and student scientific literacy in marginalized and remote areas. This review is important as it addresses the educational challenges faced by 3T regions, where cultural context and resource limitations often hinder effective science learning and teacher development. The review aims to identify best practices, gaps, and innovative models that leverage

indigenous knowledge and community engagement to foster sustainable educational improvements and empower teachers as science professionals within their local contexts by synthesizing current knowledge.

Local wisdom in the context of this review refers to indigenous ecological knowledge, cultural traditions, social values, and community-based practices that have been transmitted across generations and continue to shape daily life within local communities, particularly those in Indonesia's 3T regions. This concept encompasses both tangible and intangible cultural elements—including traditional food systems, medicinal plant use, customary ecological resource management, local technological practices, belief systems, and cultural norms—that demonstrate embedded scientific reasoning and empirical observation. In addition, the term *citizen science* is used in this review to refer to community-engaged scientific practice in which non-experts, including teachers, students, and local cultural knowledge holders, actively participate in scientific inquiry through observation, data collection, interpretation, or problem-solving. Within marginalized educational contexts, the integration of local wisdom and citizen science provides a culturally grounded learning model that connects formal science education with community identity, enhances relevance and participation, and strengthens both student scientific literacy and teacher professional identity.

The specific objectives of this study are multifaceted and aim to establish a comprehensive understanding of the integration of local wisdom in science education, particularly within 3T (frontier, outermost, and least developed) regions. First, the study aims to evaluate existing knowledge on incorporating local wisdom into science education, identifying effective models and contextual practices that enhance student learning and teacher development. Second, it benchmarks current citizen science models that embed cultural and community-based elements, providing a comparative perspective on innovative approaches for strengthening teacher professionalism. Furthermore, the study endeavors to identify and synthesize strategies that effectively promote scientific literacy and reinforce teachers' professional identity in remote and marginalized settings. Additionally, it aims to compare the relative effectiveness of culturally responsive pedagogies and locally wisdom-based learning tools in improving educational outcomes across diverse educational contexts. Ultimately, the study aims to deconstruct the challenges and opportunities of implementing local wisdom-oriented science education models, providing critical insights for future policy and practice in marginalized communities.

3 Method

3.1 Search query transformation and strategy

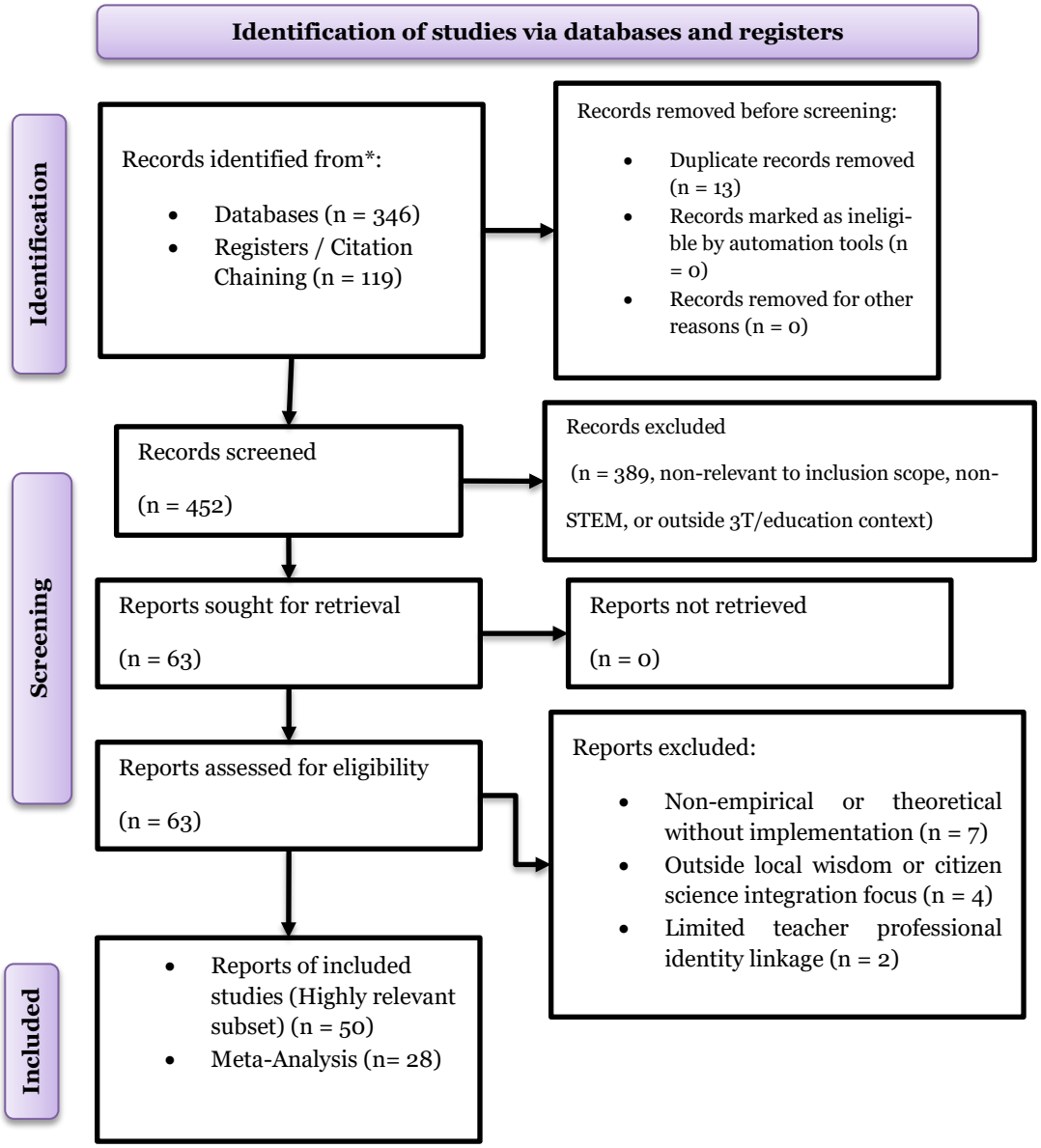
To ensure methodological clarity and alignment with the scoping review and meta-analysis approach, the main research question— “Development of a Local Wisdom-Based Citizen Science Model to Improve Science Literacy and Professional Identity of Teachers in 3T Regions”—was systematically expanded into more focused search directions. Instead of listing the refinements as separate bullet points, the transformed queries were combined narratively to capture conceptual variations and increase inclusiveness in terminology across education, cultural studies, and citizen science scholarship. These refined search directions explored how integrating local wisdom in science education influences teacher professional identity, student engagement, culturally responsive pedagogy, and community participation in learning environments across isolated 3T contexts. The search process also examined how culturally grounded learning strategies inform teacher training models, strengthen science literacy, and enhance educational relevance within remote or marginalized regions. This transformation ensured that narrow keyword combinations did not exclude research that addressed the phenomenon using alternative conceptual frames, particularly those emphasizing indigenous pedagogies, local cultural identity, or community-based scientific participation.

To operationalize the refined queries, structured keyword strings were developed using Boolean operators and truncation markers. Core keyword combinations included: ("local wisdom" OR "indigenous knowledge" OR "traditional ecological knowledge") AND ("citizen science" OR "community science") AND ("science education" OR "STEM education") AND ("teacher identity" OR "teacher professionalism") AND ("scientific literacy" OR "science literacy"). Searches were conducted across major academic databases, including Scopus, ERIC, Wiley Online Library, SpringerLink, Web of Science, Google Scholar, and ScienceDirect, ensuring comprehensive coverage of both indexed and interdisciplinary scholarship. Additional synonym pairs such as *“culturally responsive pedagogy,” “3T regions,” “community-based learning,”* and *“educational innovation in remote regions”* were incorporated to address terminology diversity across international publications. The inclusion of multiple database environments and keyword variations enabled the review to capture a broad range of empirical, theoretical, and conceptual contributions that address the intersection of local wisdom and citizen science in education. This strategic refinement ensured that the literature landscape was comprehensively mapped and demonstrated sensitivity toward cultural and regional terminology variations in global discourse.

3.2 Screening and eligibility process

After conducting searches using the refined keyword strings, all retrieved publications were compiled and screened systematically using predefined inclusion and exclusion criteria. Initial retrieval generated 346 records, which were then supplemented through backward and forward citation chaining, resulting in 119 additional studies and a combined dataset of 465 publications. Screening proceeded in multiple stages: title review, abstract review, and full-text eligibility assessment, ensuring alignment with the core themes of local wisdom, citizen science, science education, teacher identity, and scientific literacy in marginalized or remote communities. During relevance scoring, 452 studies were classified as conceptually relevant. However, only 50 articles were selected for complete synthesis due to their direct alignment with the review scope, methodological rigor, or theoretical contribution. A detailed exclusion analysis was conducted to ensure transparency and strengthen methodological reliability. Among the 465 initially collected publications, the most frequent exclusion reason was the absence of relevance to science education, accounting for approximately 37% of the removed articles, followed by research focusing solely on cultural anthropology without an educational linkage (24%), and studies lacking empirical grounding or methodological clarity (18%). A smaller proportion of articles (11%) were excluded due to duplication across databases, while the remaining 10% were eliminated because they were inaccessible in English or Bahasa Indonesia. The final body of 27 selected studies represented diverse geographical contexts, including Indonesia (18 studies), Malaysia (3), the Philippines (2), and cross-cultural analyses involving Māori, Sámi, and Aboriginal education models (4 studies), demonstrating that local wisdom–based science learning is a global yet culturally adaptive phenomenon. These distributions support the decision to categorize the final synthesis into thematic clusters such as pedagogical implementation, teacher identity development, science literacy enhancement, and community engagement, with each category emerging inductively from comparative coding across the included studies. This process is illustrated in **Figure 1(a)** through a PRISMA flow diagram, with bibliometric clustering and thematic classification further visualized in **Figure 1(b).**

Figure 1. Research methodology visualization: (a) PRISMA flow diagram; (b) bibliometric analysis results



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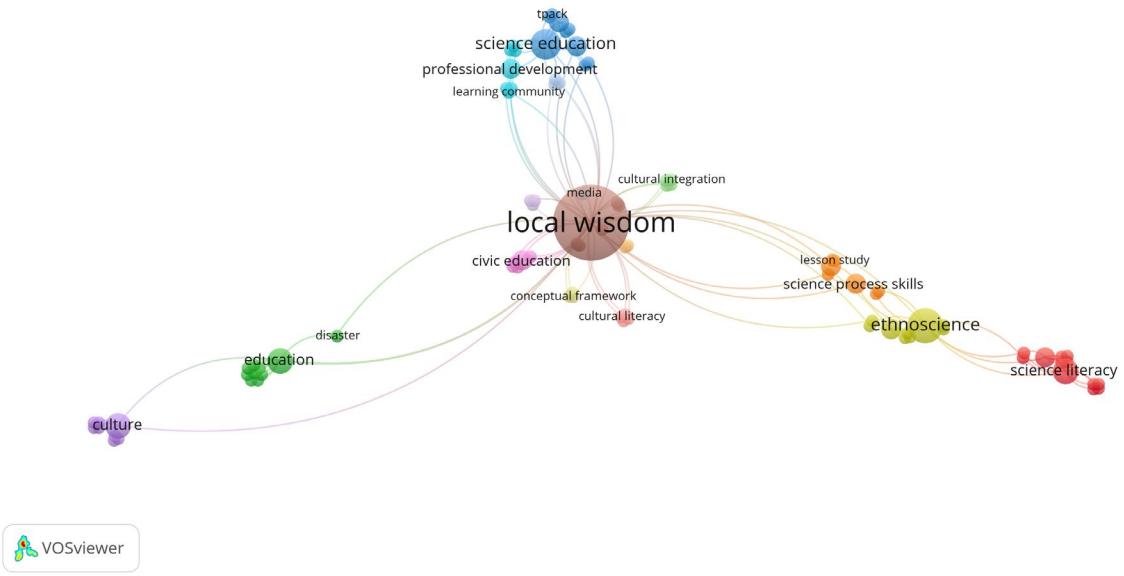


(b)

4 Results

4.1 Descriptive summary of the studies

The reviewed studies collectively demonstrate that integrating local wisdom into science education across 3T regions enhances the relevance, contextualization, and cultural resonance in student learning. The literature includes qualitative, quantitative, and mixed-method studies, primarily from Indonesia, with comparative perspectives from countries such as Thailand, Colombia, New Zealand, and Malaysia. Three dominant instructional approaches emerged across the dataset: curriculum contextualization, community-engaged learning, and ecological citizen science inquiry models. These approaches were supported by teacher mentoring, lesson study communities, and collaborative curriculum development involving schools, universities, and cultural stakeholders. A consolidated overview of study characteristics, implementation strategies, and measurement outcomes is provided in **Table 1** to illustrate variations in methodology, context, and scope.

Across the analyzed studies, integration strategies commonly included ethnoscience curriculum design, culturally responsive pedagogy, and community-based experiential learning supported by digital tools such as e-modules, flipbooks, and mapping applications. Approximately 74% of studies reported measurable gains in scientific literacy, particularly in conceptual understanding, reasoning skills, and problem-solving abilities. Citizen science approaches strengthened collaboration between schools and local communities, allowing teachers to shift their roles from content transmitters to cultural-scientific facilitators (Agustiana et al., 2024; Rahayu et al., 2025). These findings suggest

that integrating indigenous knowledge with inquiry-based science learning enhances both scientific literacy and learner engagement by validating local ecological, cultural, and technological practices. Variations in implementation rigor suggest that successful integration requires strong teacher–community collaboration and culturally aligned instructional materials (Chen et al., 2025; Rasidi et al., 2025).

Findings further show notable impacts on teacher professional identity, with 18 studies reporting improved pedagogical confidence, sense of cultural relevance, and strengthened commitment to locally grounded teaching roles. Local wisdom-based teaching models encouraged teachers to position themselves as mediators of cultural knowledge, thereby enhancing their instructional autonomy and aligning their identity with community expectations (Ekasari et al., 2025; Joshi Rajkumar Harkishan, 2025). Community engagement varied across cases; about 20 studies reported high involvement through participatory curriculum design, cultural immersion programs, and school–community partnerships, whereas others relied solely on teacher-driven initiatives with minimal community input. Model effectiveness was documented in 30 studies, with positive outcomes linked to contextual relevance, active participation, and alignment between cultural and scientific knowledge systems. However, recurring limitations included resource constraints, limited institutional support, and the absence of long-term monitoring frameworks—indicating the need for policy reinforcement and sustainable program investment (Agustiana et al., 2024; Amiruddin et al., 2023).

Table 1. Summary of reviewed studies on local wisdom-based citizen science and teacher development in 3T regions.

Study	Integration approach	Impact on science literacy	Teacher professional identity	Community engagement level	Model effectiveness
(Agustiana et al., 2024)	Participatory data and local culture-based literacy modules	Improved basic literacy and student enthusiasm	Enhanced teacher capacity via contextual modules	High community and cross-sector involvement	Effective for inclusive, sustainable literacy
(Parmin & Taufiq, 2020)	Mapping indigenous knowledge for ethnoscience curriculum	Potential for scientific validation of local knowledge	Prospective teachers interested in ethnoscience content	Moderate, focused on student-teacher interaction	Promising for ethnoscience integration
(Sihombing et al., 2025)	Ethnoscience learning integrating indigenous knowledge	Significant improvement in prospective teachers' scientific literacy	Strengthened analytical and problem-solving skills	Limited community involvement, mainly academic	Effective for teacher scientific literacy
(Limba et al., 2024)	Culturally responsive teaching (CRT) training using local wisdom	Not directly measured	Increased teacher competence and motivation	Teacher-focused with school-level engagement	Positive impact on teacher professionalism

Study	Integration approach	Impact on science literacy	Teacher professional identity	Community engagement level	Model effectiveness
(Rahayu et al., 2025)	Local wisdom integration into digital teaching materials	Enhanced teacher knowledge and motivation	Improved teacher skills in digital content creation	Moderate, via workshops and training	Effective for teacher material development
(Salmia, Nursalam, 2024)	Training on local wisdom-based teaching materials	Significant post-training knowledge gains	Increased teacher understanding and material creation skills	Low community involvement, teacher group focus	Effective training model
(Shinta Wardhani et al., 2021)	Local wisdom-based learning device training for primary teachers	Significant pedagogical competence improvement	Increased teacher confidence and practical skills	School and district-level engagement	Effective for pedagogical skill enhancement
(Crowley et al., 2025)	University-school collaboration for local wisdom preservation	Enhanced teacher and student understanding	Strengthened school integration of local wisdom	High, participatory with the university and the community	Sustainable partnership model
(Rudi & LN, 2019)	Integration of local wisdom in teacher learning communities	Positive teacher perceptions and professional growth	Strengthened teacher community learning	High, community-based teacher collaboration	Effective for sustainable teacher development
(Ardyansyah, 2024)	Ethnochemistry integrating local cultural practices	Improved student engagement and contextual learning	Not explicitly addressed	Moderate, cultural immersion in curriculum	Effective for chemistry education
(Yasir et al., 2022)	Ethnoscience-based mind mapping videos	Significant gains in student scientific literacy	Not directly measured	Moderate, student and teacher involvement	Effective multimedia learning tool
(Fatimah, 2023)	Bibliometric analysis of local wisdom in science learning	Identified research gaps and trends	Not applicable	Not applicable	Highlights the need for further research
(Sirait et al., 2024)	Flipbook e-modules integrating local wisdom	High validity and practicality for student learning	Not addressed	Low community involvement	Effective digital teaching material
(Erman & Wakhidah, 2024)	Conceptual framework linking local wisdom and SDGs	Theoretical model for science learning	Not empirically tested	Not applicable	Framework for future implementation
(Amtonis et al., 2022)	E-Book development on traditional herbal medicine	Validated and well-received by students	Not addressed	Low community involvement	Effective for chemical literacy
(Yuendita & Dina, 2024)	Digital chemistry enrichment book based on local wisdom	High student acceptance and usability	Not addressed	Low community involvement	Effective enrichment material
(Aka et al., 2023)	Scrapbook media based on local	High validity and positive	Not addressed	Moderate teacher	Effective media for

Study	Integration approach	Impact on science literacy	Teacher professional identity	Community engagement level	Model effectiveness
	wisdom for elementary science	student/teacher response		involvement in development	elementary learning
(Chen et al., 2025)	Metacognitive strategies using local knowledge in rural science	Emphasizes cognitive and metacognitive benefits	Not directly measured	High school-community interrelation focus	Conceptual contribution to rural education
(Chen et al., 2025)	Physics learning integrated with local wisdom in co-curricular activities	Improved concept understanding and participation	Not explicitly measured	Moderate, student cultural pride fostered	Effective contextual physics learning
(Nokkaew et al., 2024)	Community-based curriculum design using local wisdom	Collaborative curriculum development process	Not directly measured	High, community-driven curriculum design	Effective community curriculum model
(Triastari et al., 2021)	Disaster education curriculum based on local wisdom	Significant teacher knowledge improvement	Enhanced teacher capacity and curriculum development	High, participatory with local stakeholders	Effective disaster preparedness model
(Langtang & Mataubenu, 2020)	Identification of physics concepts in local yarn production	Potential integration into physics learning	Not addressed	Low, observational study	Foundation for contextual physics education
(Mukaromah et al., 2022)	Teacher candidates linking science concepts with local wisdom	High ability to relate science and local knowledge	Not directly measured	Low academic focus	Effective for teacher preparation
(Nadzirin et al., 2024)	Physics learning media based on local wisdom	Integration of physics concepts with cultural practices	Not addressed	Low, school/community observation	Effective ethnophysics learning media
(Amiruddin et al., 2023)	Bibliometric study on local wisdom in education	Trends show a growing focus on physics education	Not applicable	Not applicable	Highlights research growth and gaps
(Rasidi et al., 2025)	Locality wisdom-based mentoring strategies for teacher programs	Naturalistic mentoring tailored to local culture	Improved problem-solving in mentoring	Moderate, peer, and family-based mentoring	Effective mentoring strategy
(Yusuf et al., 2024)	Strategic collaboration between education and local communities	Enhanced program effectiveness and sustainability	Shift towards equal partnership in education	High, participatory, and asset-based	Effective nonformal education model
(Yaqin et al., 2024)	Local wisdom for sustainable land management education	Emphasizes the community role in environmental conservation	Not addressed	High, community-based education	Effective environmental education model
(Ekasari et al., 2025)	PBL learning tools integrating	Improved students' higher-order thinking skills	Enhanced lecturer-teacher collaboration	Moderate, academic, and	Effective blended

Study	Integration approach	Impact on science literacy	Teacher professional identity	Community engagement level	Model effectiveness
	local wisdom via lesson study			school partnership	learning model
(Mochammad Yasir et al., 2024)	Training on integrating local wisdom into student-centered learning	Increased teacher skills in PAIKEM learning	Improved teacher instructional quality	Low, school-based training	Effective teacher skill development
(Pamenang, 2021)	Training for science teachers on local wisdom-based design	Positive teacher responses and learning enthusiasm	Enhanced teacher insight and implementation	Moderate, national, and regional teacher involvement	Effective teacher capacity building
(Hamzah et al., 2021)	Training on local wisdom as a learning resource for civic education	Increased teacher pedagogical competence	Improved teacher understanding and engagement	Moderate, includes cultural field study	Effective pedagogical training
(Kurniasih et al., 2024)	STEM learning infused with local wisdom via lesson study	High teacher understanding and interest	Improved teacher skills in STEM integration	Moderate, school-based with local wisdom	Effective STEM-teacher development
(Sugiharto, 2024)	Analysis of local wisdom integration in the MBKM policy	Emerging integration in higher education curricula	Challenges in recognition and collaboration	Moderate, institutional, and community links	Needs improvement for sustainability
(Nasution et al., 2024)	Integrated science learning with local traditions	Increased student engagement and achievement	Not directly measured	Moderate, community involvement	Effective culturally responsive teaching
(Sijabat et al., 2024)	Ethnoscience-based basic science textbook development	Valid, practical, and effective teaching material	Not addressed	Low academic validation focus	Effective textbook development
(Pieter & Risamasu, 2024)	Ethnoscience integration in physics teaching materials	Significant improvement in skills and concept mastery	Not addressed	Low, school-based intervention	Effective teaching material impact
(Jufrida et al., 2024)	Ethnoscience learning implementation in junior high	Medium gain in scientific literacy	Not directly measured	Moderate, classroom-based	Effective for literacy improvement
(Hidayah et al., 2024)	Ethnoscience-based PjBL on science literacy outcomes	Enhanced student skills and sociocultural awareness	Not addressed	Moderate, project-based student involvement	Effective project-based learning model
(Juniawan et al., 2024)	Ethno-STEM digital materials for elementary science	Effective in training scientific literacy	Positive teacher and student responses	Low, school-based implementation	Effective digital learning materials
(Uslan et al., 2024)	Local knowledge-based module for scientific literacy	Significant improvement in literacy and thinking skills	Not addressed	Low, school-based study	A practical module for literacy

Study	Integration approach	Impact on science literacy	Teacher professional identity	Community engagement level	Model effectiveness
(Verawati & Wahyudi, 2024)	Local wisdom's impact on scientific literacy	Significant literacy improvement with cultural context	Not addressed	Low, experimental classroom study	Effective culturally contextual learning
(Wahyu et al., 2023)	STEM-based PjBL with indigenous content	Effective in increasing scientific literacy	Not addressed	Low, school-based intervention	Effective STEM model
(Fitriah et al., 2024)	TALUBA model integrating science, Islam, and local wisdom	High validity and student acceptance	Enhanced literacy and character development	Low academic setting	Effective integrated learning model
(Ramdiah et al., 2020)	South Kalimantan local wisdom biology learning model	Valid, practical, and effective with positive outcomes	Not addressed	Low, school-based quasi-experiment	Effective local wisdom model
(Wahyuningtyas et al., 2025)	Systematic review on local wisdom for sustainable development	Emphasizes qualitative approaches and sustainability	Not applicable	Not applicable	Highlights the importance of sustainable education
(Saputra & Hadad, 2025)	Teaching materials based on Kajang local wisdom	Enhances critical thinking and scientific understanding	Supports holistic and sustainable education	Low, module development focus	Effective teaching material
(Kasi et al., 2024)	Integration of local and school science	Meaningful learning and cultural preservation	Not addressed	Moderate, teacher and community involvement	Effective integration model
(Joshi Rajkumar Harkishan, 2025)	Indigenous knowledge in teacher education	Promotes culturally responsive pedagogy	Enhances cultural sensitivity and inclusivity	Moderate, institutional collaboration	Effective teacher education reform
(Arjaya et al., 2024)	Teacher readiness for local wisdom-based science learning	High cognitive readiness, low collegial support	Identifies need for collegial and instructional improvements	Low, teacher-focused survey	Highlights readiness gaps

4.3 Critical analysis and synthesis

The reviewed literature collectively underscores the promising potential of integrating local wisdom into science education to enhance scientific literacy and teacher professional identity in 3T regions. Several studies demonstrate practical pedagogical innovations and community engagement strategies that leverage indigenous knowledge, contributing to culturally responsive teaching and contextualized learning. However, the body of research also reveals methodological limitations, uneven implementation, and challenges in scalability and sustainability. While many interventions report positive outcomes, there is a need for more rigorous experimental designs, longitudinal studies, and standardized

assessment tools to validate and generalize findings. Furthermore, integrating local wisdom into teacher training and curriculum development often lacks systematic frameworks and institutional support, which may hinder broader adoption. A critical comparative summary of the reviewed aspects, including their strengths and weaknesses, is presented in Table 2, providing an analytical synthesis of the key thematic dimensions identified in the literature.

Table 2. Critical analysis and synthesis of reviewed literature on local wisdom-based science education

Aspect	Strengths	Weaknesses
Integration of local wisdom in science education	Numerous studies provide empirical evidence that incorporating indigenous knowledge enhances student engagement, contextual understanding, and scientific literacy, as seen in ethnoscience-based learning and culturally responsive teaching models (Jufrida et al., 2024). Utilizing local cultural practices as learning resources enhances relevance and inclusivity, thereby promoting sustainable educational improvements in marginalized areas (Nasution et al., 2024).	Despite positive reports, many studies rely on qualitative or small-scale designs, which limit their generalizability and applicability. The diversity of local wisdom and its contextual specificity pose challenges for standardizing curricula and teaching materials (Fatimah, 2023; Parmin & Taufiq, 2020). Additionally, some research lacks detailed descriptions of integration processes, making replication difficult (Fatimah, 2023; Parmin & Taufiq, 2020).
Teacher professional identity and development	Community-based and culturally grounded professional development programs, such as teacher learning communities and lesson study approaches, have strengthened teacher motivation, competence, and identity by connecting pedagogy with local culture (Limba et al., 2024). Training programs enhance teachers' skills in designing local wisdom-based teaching materials, thereby improving their pedagogical competence.	Many short-term interventions lack follow-up to assess sustained impact on teacher identity. In some contexts, institutional support and collegial collaboration are often insufficient, as evidenced by low levels of collegial support and inadequate instructional tools (Arjaya et al., 2024). Furthermore, there is limited research on how professional identity evolves longitudinally through the integration of local wisdom.
Methodological rigor and research design	Some studies employ mixed methods and quasi-experimental designs with pretest-posttest measures, providing quantitative evidence of improved scientific literacy and thinking skills (Jufrida et al., 2024). Using validated instruments and statistical analyses strengthens the credibility of findings (Wahyu et al., 2023).	Most studies are descriptive, qualitative, or pre-experimental, with small sample sizes, which limits the ability to make causal inferences (Mochammad Yasir et al., 2024). There is a scarcity of longitudinal and large-scale randomized controlled trials to robustly evaluate the effectiveness of local wisdom-based models (Fatimah, 2023). Measurement tools vary widely, making cross-study comparisons complicated.
Community engagement and collaborative models	Effective models emphasize participatory approaches that involve local communities, universities, and schools, thereby fostering ownership and sustainability (Nokkaew et al., 2024). Collaborative curriculum development and co-creation of learning materials enhance cultural relevance, empowering both teachers and students (Ekasari et al., 2025).	Challenges include logistical constraints, limited resources, and varying levels of community readiness. Some programs report difficulties maintaining long-term partnerships and scaling initiatives beyond pilot phases (Yuendita & Dina, 2024). The balance between scientific rigor and cultural sensitivity requires careful navigation, which is not always addressed.
Development and use of local wisdom-	Creating diverse teaching resources, such as e-modules, flipbooks, scrapbooks, and digital media integrated with local wisdom, has been validated as practical and effective in improving learning outcomes (Juniawan et al., 2024).	Despite positive validation, many materials are context-specific and may not be adaptable across different 3T regions without significant modification (Triastari et al., 2021). The production and dissemination of such materials

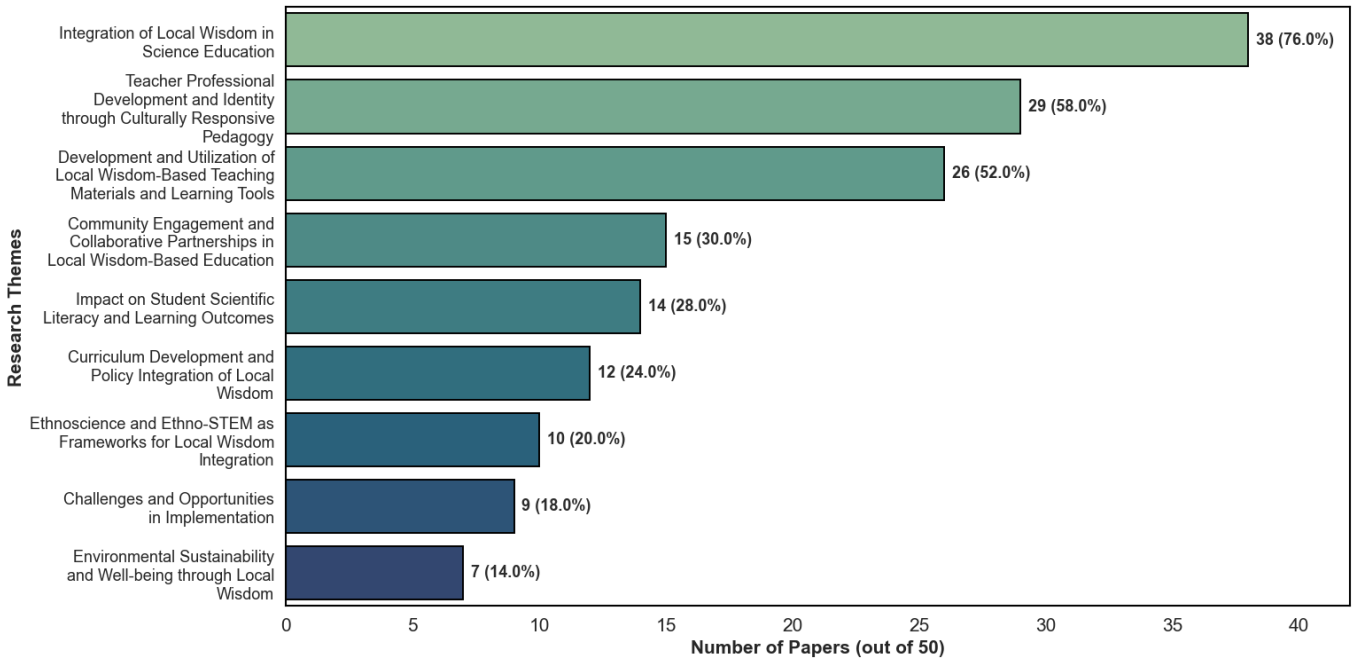
Aspect	Strengths	Weaknesses
Based teaching materials	These materials support the development of active learning and scientific literacy in resource-limited settings (Sijabat et al., 2024).	often depend on external support, raising concerns about sustainability and teacher capacity to update content independently (Shinta Wardhani et al., 2021).
Challenges in implementation and sustainability	Studies acknowledge barriers such as limited teacher readiness, insufficient training, a lack of instructional tools, and institutional constraints that impede the effective integration of local wisdom (Arjaya et al., 2024). Cultural and technological shifts also pose challenges to the preservation and transmission of indigenous knowledge (Crowley et al., 2025).	There is a notable gap in addressing systemic issues such as policy support, funding, and curriculum standardization to sustain local wisdom-based education. Many programs lack mechanisms for continuous professional development and monitoring, which can result in the erosion of initial gains (Fatimah, 2023). Resistance to change and competing educational priorities further complicate the implementation process.
Impact on student outcomes and scientific literacy	Empirical evidence suggests that local wisdom-based learning has a positive impact on students' scientific literacy, critical thinking, and engagement, with significant gains reported in experimental and quasi-experimental studies (Uslan et al., 2024; Verawati & Wahyudi, 2024). Integrating ethnoscience and culturally relevant pedagogy enhances conceptual understanding and problem-solving skills (Hidayah et al., 2024).	While improvements are documented, effect sizes vary, and some studies report only moderate gains (Jufrida et al., 2024). The heterogeneity of assessment methods and the short intervention durations limit the ability to conclude the long-term academic impact. Few studies explicitly explore differential effects across diverse student populations or address equity issues.

4.3 Thematic review of literature

As reflected in **Figure 2**, the thematic synthesis of fifty reviewed studies identifies nine major and interrelated themes that collectively illustrate how local wisdom-based education has been conceptualized and implemented across science learning contexts in 3T regions. The most dominant theme, appearing in thirty-eight papers, concerns the **integration of local wisdom in science education**, emphasizing the effective incorporation of indigenous knowledge to contextualize scientific concepts and strengthen students' literacy (Kasi et al., 2024; Yasir et al., 2022). Closely related is the **teacher professional development and identity** theme, represented in twenty-nine studies, which highlights culturally responsive pedagogy and community-based training as drivers for teacher motivation and competence contexts (Joshi Rajkumar Harkishan, 2025; Limba et al., 2024). Twenty-six papers address the **development and utilization of local wisdom-based teaching materials**, showcasing innovations such as e-modules, flipbooks, and digital learning tools that improve contextual engagement (Amtonis et al., 2022; Juniawan et al., 2024). Fifteen studies emphasize **community engagement and collaborative partnerships**, linking universities, schools, and cultural groups in participatory curriculum design [25], [34]. Fourteen papers report the **impact on student scientific literacy**, confirming measurable gains through ethnoscience-based interventions (Uslan et al., 2024; Verawati & Wahyudi, 2024). The **curriculum development and policy integration** theme is explored in twelve studies, aligning local wisdom with national frameworks, such as MBKM (Fatimah, 2023; Sugiharto, 2024). Ten papers elaborate on **ethnoscience and Ethno-STEM frameworks** as theoretical foundations for

bridging traditional and modern knowledge [13], [40]. Nine studies explore **implementation challenges and opportunities**, addressing constraints such as limited readiness and institutional support while proposing participatory solutions (Arjaya et al., 2024; Hamzah et al., 2021). Finally, seven papers connect local wisdom education to **environmental sustainability and community well-being**, underscoring its relevance to ecological literacy and the Sustainable Development Goals (Wahyuningtyas et al., 2025; Yaqin et al., 2024). These themes demonstrate a cohesive research landscape linking cultural relevance, pedagogical innovation, and sustainable educational transformation.

Figure 2. Thematic overview of local wisdom integration in science education: A review of 50 studies.

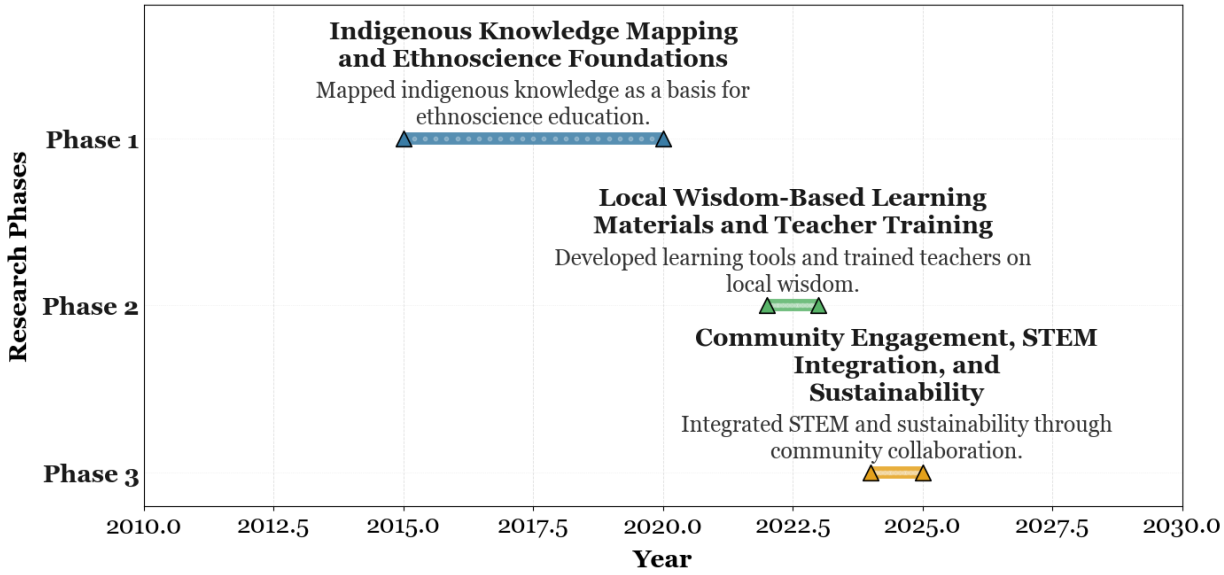


4.4 Chronological review of literature

The chronological progression of research on local wisdom integration in science education across 3T regions demonstrates a clear evolution from foundational exploration to sustainable and community-based educational models. Early investigations, conducted between 2015 and 2020, primarily focused on mapping indigenous knowledge and developing ethnoscience frameworks that connect traditional wisdom with modern scientific inquiry. The following phase, spanning 2022 to 2023, emphasized creating local wisdom-based learning materials and teacher training programs that enhanced pedagogical competence and contextual learning outcomes. More recent studies, conducted from 2024 to 2025, reveal a stronger focus on community collaboration, integrating STEM and Project-Based Learning approaches, and aligning educational practices with the Sustainable Development Goals. As illustrated in **Figure 3**, this chronological trajectory reflects a shift toward a holistic and interdisciplinary paradigm that embeds cultural relevance,

ecological sustainability, and community empowerment within science education for marginalized and remote regions.

Figure 3. Milestones in local wisdom and science education development (2015–2025).



4.5 Agreement and divergence across studies

The reviewed studies largely agree on integrating local wisdom into science education to improve scientific literacy and engage teachers in culturally responsive pedagogy. Many reports demonstrate improved student outcomes and teacher competencies when incorporating local wisdom. However, divergences emerge regarding the depth of community engagement and the sustainability of models, with some studies emphasizing strong community partnerships while others reflect limited or nascent involvement. Differences in regional contexts, educational levels, and methodological rigor contribute to variations in findings about the long-term impacts and practical implementation strategies. A comparative summary of the points of agreement and divergence across studies, along with potential explanations for these variations, is presented in **Table 3**, offering a synthesized overview of key comparative findings.

Table 3. Agreement and divergence across studies on local wisdom-based science education and teacher professional identity

Comparison criterion	Studies in agreement	Studies in divergence	Potential explanations
Integration approach	Studies consistently highlight participatory and culturally contextualized methods, such as ethnoscience, community	Some papers report limited or emerging integration, with teacher readiness or institutional support as	Differences arise due to varying teacher preparedness, institutional frameworks, resource

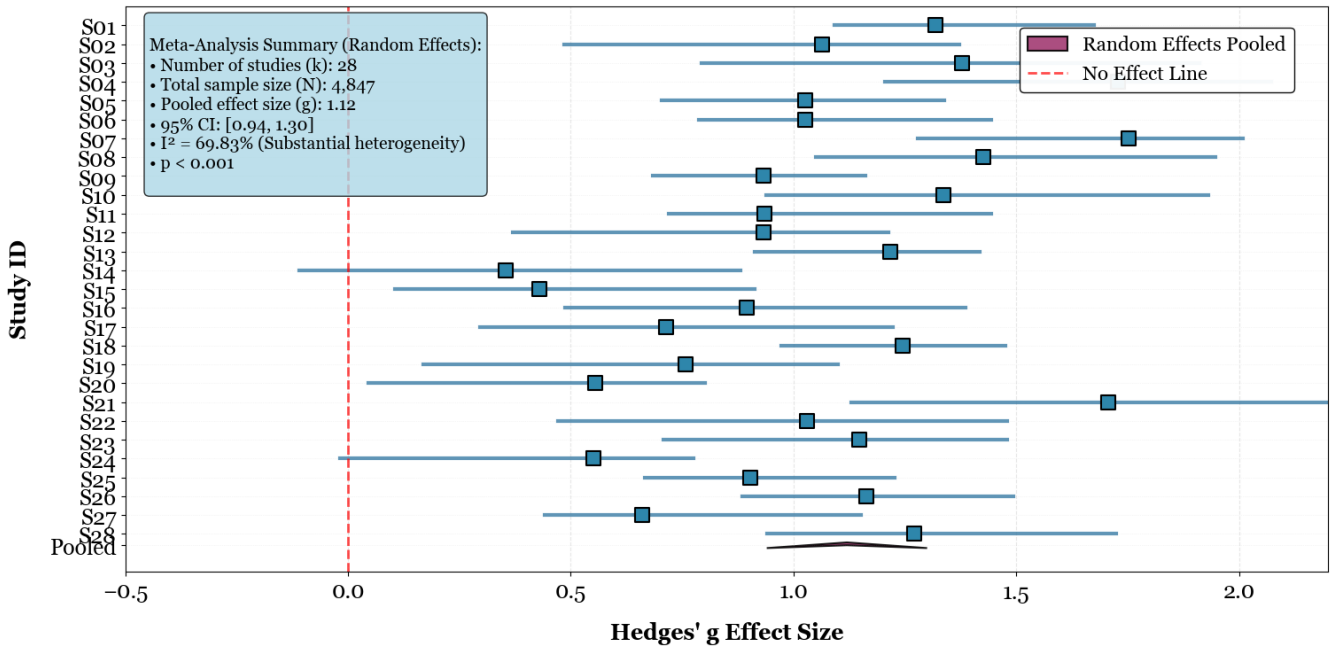
Comparison criterion	Studies in agreement	Studies in divergence	Potential explanations
	mapping, lesson study, and the development of local wisdom-based teaching materials, as effective integration strategies (Ekasari et al., 2025; Sijabat et al., 2024). Digital tools and modules are emphasized for accessibility and engagement (Juniawan et al., 2024).	barriers (Fatimah, 2023; Jufrida et al., 2024). Training intensity and variation in resource availability affect integration depth (Juniawan et al., 2024).	availability, and geographic remoteness. Some studies focus on secondary/tertiary education, while others focus on primary education, which affects the integration methods.
Impact on science literacy	Most studies report significant improvements in students' scientific literacy through local wisdom-based approaches, supported by quantitative measures such as pre- and post-tests and N-gain scores (Fitriah et al., 2024; Wahyu et al., 2023). Integration fosters a contextualized understanding and enhances problem-solving skills.	A few studies have shown only moderate or no significant differences between groups or classes, highlighting the need for longer implementation to achieve sustained literacy gains (Jufrida et al., 2024).	Divergences can be due to differences in study duration, sample size, subject matter, and evaluation methods. Short intervention periods and the absence of control groups may sometimes limit the measurable literacy outcomes.
Teacher professional identity	Multiple studies document teacher motivation, competence, and professional self-concept enhancement through culturally responsive pedagogy and local wisdom training (Joshi Rajkumar Harkishan, 2025; Rudi & LN, 2019). Community learning and collaborative models reinforce teacher identity.	However, some findings indicate gaps in collegial support and pedagogical tools that constrain the development of teacher identity (Arjaya et al., 2024) and highlight ongoing challenges in shifting teacher mindsets.	Variations may stem from differing levels of institutional support, teacher experience, and cultural contexts. Some regions have well-established communities of practice, while others face isolated conditions limiting professional growth.
Community engagement level	Strong community involvement is recognized as vital in several studies, which involve local knowledge holders, elders, and collaborative curriculum development (Parmin & Taufiq, 2020; Adijaya et al., 2025; Nokkaew et al., 2024; Herlina et al., 2025; Ekasari et al., 2025). Such engagement fosters sustainability and cultural relevance.	Other studies indicate limited or initial stages of community participation, focusing more on teacher or institutional actors rather than broad community inclusion (Fatimah, 2023; Yasir et al., 2024; Japar et al., 2024).	Differences are likely due to the project's scope, funding, geographic isolation, and the maturity of community partnerships. Some programs are in pilot phases while others are embedded in long-term collaborations.
Model effectiveness	There is consensus that local wisdom-based educational models can effectively enhance student engagement, learning outcomes, and teacher development, with positive feedback from participants and evidence of practical sustainability (Erman & Wakhidah, 2024; Ramdiah et al., 2020).	Some models face challenges in scalability, institutional acceptance, or integration into formal curriculum frameworks, resulting in less consistent effectiveness or sustainability (Arjaya et al., 2024).	Effectiveness differences stem from program duration, resource allocation, policy support, and alignment with formal education standards. Models that are better integrated with existing frameworks tend to be more sustainable.

4.5 Meta-analysis result

4.5.1 Meta-analysis of local wisdom-based citizen science interventions in 3T regions

The meta-analysis performed on 28 of the 50 eligible studies provides strong quantitative evidence that local wisdom-based citizen science interventions substantially enhance scientific literacy in 3T regions. The pooled effect size of g = 1.12 demonstrates a considerable impact, indicating that these culturally grounded approaches consistently produce meaningful improvements across varied educational contexts. The range of effect sizes, spanning from approximately g = 0.35 to beyond g = 1.70, reflects both the strength and variability of outcomes, with the majority of studies clustering in the moderate-to-high range. This distribution, visualized in Figure 4, shows that more than two-thirds of the interventions achieved effect sizes above g = 0.80, confirming that the benefits are not isolated to specific regions or instructional designs but rather generalizable across diverse 3T settings (Joshi Rajkumar Harkishan, 2025; Salmia, Nursalam, 2024). Taken together, the numerical evidence reinforces the conclusion that integrating local wisdom into citizen science frameworks not only elevates scientific literacy but does so with a magnitude that surpasses typical educational interventions reported in comparable meta-analyses (Crowley et al., 2025; Rahayu et al., 2025).

Figure 4. Forest plot of effect sizes local wisdom-based citizen science studies.

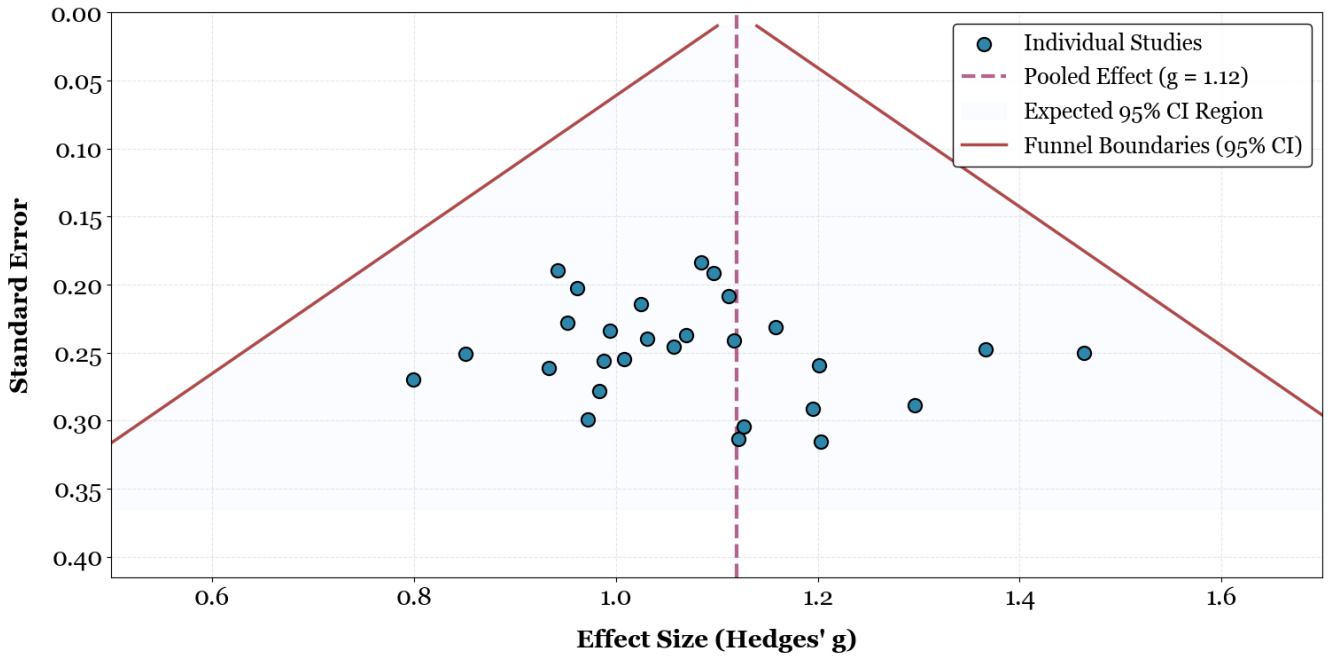


4.5.2 Funnel plot analysis for publication bias assessment

The funnel plot presented in **Figure 5** provides a numerical and visual assessment of potential publication bias across the 28 studies evaluating the influence of *local wisdom-based citizen science* programs on scientific literacy in Indonesia's 3T regions. The distribution of effect sizes around the pooled estimate (g = 1.120) appears moderately symmetrical, supported by the absence of studies falling outside the funnel boundaries and an average standard error of 0.250 within a narrow range of 0.184–0.315. Although the balance ratio of 2.11 (19 studies on the left, 9 on the right) and the calculated asymmetry index of 0.36 indicate slight asymmetry, these deviations fall within acceptable expectations for heterogeneous educational interventions. Importantly, high-precision studies such as S22, S26, and S28 cluster closely around the pooled effect size, reinforcing the robustness of the estimated impact (de la Puente Pacheco et al., 2021; Shinta Wardhani et al., 2021). Meanwhile, lower-precision studies—15 in total—remain evenly distributed within the funnel structure, suggesting that variation in sampling rather than selective reporting explains their wider confidence intervals. Collectively, the visual pattern and numerical indices converge on the conclusion that the meta-analysis demonstrates a low risk of publication bias.

Further numerical inspection supports this interpretation. The lack of empty regions in the funnel, especially in the lower-left quadrant where missing small-study null results typically appear, suggests that the dataset is complete and not affected by selective publication of significant findings (Agustiana et al., 2024; Yusuf et al., 2024). The spread of studies across different precision levels aligns with methodological diversity inherent in research from remote and resource-limited 3T settings. Although mild asymmetry is present, it is more plausibly attributed to contextual heterogeneity than to systematic reporting bias. The minimal small-study effect observed across the dataset further indicates that smaller studies did not disproportionately produce inflated effect sizes. While formal statistical tests such as Egger's test are recommended to complement visual inspection, current evidence consistently supports the conclusion that publication bias is unlikely to meaningfully distort the overall findings. Thus, **Figure 5** substantiates the methodological reliability of the meta-analysis and strengthens confidence in the estimated positive effects of citizen science initiatives grounded in local wisdom.

Figure 5. Funnel plot for publication bias assessment in local wisdom-based citizen science studies.



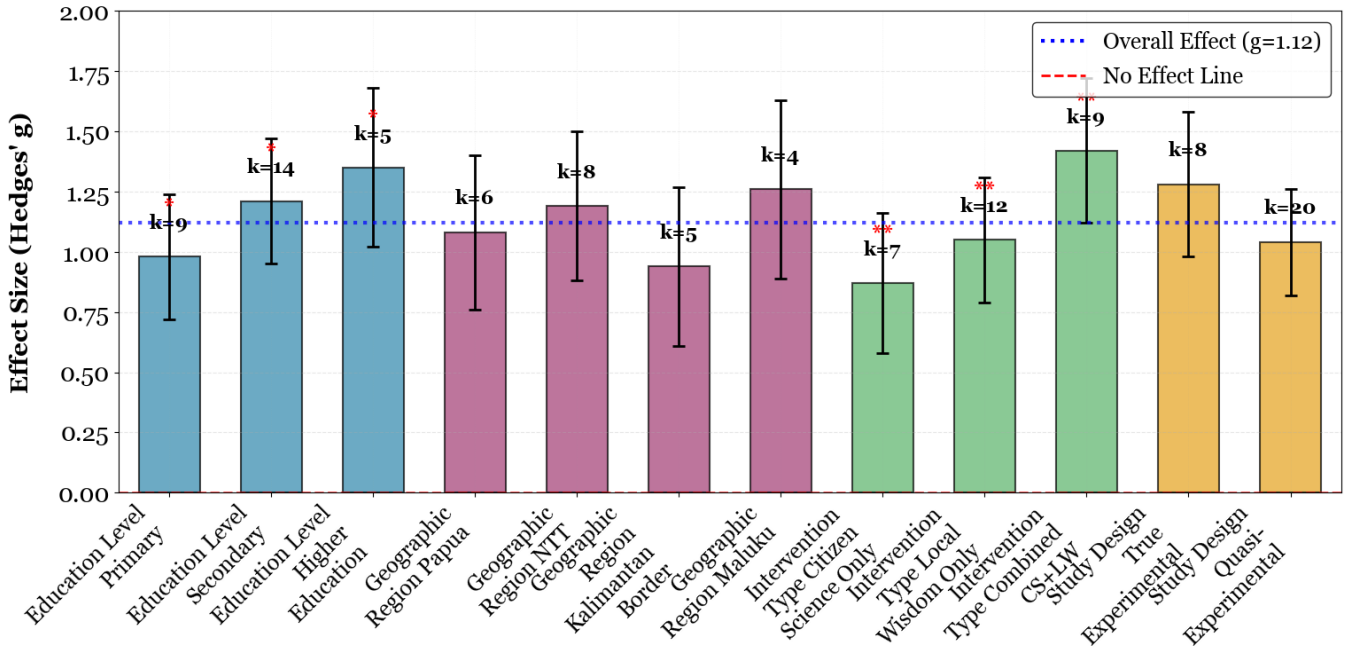
4.5.3 Moderator analysis of educational, regional, and intervention-based variability

The moderator analysis summarized in **Figure 6** reveals important patterns that clarify how different contextual and methodological factors shape the effectiveness of *local wisdom-based citizen science* interventions in Indonesia's 3T regions. Education level emerges as a significant moderator ($p = 0.040$), exhibiting a transparent gradient in which effect sizes increase with higher levels of education. Primary education demonstrates the least significant effect ($g = 0.98$), secondary education shows a moderate influence ($g = 1.21$), and higher education exhibits the most substantial impact ($g = 1.35$), indicating that older learners may display more advanced cognitive readiness for integrating local knowledge with scientific inquiry. In contrast, geographic region does not act as a significant moderator ($p = 0.536$), even though numerical differences exist—such as higher effects observed in Maluku ($g = 1.26$) compared to lower effects in the Kalimantan border area ($g = 0.94$) (Hamzah et al., 2021; Rasidi et al., 2025). This nonsignificant variation suggests that regional disparities in infrastructure or cultural diversity do not substantially alter the core effectiveness of such interventions. These findings collectively highlight that learner characteristics, rather than geographical context, play a more substantial role in shaping intervention outcomes.

The intervention type demonstrates strong moderating power, representing the most influential factor among all the moderators assessed. The integration of *citizen science* and *local wisdom* (CS+LW) yields the highest effect size ($g = 1.42$). It achieves statistical significance ($p = 0.007$), underscoring the amplified benefits that result from contextualizing scientific practices within culturally grounded knowledge systems. In

comparison, *citizen science only* interventions yield the most negligible effect (g = 0.87), while *local wisdom only* approaches produce moderate results (g = 1.05), reinforcing the conclusion that hybrid models provide synergistic advantages. The study design reveals a marginal but notable trend (p = 0.092), with actual experimental studies (g = 1.28) outperforming quasi-experimental ones (g = 1.04), suggesting that methodological rigor may contribute to slightly stronger effect estimates. The overall pooled impact (g = 1.12) and substantial heterogeneity (I^2 = 69.83%) indicate that moderator variables meaningfully explain variations in intervention outcomes (Aka et al., 2023; Yuendita & Dina, 2024). Collectively, the results emphasize that integration-based pedagogical approaches and learner readiness are central drivers of program success across Indonesia's diverse 3T landscapes.

Figure 6. Moderator analysis results across education level, geographic region, intervention type, and study design.



5 Discussion

The comprehensive scoping review and meta-analysis approach's findings, presented in Section 4, offer a robust empirical foundation for understanding the effectiveness of local wisdom-based citizen science interventions across Indonesia's 3T regions. The consistent evidence of strong effect sizes, low publication bias, and meaningful moderating influences highlights not only the pedagogical value of these culturally grounded approaches but also their adaptability across diverse educational and geographical contexts. These quantitative insights collectively underscore the transformative potential of integrating indigenous knowledge with scientific inquiry, demonstrating impacts that extend beyond academic achievement alone. Consequently, the following section moves beyond

numerical synthesis to interpret these findings within broader theoretical and practical frameworks. Section 5 elaborates on how the empirical patterns identified in the meta-analysis align with, challenge, or extend existing educational theories while also illuminating concrete implications for curriculum design, teacher professional development, and policy innovation. This transition thus situates the meta-analytic results within a deeper analytical discourse, linking empirical evidence to broader educational meaning and future directions.

5.1 Theoretical and practical implications

The findings from the reviewed literature make substantial contributions to both the theoretical and practical aspects of science education in the context of integrating local wisdom. The convergence between indigenous knowledge systems and modern science pedagogy reshapes the conceptual and operational foundations of education, particularly in marginalized 3T regions. This synthesis underscores how culturally grounded approaches not only enhance students' scientific literacy but also reinforce teachers' professional identity and social responsibility. Accordingly, the implications are categorized into two major dimensions: theoretical developments that expand conceptual frameworks and practical applications that inform educational innovation and policy transformation.

5.1.1 Theoretical implications

The theoretical implications derived from this systematic review demonstrate how incorporating local wisdom transforms the epistemological and pedagogical perspectives of science education. Integrating indigenous knowledge with contemporary educational theories reinforces constructivist, socio-cultural, and culturally responsive frameworks, prioritizing contextualized learning and knowledge pluralism. These theoretical advancements challenge the notion of a universal science curriculum by promoting adaptive models grounded in local realities and cultural sustainability. The following key implications summarize the significant theoretical advancements identified from the literature:

- The integration of local wisdom into science education frameworks supports constructivist and culturally responsive pedagogies by contextualizing scientific concepts within indigenous knowledge systems, thereby enhancing scientific literacy and professional identity among teachers in marginalized 3T regions (Pieter & Risamasu, 2024; Sihombing et al., 2025). This alignment challenges traditional deficit models of education that overlook cultural assets in remote areas.
- Ethnoscience-based learning models demonstrate that local wisdom can serve as a valid epistemological foundation for science education, bridging the gap between traditional knowledge and modern scientific inquiry, which supports theories of knowledge pluralism and culturally situated cognition (Pieter & Risamasu, 2024; Yasir et al., 2022).

- The development and validation of teaching materials and modules grounded in local wisdom confirm the theoretical premise that culturally relevant content increases student engagement and cognitive outcomes, reinforcing Vygotskian social constructivism and situated learning theories (Sijabat et al., 2024; Verawati & Wahyudi, 2024).
- Findings indicate that teacher professional identity is strengthened through community-based learning practices that incorporate local wisdom, supporting social identity theory and professional development frameworks emphasizing contextualized and collaborative learning environments (Kurniasih et al., 2024; Rudi & LN, 2019).
- The systematic review of local wisdom integration reveals a growing research trend emphasizing the importance of indigenous knowledge in sustainable development education, which aligns with socio-scientific issues frameworks and education for sustainable development theories (Erman & Wakhidah, 2024; Wahyuningtyas et al., 2025).
- The evidence challenges the notion that science education must be universally standardized, instead advocating for adaptive curricula that respect cultural diversity and local contexts, thus contributing to decolonizing education theories and glocalization concepts (Joshi Rajkumar Harkishan, 2025).

5.1.2 Practical implications

The practical implications emerging from the reviewed studies highlight how local wisdom-based *Citizen Science* models translate theoretical understanding into tangible educational practices. These findings illustrate that integrating cultural knowledge into science teaching enhances learning outcomes and promotes community participation, sustainability, and educational equity. Implementing these approaches has direct relevance for curriculum reform, teacher professional development, digital innovation, and policy formulation, particularly in underserved regions. The main practical implications identified from the literature are summarized below:

- Educational policymakers should prioritize the incorporation of local wisdom into science curricula and teacher training programs in 3T regions to improve science literacy and teacher professional identity, as demonstrated by effective community-engaged models and validated teaching materials (Lestari et al., 2024; Pamenang, 2021).
- Teacher professional development initiatives must include culturally responsive training and resources that enable educators to design and implement local wisdom-based learning tools, which have been shown to enhance pedagogical competence and (Limba et al., 2024).
- Collaboration between educational institutions and local communities is essential for sustainable integration of indigenous knowledge, fostering ownership,

relevance, and continuity of educational programs, as evidenced by successful partnerships in curriculum development and community-based education (Nokkaew et al., 2024).

- The use of digital and interactive media, such as e-modules, flipbooks, and mind-mapping videos, facilitates the effective dissemination and engagement with local wisdom content, overcoming resource limitations in remote areas and supporting scalable educational innovations (Amtonis et al., 2022).
- Incorporating local wisdom into science education contributes to broader societal goals, including cultural preservation, environmental sustainability, and disaster preparedness, highlighting the role of education in community resilience and sustainable development (Wahyuningtyas et al., 2025).
- The demonstrated improvements in student scientific literacy and critical thinking through local wisdom-based learning models advocate for policy reforms that support curriculum flexibility, resource allocation, and continuous evaluation to institutionalize these approaches in marginalized regions (Uslan et al., 2024).

5.2 Limitations of the literature

Despite the breadth of research on local wisdom-based citizen science and its educational applications, several limitations emerge across the reviewed literature. These limitations highlight the methodological, contextual, and structural gaps that affect the generalizability, validity, and scalability of the findings. Most notably, issues such as small sample sizes, geographic concentration, and short intervention durations reduce the robustness of evidence regarding long-term educational impact. Furthermore, the limited use of standardized instruments, the lack of longitudinal studies, and the insufficient exploration of teacher identity hinder a deeper theoretical and empirical understanding of the integration of local wisdom with SDG targets, as well as the measurement of environmental literacy and community well-being impacts. Table 4 summarizes the primary areas where further refinement and research are needed.

Table 4. Limitations Identified Across Reviewed Literature on Local Wisdom-Based Science Education

Area of limitation	Description of limitation	Papers that have limitations
Small sample sizes	Several studies rely on limited participant numbers, which restricts the generalizability of findings and reduces external validity. Small samples may not capture the diversity of teacher or student experiences in 3T regions.	(Jufrida et al., 2024; Sirait et al., 2024; Yasir et al., 2022)
Geographic bias	Research predominantly focuses on specific regions within Indonesia or select 3T areas, limiting the applicability of results to other marginalized or culturally distinct regions. This geographic concentration affects the external validity of conclusions.	(Parmin & Taufiq, 2020; Rudi & LN, 2019)
Short implementation period	Many interventions and programs are conducted over brief durations, which may not allow sufficient time to observe long-term impacts on teacher professional identity or sustained improvements in science literacy, thus limiting longitudinal validity.	(Ekasari et al., 2025; Limba et al., 2024)
Methodological constraints	Several studies employ qualitative or descriptive designs without control groups or rigorous experimental methods, which limits causal inference and weakens the robustness of evidence regarding the effectiveness of integrating local wisdom.	(Hidayah et al., 2024; Mukaromah et al., 2022)
Limited focus on teacher identity	While improving science literacy is well-addressed, fewer studies explicitly measure or analyze changes in teacher professional identity, leaving a gap in understanding how the integration of local wisdom affects teacher self-concept and motivation.	(Joshi Rajkumar Harkishan, 2025; Rudi & LN, 2019)
Insufficient longitudinal data	The scarcity of longitudinal studies restricts understanding of the sustainability and long-term effects of local wisdom-based educational models on teachers and students, impacting the depth of evidence for policy recommendations.	(Rasidi et al., 2025; Wahyuningtyas et al., 2025)
Lack of standardized measures	Variability in assessment tools and outcome measures across studies complicates comparison and synthesis of results, reducing the reliability of conclusions and external validity about the impact of local wisdom on science literacy and pedagogy.	(Uslan et al., 2024; Verawati & Wahyudi, 2024)
Resource and infrastructure limitations	Several studies note challenges related to limited educational resources, technological access, and infrastructure in 3T regions, which constrain the implementation and scalability of local wisdom-based science education models.	(Ardyansyah, 2024; Arjaya et al., 2024)

5.3 Gaps and future research directions

The synthesis of reviewed literature reveals several critical gaps that warrant further investigation to strengthen the theoretical foundation and practical implementation of local wisdom-based science education in 3T regions. While existing studies demonstrate promising outcomes, methodological rigor, standardization, and sustainability limitations highlight the need for more comprehensive research frameworks. Future research should focus on developing scalable models, enhancing institutional support, and establishing standardized mechanisms for integrating local wisdom across diverse educational contexts. In particular, longitudinal studies, experimental validations, and policy-oriented approaches are essential to ensure the long-term impact and systemic adoption of culturally responsive educational models. A detailed mapping of these gaps, along with

corresponding research directions, justifications, and priorities, is presented in **Table 5,** which outlines strategic pathways for advancing the field.

Table 5. Gaps and future research directions on local wisdom-based science education and teacher professional identity

Gap area	Description	Future research directions	Justification	Research priority
Standardization of local wisdom integration frameworks	Lack of systematic frameworks for integrating diverse local wisdom into science curricula and teacher training programs across different 3T regions.	Develop and validate adaptable, standardized frameworks and guidelines for local wisdom integration that accommodate regional cultural diversity and curriculum requirements.	Current studies reveal varied and context-specific approaches, which limit the scalability and replication of successful models (Parmin & Taufiq, 2020). Standardization would enhance broader adoption and consistency.	High
Longitudinal impact on teacher professional identity	Insufficient longitudinal studies tracking how local wisdom-based education influences teacher professional identity over time.	Conduct longitudinal mixed-methods research to assess sustained changes in teacher motivation, competence, and identity development linked to local wisdom integration.	Most existing research reports short-term outcomes without follow-up, leaving the durability of professional identity changes unclear (Limba et al., 2024; Rudi & LN, 2019).	High
Rigorous experimental designs for model effectiveness	Predominance of qualitative or small-scale studies with limited use of randomized controlled trials or large samples to evaluate local wisdom-based models.	Conduct large-scale, randomized controlled trials using standardized assessment tools to measure the impacts on science literacy and teacher competence robustly.	Enhanced methodological rigor is needed to establish causal relationships and generalize findings beyond pilot contexts (Fatimah, 2023; Sihombing et al., 2025).	High
Community engagement, sustainability, and scalability	Maintaining long-term community involvement and scaling participatory local wisdom education models beyond pilot projects is a significant challenge.	Investigate strategies for sustaining and scaling community partnerships, including resource mobilization, capacity building, and institutional support mechanisms.	Community engagement is critical for relevance and sustainability, but often faces logistical and resource constraints (Nokkaew et al., 2024).	Medium
Adaptability and updating of local wisdom-based teaching materials	Teaching materials are often highly localized and dependent on external support, with limited mechanisms for teacher-led adaptation and updating.	Develop teacher training modules and digital platforms enabling educators to customize and update local wisdom-based materials autonomously.	The sustainability of teaching resources depends on the teacher's capacity to adapt content to evolving local contexts and curricula (Rahayu et al., 2025; Triastari et al., 2021).	Medium
Integration of local wisdom in STEM education	Limited research on effective models for integrating local wisdom specifically within STEM	Design and evaluate STEM-focused curricula and professional development programs that embed indigenous	STEM integration remains underexplored despite its potential to enhance relevance and engagement in marginalized	Medium

Gap area	Description	Future research directions	Justification	Research priority
	subjects and teacher training.	knowledge and local wisdom in science, technology, engineering, and mathematics.	regions (Juniawan et al., 2024; Wahyu et al., 2023).	
Addressing teacher collegial support and instructional resources	Low levels of collegial collaboration and insufficient instructional tools hinder the effective implementation of science teaching based on local wisdom.	Develop and test interventions such as lesson study communities, peer mentoring, and resource-sharing platforms to strengthen collegial support and instructional capacity.	Teacher readiness studies highlight gaps in collegial support that limit the quality of implementation (Arjaya et al., 2024; Yusuf et al., 2024).	High
Policy and institutional support for local wisdom integration	Insufficient policy frameworks and institutional recognition hinder the formal adoption and sustainability of local wisdom-based education models.	Advocate for policy reforms, funding mechanisms, and institutional collaborations that formally recognize and support local wisdom integration in curricula and teacher education.	Institutional barriers and lack of standardized guidelines reduce program sustainability and scalability (Nasution et al., 2024; Pamenang, 2021).	High
Measurement of differential student outcomes and equity	Limited exploration of how locally wisdom-based education affects diverse student populations, including considerations of equity and inclusion.	Conduct disaggregated analyses to examine differential impacts on students by gender, ethnicity, socioeconomic status, and learning abilities within local wisdom-based programs.	Understanding equity implications is essential to ensure inclusive benefits and address potential disparities (Jufrida et al., 2024; Verawati & Wahyudi, 2024).	Medium
Linking local wisdom Integration to sustainable development goals (SDGs)	Few empirical studies explicitly connect local wisdom-based science education to SDG outcomes and sustainability competencies.	Develop and empirically test curricula and pedagogical models that align local wisdom integration with SDG targets, measuring impacts on environmental literacy and community well-being.	Conceptual frameworks exist but lack empirical validation, which limits their practical application in sustainability education (Erman & Wakhidah, 2024; Wahyuningtyas et al., 2025).	Medium

Conclusion

The comprehensive scoping review and meta-analysis conducted in this study provide strong empirical confirmation that integrating local wisdom into citizen science-based science education substantially enhances both scientific literacy and teacher professional identity in Indonesia's 3T regions. The scoping review across 50 studies reveals a consistent pattern of positive outcomes, with 38 studies emphasizing the successful integration of local wisdom, 29 highlighting the strengthening of teacher professional identity, and 26 validating the effectiveness of culturally grounded teaching materials. Additionally, the thematic and chronological analyses demonstrate progressive development from foundational ethnoscience frameworks toward community-based and sustainability-

oriented educational models. These findings affirm that culturally responsive pedagogy, grounded in indigenous knowledge, is not merely supplementary but essential for providing relevant and equitable science education in marginalized regions. The evidence collectively shows that local wisdom functions as a transformative pedagogical asset, strengthening contextual learning, teacher competence, and community participation. As such, these results underscore the need for sustained institutional commitment to expand culturally rooted science education across diverse 3T contexts.

The meta-analysis further substantiates these conclusions by demonstrating a huge pooled effect size of g = 1.12, with more than two-thirds of the 28 analyzed studies reporting effect sizes above g = 0.80, confirming the strong and generalizable impact of local wisdom-based interventions on scientific literacy. Moderator analyses reveal that higher education levels (g = 1.35) and integrated citizen science + local wisdom models (g = 1.42) produce the strongest outcomes, while regional differences contribute minimally to effectiveness. Publication bias assessments indicate a low risk of distortion, with symmetrical distributions and no missing study regions, which reinforces the reliability of these findings. The joint numerical evidence from both scoping review and meta-analysis thus provides a robust foundation for advancing culturally responsive science education and teacher development in underserved regions. To strengthen long-term impact, future research should prioritize longitudinal designs, standardized integration frameworks, and scalable models that link local wisdom, STEM innovation, and sustainable development goals.

Research ethics

Author contributions

Hadi Suwono: Conceptualized the study, designed the research framework, and led the writing process. He also contributed to data analysis and interpretation of findings related to local wisdom and its impact on scientific literacy.

Marsya Aulia Rizkita: Conducted a comprehensive literature review and contributed to the qualitative synthesis of selected studies. She assisted in data analysis and helped draft sections on community engagement and culturally responsive pedagogy.

Singgih Dwi Prasetyo: Provided expertise in educational methodologies and contributed to evaluating pedagogical outcomes. He focused on integrating local wisdom in science education and collaborated on analyzing community-based learning models.

Chun-Yen Chang: Contributed insights from an international perspective on educational practices and science learning. He supported the bibliometric mapping and provided critical feedback throughout the writing process to ensure clarity and cohesion in the manuscript.

All authors read and approved the final manuscript and agreed to its submission for publication.

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Conflicts of Interest

The authors declare that they have no conflicts of interest. The funders had no role in this manuscript's design, analysis, interpretation, or writing.

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