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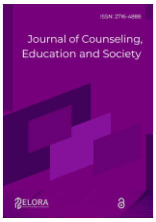

Electronic portfolio assessment for metacognitive development in chemistry: needs analysis and conceptual framework for AI-enhanced implementation

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ABSTRACT

Grounded in self-regulated learning theory and formative assessment frameworks, this study investigates the theoretical basis for integrating electronic portfolios with artificial intelligence to support metacognitive assessment in secondary school chemistry, specifically in learning buffer solutions. A qualitative descriptive design was employed as the define stage of the 4D development model (Define, Design, Develop, Disseminate). Data were collected through semi-structured interviews with two chemistry teachers selected via purposive sampling to represent contrasting instructional contexts: a public senior high school implementing the *Kurikulum Merdeka* and a boarding school with restricted digital infrastructure. Interviews were supplemented by a systematic literature review. Data were analyzed using thematic analysis, involving familiarization, open coding, theme development, and synthesis. Trustworthiness was established through member checking and data triangulation between interview findings and literature. The findings reveal four interrelated barriers to effective metacognitive assessment: a persistent feedback bottleneck arising from high teacher workload; disparities in digital access across school contexts; students' overreliance on algorithmic procedures at the expense of conceptual understanding; and a gap between authentic assessment ideals and operational classroom realities. These findings establish a theoretically grounded rationale for developing an AI-enhanced electronic portfolio that positions artificial intelligence as an automated scaffolding mechanism for formative feedback, rather than merely a technological add-on. The proposed conceptual framework offers design principles for subsequent development and empirical validation of the assessment system.

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Introduction

Drawing on self-regulated learning theory (Zimmerman, 2002) and formative assessment frameworks (Black & Wiliam, 1998), this study examines the conditions under which electronic portfolios can be theoretically and practically justified as instruments for metacognitive assessment in chemistry education. Within this framework, metacognition students' capacity to plan, monitor, and evaluate their own cognitive processes is understood not merely as an individual cognitive trait but as a socially mediated and assessment-responsive competence that can be cultivated through structured reflective practices. The paradigm of chemistry education in the twenty-first century has undergone a substantial shift toward the development of higher order thinking skills, in which this metacognitive dimension plays a central role in supporting students' academic achievement. These skills are essential for understanding complex and abstract scientific concepts (Gün-Tosik et al., 2023; Zeng et al., 2023). Within the context of secondary school chemistry, buffer solutions are widely recognized as one of the most conceptually challenging topics. Mastery of this material requires students to integrate macroscopic phenomena with submicroscopic reasoning related to pH stabilization mechanisms (Ashari, 2025; Genes et al., 2021). However, recent empirical studies indicate that many students demonstrate low levels of metacognitive awareness and experience difficulties in regulating their thinking when confronted with multistep chemical problem solving tasks (MacNeil et al., 2024; Wardana et al., 2020). This condition underscores the urgent need for assessment instruments that move beyond the measurement of final learning outcomes and are capable of capturing student cognitive processes throughout the learning experience (Dwi Septian et al., 2020; Nawawi et al., 2024).

In response to this challenge, innovative pedagogical approaches like electronic portfolios have been adopted to promote active learning and self-regulation. An electronic portfolio functions as an authentic assessment tool by providing a digital space for collecting diverse learning artifacts and reflective journals (Masluhah & Afifah, 2022; Yanti & Thohir, 2024). Through continuous documentation and reflection, electronic portfolios facilitate longitudinal monitoring of student progress and foster sustained reflective practices that support metacognitive development (Butakor, 2024; Liping et al., 2023). Nevertheless, the pedagogical benefits of electronic portfolios are strongly influenced by the extent to which they are systematically integrated into instructional and assessment practices to support meaningful learning (Ait Mama, 2023). In the Indonesian chemistry education context, however, the implementation of electronic portfolios remains constrained by a persistent feedback bottleneck.

Despite their theoretical advantages, the implementation of electronic portfolios in Indonesian secondary school chemistry classrooms remains constrained by several practical limitations. Preliminary field investigations conducted through interviews with chemistry practitioners reveal a substantial gap between ideal assessment principles and classroom realities. Teachers in public schools reported that high administrative workloads and limited instructional time constitute major deterrents to the consistent implementation of comprehensive electronic portfolios. Furthermore, in specialized educational contexts such as boarding schools, restricted access to digital devices and infrastructural limitations necessitate assessment platforms that are both flexible and highly automated. These findings indicate that, in the absence of technological support for assessment and feedback processes, electronic portfolios are often perceived as burdensome rather than pedagogically beneficial tools.

Recent developments in artificial intelligence (AI) offer promising opportunities to address these challenges. Artificial intelligence based systems are capable of providing timely and personalized feedback that approximates instructional guidance typically delivered by teachers (Trajkovski & Hayes, 2025). By analyzing students' reflective writings and project-based learning outcomes, such systems can support teachers in gaining deeper insights into students' metacognitive processes while reducing the demands of manual assessment (Ni & Lam, 2025; Pacheco et al., 2025). The integration of artificial intelligence within electronic portfolio assessment is also aligned with broader educational trends that emphasize learner autonomy, self-regulation, and meaningful engagement in technology-supported learning environments (Khasawneh et al., 2025; Le et al., 2024).

A critical review of existing literature reveals that while electronic portfolio tools have been deployed in science education internationally, no validated instruments specifically designed to capture metacognitive monitoring and evaluation processes in the chemistry context of buffer solutions have been identified in Indonesian secondary school settings. Moreover, the integration of artificial intelligence as an automated formative feedback mechanism within such portfolios remains theoretically underdeveloped in the local literature. This study does not develop or validate a fully operational instrument; rather, it establishes the empirical and theoretical rationale for such development by conducting a systematic needs analysis and proposing a conceptual framework. The study addresses three interdependent questions: What are the current barriers to effective metacognitive assessment in Indonesian secondary chemistry classrooms? What theoretical principles from self-regulated learning and formative assessment research should guide the design of an AI-enhanced electronic portfolio? And what design criteria emerge from the intersection of field data and theoretical synthesis? By clarifying these foundational questions, this study provides the empirical and conceptual basis for the subsequent Design and Develop stages of the 4D model, ensuring that the resulting assessment system is both theoretically coherent and contextually responsive to Indonesian classroom realities.

Method

This study employed a qualitative descriptive design, constituting the Define stage of the 4D development model (Define, Design, Develop, Disseminate). The study aimed to conduct a systematic situational analysis of current chemistry assessment practices related to metacognitive skills, generating both empirical and theoretical foundations for the subsequent design of an AI-enhanced electronic portfolio. A qualitative approach was selected because the central research questions concern contextual barriers, teacher perceptions, and theoretical adequacy of existing frameworks phenomena that require interpretive depth rather than statistical generalization (Creswell & Poth, 2018). This design is appropriate for exploring contextual challenges and instructional needs prior to educational product development (Borg & Gall, 2003; Creswell & Poth, 2018).

The participants were two chemistry teachers selected through purposive sampling to represent contrasting instructional contexts in Indonesia, consistent with the criterion of maximum variation sampling in qualitative inquiry (Patton, 2015). While the small sample size does not permit claims of representativeness or theoretical saturation, it was deemed appropriate for the exploratory aims of this needs analysis phase, which sought depth of contextual understanding rather than breadth of generalization. The participants included one teacher from a public senior high school implementing the *Kurikulum Merdeka* and one teacher from a boarding school, where instructional practices and access to digital infrastructure differ substantially. Such variation was intended to capture a broader perspective on assessment constraints and needs across educational settings (Patton, 2015).

Data were collected through a systematic review of relevant literature and semi-structured interviews. Each participant was interviewed once for approximately 45 to 60 minutes using a pre-tested interview protocol developed by the research team and reviewed by two expert supervisors for content validity. The literature review was conducted to identify dominant frameworks of metacognitive assessment, reported challenges in electronic portfolio implementation, and emerging technological approaches in science education. The interviews explored assessment practices for buffer solution topics, teachers' perceptions of students' metacognitive difficulties, and practical challenges associated with digital and AI-assisted assessment.

Interview transcripts were analyzed using thematic analysis (Braun & Clarke, 2006), following the six-phase procedure of data familiarization, open coding, theme construction, theme review, theme definition, and report writing. Coding was conducted independently by the first author, followed by collaborative review with the second author; disagreements were resolved through discussion until consensus was achieved. A total of 38 initial codes were generated, subsequently clustered into 12 sub-themes and four overarching themes. To enhance analytical credibility, the systematic literature review served as a second data source for theoretical triangulation: interview-derived themes were cross-referenced with findings from peer-reviewed studies to identify areas of convergence and divergence, thereby strengthening the interpretive basis for the proposed conceptual framework. It is important to note that in this study, literature functions as a theoretical lens rather than a co-equal empirical data source; triangulation refers to the alignment of experiential evidence from teachers with established theoretical and empirical claims from the literature. Member checking was completed by returning summarized interview analyses to both participants, who confirmed the accuracy of interpretation. No discrepancies requiring modification were identified.

Consistent with the 4D development model, this Define stage provides the empirical foundation and theoretical rationale necessary to guide the subsequent Design phase, in which the conceptual framework will be operationalized into concrete assessment components and AI integration specifications

Results and Discussions

The thematic analysis of interview data, cross-referenced with the systematic literature review, generated four interrelated themes that together construct a theoretically grounded argument for the development of an AI-enhanced electronic portfolio. These themes do not operate in isolation; rather, they constitute a dialectical structure in which each identified barrier creates the conditions that render AI-enhanced portfolio assessment both necessary and theoretically defensible. Theme 1 (The Paradox of Authentic Assessment) establishes the foundational tension between assessment ideals and operational realities. Theme 2 (Contextual Barriers and Digital Equity) reveals how infrastructural constraints compound this tension in diverse school settings. Theme 3 (Metacognitive Deficiencies in Buffer Solution Mastery) identifies the specific cognitive and assessment inadequacies that current instruments fail to address. Theme 4 (The Transformative Role of Artificial Intelligence) presents AI integration as the theoretically grounded response to the preceding three challenges. Both participants endorsed all four themes during member checking. Table 1 provides a synthesis of empirical evidence and theoretical alignment across these themes.

Table 1. Synthesis of Theoretical Framework and Empirical Findings

Theme	Empirical Evidence (Interview Highlights)	Literature Alignment	AI-Enhanced Portfolio Role
The Paradox of Authentic Assessment: Ideals and Operational Reality	Teachers acknowledged the importance of authentic assessment for capturing students' metacognitive processes; however, its implementation remained limited due to a persistent feedback bottleneck and high administrative workload. As a result, e-portfolios were used inconsistently and primarily for documenting completed tasks.	Consistent with prior studies, e-portfolios tend to function as digital repositories rather than reflective assessment tools when instructional time and teacher capacity for individualized feedback are constrained (Ait Mama, 2023; Ichsan et al., 2020; Masluhah & Afifah, 2022).	Within this paradox, AI-enhanced e-portfolios are positioned as an automated scaffolding mechanism that supports timely formative feedback, enabling reflective engagement while reducing the operational burden placed on teachers (Le et al., 2024; Pacheco et al., 2025).
Contextual Barriers and Digital Equity: Navigating Technological Austerity in Diverse School Settings	Interview findings revealed stark disparities in digital access across school contexts. In boarding schools, strict device regulations resulted in technological austerity, with students relying on limited, scheduled computer laboratory sessions to complete digital assessment tasks.	The literature highlights the necessity of infrastructure-sensitive and inclusive digital assessment frameworks, emphasizing that innovations effective in technology-rich environments may not translate directly to resource-constrained settings (Khasawneh et al., 2025; van Laar et al., 2020).	In response to these contextual constraints, the proposed e-portfolio system prioritizes efficiency and low technical complexity. AI-supported features are intended to maximize cognitive and metacognitive engagement within limited access periods, thereby mitigating inequities arising from restricted digital infrastructure.
Metacognitive Deficiencies in Buffer Solution Mastery: Beyond Algorithmic Proficiency	Teachers reported that students demonstrated strong algorithmic proficiency in buffer-related calculations, such as pH determination, yet struggled to explain sub-microscopic mechanisms and chemical reasoning underlying buffer action.	This discrepancy reflects patterns of mechanical learning identified in chemistry education research, where procedural fluency masks deficiencies in conceptual understanding and metacognitive awareness (Ashari, 2025; Kusumaningrum & Kristyasari, 2022; Salame et al., 2022).	AI-enhanced e-portfolios incorporate structured reflective prompts that externalize students' reasoning processes, shifting assessment focus from final numerical outcomes toward conceptual explanation and metacognitive regulation, particularly in planning, monitoring, and evaluation stages (Nawawi et al., 2024).
The Transformative Role of Artificial Intelligence: Mitigating the Assessment–Pedagogy Gap	Teachers perceived artificial intelligence as a practical support for reducing the workload associated with evaluating reflective artifacts, while simultaneously enabling more frequent and individualized feedback.	Previous studies emphasize that timely feedback and diagnostic insight are essential conditions for effective metacognitive development, yet are often difficult to achieve through manual assessment alone (Ni & Lam, 2025; Trajkovski & Hayes, 2025).	In this framework, artificial intelligence functions as a complementary diagnostic tool that analyzes students' reflective data to identify patterns in metacognitive processes, thereby supporting teachers' instructional decision-making without replacing professional judgement (Ifenthaler & Yau, 2020).

The Paradox of Authentic Assessment: Ideals and Operational Reality

The first major finding reveals a clear dichotomy between the theoretical foundations of authentic assessment and its operational realization in chemistry classrooms. Both participants demonstrated strong conceptual alignment with the paradigm shift in twenty first century education, acknowledging that metacognitive dimensions such as planning, monitoring, and self evaluation extend beyond the evaluative scope of conventional multiple choice assessments (Ichsan et al., 2020; Yanti & Thohir, 2024). In the context of complex chemistry topics such as buffer solutions, traditional assessment practices tend to emphasize algorithmic accuracy while providing limited insight into students' sub microscopic reasoning and conceptual understanding (Ashari, 2025; Dwi Septian et al., 2020). As a result, although teachers recognize that electronic portfolios offer a more comprehensive framework for documenting students' cognitive processes over time (Villarroel et al., 2018), their implementation remains constrained by practical considerations related to instructional efficiency.

This constraint is primarily associated with what teachers described as a feedback bottleneck. The implementation of comprehensive electronic portfolios (Masluhah & Afifah, 2022) requires extensive time for reviewing student artifacts and generating individualized feedback, a process that is often incompatible with the current administrative and instructional conditions in Indonesian schools. The public school teacher noted that although the Kurikulum Merdeka explicitly emphasizes formative and process oriented assessment, high student teacher ratios and fixed instructional schedules necessitate a pedagogical compromise between assessment depth and curriculum coverage. Consequently, when electronic portfolios are adopted, they frequently function as digital repositories of completed assignments rather than as reflective learning tools, as teachers lack sufficient time to engage meaningfully with students' reflective outputs (Ait Mama, 2023; Nurhayati & Sumbawati, 2014).

The findings further indicate that this assessment workload has direct implications for students' metacognitive development. Effective metacognitive regulation relies on timely and specific feedback that enables learners to monitor and adjust their cognitive strategies during the learning process (Muteti et al., 2021; Stanton et al., 2021). However, when teachers are burdened by manual evaluation demands, feedback is often delayed or remains generic, limiting its capacity to support metacognitive growth. This feedback gap is consistent with the arguments of Trajkovski and Hayes (2025), who suggest that delayed instructional responses reduce students' engagement in reflective activities and weaken the formative function of portfolio based assessment (Butakor, 2024; Liping et al., 2023). Within this context, the integration of artificial intelligence emerges as a pedagogically grounded solution. Artificial intelligence can function as an automated scaffolding mechanism that supports the provision of immediate, formative feedback, thereby sustaining students' metacognitive engagement without exacerbating teachers' administrative workload (Dwi Oktarina et al., 2025; Le et al., 2024; Pacheco et al., 2025).

Contextual Barriers and Digital Equity: Navigating Technological Austerity in Diverse School Settings

The second major theme highlights substantial contextual disparities in technological infrastructure and levels of digital readiness between public senior high schools and boarding schools. In public school settings, students generally operate within a personal device learning environment, in which smartphones and laptops are routinely integrated into instructional activities. In contrast, boarding school institutions implement strict regulations regarding personal device ownership, resulting in a condition of technological austerity where access to digital tools is centralized in computer laboratories and limited to specific, closely supervised instructional periods. This contrast underscores a fundamental issue of digital equity, as assessment innovations that function effectively in technology rich environments may not be transferable to resource restricted contexts without deliberate adaptation (van Laar et al., 2020).

The limited digital access window in boarding school contexts presents a distinctive pedagogical challenge for fostering metacognitive development. Metacognitive processes require adequate time for reflection, monitoring, and evaluation; however, when students must complete reflective tasks within narrowly constrained laboratory sessions, the depth and quality of their reflections tend to diminish. Interview data from the boarding school teacher indicate that under such conditions, student reflections often prioritize task completion over meaningful cognitive evaluation. This finding suggests that for electronic portfolios to be pedagogically viable in boarding school settings, they must be designed to minimize technical complexity and operational inefficiency. The success of digital assessment implementation in Indonesia therefore depends on moving beyond a uniform design approach and adopting an infrastructure sensitive framework that accounts for institutional variability. In this context, the demand is not merely for a digital assessment tool, but for a streamlined and highly optimized platform that maximizes cognitive engagement while minimizing time spent on technical navigation.

Within this framework, the findings offer strong justification for the integration of artificial intelligence as a mechanism for supporting digital equity. The incorporation of AI driven feedback enables the electronic portfolio to partially offset limitations in teacher student interaction time during brief laboratory sessions. The proposed AI enhanced system is conceptualized as a virtual instructional support that facilitates metacognitive processes such as planning and monitoring in real time, even when teachers are required to manage large groups of students in shared computer facilities. Consequently, the design philosophy of the proposed smart electronic portfolio must prioritize efficiency, automation, and usability to ensure that learners in digitally constrained environments, including boarding school, are not disadvantaged in developing 21st century skills. This approach aligns with broader international perspectives emphasizing inclusive and context responsive educational technology implementation (Khasawneh et al., 2025).

Metacognitive Deficiencies in Buffer Solution Mastery: Beyond Algorithmic Proficiency

The third theme examines metacognitive deficiencies in students' mastery of buffer solutions, a topic widely recognized as one of the most conceptually demanding areas in secondary chemistry education. Interview findings indicate a persistent gap between students' algorithmic performance and their conceptual understanding. Teachers reported that although many students demonstrate strong proficiency in symbolic and mathematical procedures, such as calculating pH values using the Henderson–Hasselbalch equation, they encounter substantial difficulty when asked to explain observable phenomena or sub-microscopic mechanisms underlying pH stabilization. This discrepancy indicates that success in problem solving often reflects procedural fluency rather than genuine conceptual understanding, a pattern consistently reported in prior chemistry education research (Ashari, 2025; Kusumaningrum & Kristyasari, 2022; Salame et al., 2022).

This pattern aligns with what has been described as mechanical learning, in which students rely heavily on memorized formulas without engaging in the sub-microscopic reasoning required to explain how conjugate acid–base pairs interact within a buffer system (Ashari, 2025; Kusumaningrum & Kristyasari, 2022; Salame et al., 2022). The findings suggest that this learning orientation is closely associated with deficiencies in metacognitive awareness across three essential dimensions: planning, monitoring, and evaluation. Teachers observed that students rarely engage in deliberate planning, such as identifying dominant chemical species prior to calculation. During problem solving, students also show limited monitoring behavior, seldom checking whether their numerical results are chemically reasonable or consistent with equilibrium principles. Moreover, evaluative processes are largely absent, as students infrequently reflect on the coherence of their reasoning, particularly when confronted with non-routine or contextualized buffer problems (Guo et al., 2022; Zeng et al., 2023). As a result, students remain confined to surface-level understanding that is highly vulnerable when problem complexity increases.

In addition, the study reveals a pedagogical limitation arising from the dominant assessment practices currently employed in schools. Existing instruments predominantly emphasize final numerical answers, thereby obscuring the cognitive and metacognitive processes that generate those answers. Consequently, crucial indicators of metacognitive development, such as students' ability to recognize misconceptions, revise strategies, or justify their reasoning, remain largely undetected and unaddressed (Dwi Septian et al., 2020; Nawawi et al., 2024). This limitation highlights the need for assessment approaches that explicitly capture students' thinking processes rather than merely their outcomes. By incorporating structured reflective prompts and digital learning artifacts, the proposed AI-enhanced electronic portfolio is designed to externalize students' internal cognitive processes. Such an approach supports the development of metacognitive regulation and facilitates a transition from passive formula application toward active, self-regulated learning, enabling students to engage more meaningfully with the conceptual complexity of buffer systems (Altindağ & Senemoğlu, 2013).

The Transformative Role of Artificial Intelligence: Mitigating the Assessment-Pedagogy Gap

The fourth theme highlights the role of artificial intelligence as a supportive mechanism for addressing persistent constraints in chemistry assessment practices, particularly those related to workload and feedback provision. Both participating teachers viewed artificial intelligence positively as a tool that could assist in reducing the burden associated with assessing student reflections and learning artifacts. The manual evaluation of reflective journals was identified as a time consuming process that often limits the frequency and quality of formative feedback. Consequently, artificial intelligence assisted systems were perceived as a practical means of enabling more timely and individualized feedback without increasing teachers' administrative responsibilities. This perception aligns with previous studies emphasizing that timely feedback is a critical condition for effective metacognitive development (Ni & Lam, 2025; Trajkovski & Hayes, 2025).

In addition to supporting feedback efficiency, artificial intelligence was also perceived as having potential value in improving the quality of assessment diagnosis. Teachers indicated that conventional assessment instruments frequently fail to capture students' reasoning processes and difficulties during complex chemistry learning tasks. Through the analysis of students' written reflections and learning artifacts, artificial intelligence techniques such as learning analytics and natural language processing may assist in identifying patterns related to students' planning, monitoring, and evaluation processes. These insights can provide teachers with more

Journal of Counseling, Education and Society
Vol. 7, No. 1, 2026, pp. 178-186

detailed information regarding students' metacognitive development than traditional assessments focused solely on final answers (Ifenthaler & Yau, 2020; Pacheco et al., 2025).

Furthermore, the integration of artificial intelligence within an electronic portfolio system is expected to support a more balanced distribution of instructional roles. By assisting with routine evaluative tasks, artificial intelligence enables teachers to allocate greater attention to instructional decision making, conceptual clarification, and targeted learning support. This shift allows teachers to focus on facilitating students' understanding of complex topics such as buffer solutions, rather than being overwhelmed by administrative assessment tasks (Luckin et al., 2016). In this context, artificial intelligence functions as a complementary tool that supports, rather than replaces, the professional judgement of teachers.

Overall, the findings suggest that the integration of artificial intelligence into electronic portfolio assessment offers a context-appropriate approach to strengthening metacognitive assessment in chemistry education. By addressing feedback delays, reducing assessment workload, and enhancing diagnostic insight, artificial intelligence assisted portfolios have the potential to support more effective and sustainable assessment practices. These results reinforce the relevance of developing an electronic portfolio system that incorporates artificial intelligence as a means of aligning pedagogical expectations with the practical realities of secondary school chemistry classrooms.

Conclusions

This study set out to establish the empirical and theoretical basis for developing an AI-enhanced electronic portfolio for metacognitive assessment in secondary chemistry education. The findings from semi-structured interviews with two purposively selected teachers, cross-referenced with relevant literature, reveal three systemic barriers that current assessment practices are unable to adequately address: a persistent feedback bottleneck arising from teachers' high administrative workload, significant disparities in digital infrastructure across public and boarding school contexts, and students' deep-seated reliance on algorithmic procedures that masks deficiencies in metacognitive planning, monitoring, and evaluation during buffer solution learning. These three barriers are empirically supported by the interview data and theoretically corroborated by convergent findings in the literature, lending confidence to their status as genuine and context-specific constraints rather than isolated perceptions. It is important to be transparent about the scope of what this study has and has not established. The data collected do not include any direct testing, prototyping, or validation of an AI-enhanced portfolio system; accordingly, the claim that artificial intelligence integration offers a viable solution must be understood as a theoretically derived proposition rather than an empirically demonstrated outcome. Both participating teachers expressed positive dispositions toward AI-assisted feedback, and this perception aligns with theoretical arguments advanced in the literature (Ni & Lam, 2025; Trajkovski & Hayes, 2025). However, teacher perception constitutes attitudinal data, not functional evidence of AI efficacy. The proposed conceptual framework positioning AI as an automated scaffolding mechanism for formative feedback, operating within a self-regulated learning framework is grounded in theoretical synthesis and represents a direction for subsequent development rather than a validated design. On this basis, the study makes two primary contributions. First, it provides a contextually situated needs analysis that reveals the specific conditions under which AI-enhanced portfolio assessment is theoretically justified in Indonesian chemistry classrooms. Second, it proposes design principles derived from the intersection of field data and theoretical frameworks, which will inform the Design and Develop stages of the 4D model. Future research should subject these principles to empirical scrutiny through instrument development, expert validation, and controlled classroom implementation, with explicit measurement of both metacognitive outcomes and AI system performance.

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