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Analyzing the Mathematical Literacy of Indonesian Students: Characteristics, Challenges, and Technology-Enhanced Solutions

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ABSTRACT

Purpose of the study: This study aims to uncover the characteristics of Indonesian students' mathematical literacy, the challenges they face in solving mathematical problems, and to propose effective solutions, including technology-enhanced interventions, for improvement.

Methodology: This study uses a qualitative phenomenological approach to explore students' experiences in mathematical literacy. Data were collected through AKM-based algebra tasks, interviews, and observations involving three purposively selected middle school students. Method triangulation ensured validity, while digital tools, including audio recording and NVivo software, supported systematic qualitative data coding and analysis.

Main Findings: The findings indicate that students' incorrect answers often arise from difficulties in identifying key problem elements. This misidentification triggers cascading errors across subsequent problem-solving steps, creating a domino effect. Analysis revealed distinct patterns in communication, mathematization, representation, problem-solving strategies, symbolic operations, and reasoning. These patterned error trajectories align well with digital logging, automated analysis, and real-time feedback, enabling direct application in designing digital assessment platforms, intelligent tutoring systems, and learning analytics dashboards to diagnose learning breakdowns.

Novelty/Originality of this study: This study uniquely bridges qualitative phenomenological analysis with concrete technological design, systematically translating error patterns into detection algorithms, scaffolding rules, and dashboard specifications. Unlike prior research that either describes difficulties or proposes technology, we explicitly operationalize how intelligent systems can detect and respond to cascading error patterns in real time. The result is a contextually grounded framework for AKM-aligned technology implementation tailored to Indonesian educational realities, including infrastructure constraints and teacher capacity.

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1. INTRODUCTION

Mathematics plays an essential role in the educational process in schools [1], and enhancing mathematical literacy has become an urgent necessity to develop a generation capable of applying mathematical concepts in daily life [2]-[4]. Mathematical literacy is a crucial skill that students must master globally and serves as one of the parameters for assessing a nation's quality through the Programme for International Student Assessment (PISA), which evaluates student literacy on a global scale [5]-[7]. Implementing PISA has increased the trend of mathematical literacy capabilities in various countries, including Indonesia. The Indonesian Ministry of Education and Culture has established six essential literacies, including numerical literacy or mathematical literacy, as an integral part of the fundamental skills that Indonesian students must possess [8], [9]. Mathematical literacy encompasses the ability to formulate, apply, and interpret mathematics in various life contexts [10]-[12]. The literature identifies mathematical literacy as a critical cognitive skill for students, encompassing an understanding of mathematical concepts and the ability to relate mathematics to everyday life [13], [14]. Therefore, mastering mathematical literacy positively impacts students' ability to solve problems and apply mathematical knowledge in real-world situations.

Students with good mathematical literacy tend to be more confident in solving complex mathematical problems, highlighting the importance of this skill in daily life and educational contexts [15]. However, in reality, Indonesian students' mathematical literacy remains low. An Organization for Economic Co-operation and Development (OECD) survey through the 2018 PISA assessment showed that Indonesia ranked 71st out of 77 countries in mathematical literacy, scoring 379 [16]. Furthermore 2023, Indonesia's mathematical literacy score declined to 366 [17]. In addition to PISA data, various empirical studies conducted by Dewantara et al. [18], Fauzi & Chan [19], and Jailani et al. [20] also indicate the low mathematical literacy of Indonesian students, attributed to their difficulties in identifying contextual problems and applying mathematical formulas to solve mathematical problems. Therefore, the Indonesian government must take adequate measures to evaluate and address this issue.

At the end of 2020, the Indonesian government introduced the Minimum Competency Assessment (AKM) as an alternative to the National Examination (UN) to improve educational quality by measuring students' basic skills, including mathematical literacy [10], [21], [22]. However, AKM has not yet been successful in addressing the persistently low levels of mathematical literacy, as many students still obtain low scores and there is limited information about the underlying causes (Kemendikbudristek, 2022). Rather than focusing solely on test results, it is crucial to understand students' problem-solving characteristics and the specific obstacles they encounter when working on mathematical tasks. Such insights can guide reflective evaluations to improve teaching methods and support teachers in more effectively fostering mathematical literacy.

Bridging qualitative understanding with technological innovation represents a critical frontier in mathematics education research. Numerous studies have documented students' mathematical literacy challenges, and others have demonstrated technology's potential to enhance learning. However, few have systematically translated qualitative insights about students' actual problem-solving processes into specific, actionable technology design requirements.

This translation is particularly urgent in the Indonesian context, where the recent shift to computer-based AKM assessment creates both opportunities and imperatives. On the one hand, there are opportunities to leverage digital platforms for process-logging, adaptive feedback, and learning analytics. On the other hand, there are imperatives to ensure that technology genuinely addresses students' documented difficulties rather than merely digitizing traditional assessments.

The present study addresses this gap by adopting a phenomenological approach to understand in depth students' lived experiences with AKM problems, and then explicitly operationalizing these insights into a technology-enhanced framework that respects Indonesia's infrastructural realities, teacher capacity, and pedagogical values. The aim is not simply to describe what students struggle with, but to show how technology can detect these struggles in real time, provide appropriate scaffolding, and inform teacher intervention, grounded in authentic qualitative understanding rather than technological determinism.

Although many studies have explored aspects of mathematical literacy, the majority have relied on PISA problems as the primary instrument [18], [23]- 26], and a literature review by Muhaimin et al. [2] similarly revealed that PISA problems are most frequently used to measure or analyze students' mathematical literacy; however, there remains a significant research gap in the form of a limited understanding of students' mathematical literacy processes within digital assessment contexts and a lack of qualitative studies that investigate mathematical literacy using AKM problems from a technological perspective. Through this analysis, the study proposes steps that need to be taken to improve mathematical literacy and, at the same time, offers insights that can inform innovation in digital learning and assessment particularly the design of AKM-oriented digital assessment tools, intelligent tutoring systems, and learning analytics that are capable of diagnosing and scaffolding students' problem-solving processes in a more targeted and data-informed way.

2. THE COMPREHENSIVE THEORETICAL BASIS

2.1. Overview of Framework Mathematical Literacy

Literacy is a fundamental ability that students must master at school to solve everyday problems [27], [28]. This is supported by the statement from Astuti [29] that literacy skills must be mastered by students in this century to fulfil their daily lives. From these definitions, literacy skills are abilities that a person must have to help him solve problems related to everyday life. Looking at the definition of literacy, this ability is essential to master and is part of 21st-century skills. The four domains of 21st-century skills are literacy, inventive thinking, effective communication, and high productivity [30]-[32]. Then, literacy skills are needed in everyday life to obtain information around us well [33]-[35]. Not only that, according to Nail-Chiwetalu & Ratner [36], the ability to process information is needed to justify the truth of the information obtained. The importance of literacy places this ability in the competencies that students must master at each level of education. Stacey [13] classifies basic literacy into 6, namely language literacy, mathematics literacy, scientific literacy, financial literacy, digital literacy, cultural literacy, and citizenship.

Mathematical literacy is a person's skill in understanding and processing practical mathematical problems related to data and calculations to quickly adapt to the continuously developing world of life [37]. Sumirattana et al. [38] define mathematical literacy as skills in various life problems to formulate, use, and interpret mathematical problems. Another source from the OECD [11], [39] states that the ability to formulate is an effort to identify problems from mathematical problems, and the ability to apply is to use various formulas to solve problems and to interpret them to provide evaluations involving the context of the problem. From these several definitions, it can be concluded that mathematical literacy is a person's mastery in formulating, implementing, and interpreting mathematics efficiently from various contexts, content, and life processes.

The definition of mathematical literacy refers to an individual's capacity to formulate, use, and interpret mathematics. These three words provide a structure for organizing mathematical processes that describe how individuals connect the problem context with mathematics and solve the problem. Items in the mathematical literacy assessment in PISA are assigned to one of three mathematical processes [11], [39]. The three mathematical processes include (1) Formulating the situation mathematically, (2) using mathematical concepts, facts, procedures, and reasoning, and (3) interpreting, applying, and evaluating mathematical results. The formulation process shows how effectively students can recognize and identify mathematical problems to use in problem situations and then provide the necessary mathematical structure to formulate contextualized problems into mathematical form. The process of applying concepts shows how well students can carry out calculations and manipulations and apply the concepts and facts they know to obtain solutions to problems that are formulated mathematically. The interpretation process shows how effectively students can reflect on mathematical solutions or conclusions, interpret them in the context of real-world problems, and determine whether the results or conclusions make sense. The relationship between these processes is visualized in Figure 1.

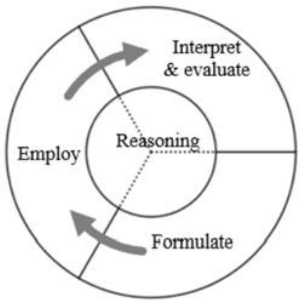


Figure 1. Mathematical literacy process by OECD (OECD, 2019a)

The better the basic mathematical skills, the better the mathematical literacy. These mathematical fundamentals are explained in OECD [39] as follows: (1) Communication, mathematical literacy involves communication. Individuals perceive some challenges and are stimulated to recognize and understand problem situations. Once a solution is found, students may need to provide students with explanations or justifications for the answers obtained; (2) Mathematization, mathematical literacy can involve transforming problems defined in the real world into mathematical form or interpreting and evaluating mathematical results or mathematical models about original problems; (3) Representation, this essential mathematical ability requires selecting, interpreting, using various representations to identify situations, or to present one's work. The representation in question includes graphs, tables, diagrams, images, equations, and formulas; (4) Reasoning and argumentation, this ability involves a logically rooted thought process that explores and connects the elements of a problem to conclude it, examine the justification given, or provide justification for a solution; (5) Designing strategies to solve problems, in mathematics requires the ability to design strategies to solve problems mathematically and this mathematical ability can be used at every stage of the problem-solving process; (6) Using symbolic, formal and technical language and operations. Mathematical literacy requires symbolic, formal, and technical language and operations. The symbols, formalities, and techniques used vary according to the specific mathematical content knowledge required for the particular task of formulating, solving, or interpreting mathematics; (7) Using mathematical tools, mathematical tools include physical tools, such as measuring tools, as well as calculators and computer-based tools which are increasingly available. In addition to knowing how to use these tools to help them complete math assignments, students need to know the limitations of these tools.

Whether mathematical literacy skills are excellent or bad, something certainly influences them. Various mathematical literacy studies have previously been conducted, and these researchers revealed factors that influence whether students' mathematical literacy is good or bad. Students' low mathematical literacy is not without reason; some factors influence this ability. After reviewing data from 20 SLR articles, we found factors influencing mathematical literacy. There were too many factors, so we categorized the findings into internal and external factors. Internal factors arise from within the individual, in contrast to external factors originating from outside the individual. Internal factors obtained include confidence, motivation, quantity of practice, gender, self-efficacy, anxiety, learning discipline, reading literacy habits, academic values, age, experience, and critical thinking [18], [40]-[45]. Then external factors consist of the learning process, student and teacher ratio, learning model, mathematical modelling, learning approach, teacher support, ICT, textbooks, school level, meaningful learning, culture, local resources, and teacher experience [46]-[50].

However, the literature review on mathematical literacy should not stop at identifying these influencing factors. The relationship between mathematical literacy and pedagogical approaches deserves further exploration. Effective pedagogical strategies, such as inquiry-based learning, problem-based learning, contextual learning, and technology-enhanced instruction, have been shown to play a pivotal role in strengthening students’ ability to connect mathematical concepts with real-world contexts [11], [51]. Teachers who adopt constructivist and student-centered pedagogies tend to promote higher mathematical literacy because they encourage reasoning, exploration, and the application of mathematics in meaningful situations [52]-[54]. Moreover, effective teaching strategies, including scaffolding, collaborative learning, and the integration of digital tools, help students develop essential literacy processes such as problem formulation, interpretation, and reflection [55]. Pedagogical models that emphasize dialogue, feedback, and metacognitive awareness have also been proven to improve mathematical reasoning and literacy outcomes. Therefore, mathematical literacy development is not merely a cognitive skill but also a pedagogical and instructional challenge that requires deliberate, reflective, and adaptive teaching strategies aligned with students’ learning needs.

In addition, greater emphasis should be placed on cultural and socio-economic barriers in the field of mathematical literacy. Research indicates that students’ cultural background, home language, and socio-economic status strongly shape their access to mathematical concepts, learning attitudes, and problem-solving performance [39], [56]. Addressing these aspects would not only provide a more holistic understanding of the determinants of mathematical literacy but also highlight the equity dimension of mathematics education.

2.2. Technology as a Critical External Factor in Mathematical Literacy Development

While traditional factors such as pedagogical approaches, teacher support, and textbooks significantly influence mathematical literacy [46], [47], the role of technology has become increasingly pivotal in 21st-century mathematics education. Information and Communication Technology (ICT), when effectively integrated, can address multiple fundamental mathematical skills simultaneously: dynamic geometry software (e.g., GeoGebra) supports mathematization and representation; spreadsheet environments scaffold reasoning and symbolic operations; and computer algebra systems enable students to focus on problem formulation and interpretation by reducing computational load [57]-[59].

However, technology's impact on mathematical literacy is mediated by how it is used. Instrumental applications, such as drill-and-practice programs or calculator use for mere computation, show limited effects on higher-order literacy processes [60]. In contrast, uses that engage students in mathematical modeling, exploration of multiple representations, and collaborative problem-solving demonstrate stronger gains [61]. This distinction underscores that teachers' Technological Pedagogical Content Knowledge (TPACK), their ability to orchestrate technology in ways that enhance conceptual understanding and literacy processes, is as crucial as technology access itself [62]-[64].

Recent developments in educational technology offer promising tools for mathematical literacy development:

1. Adaptive Learning Technologies: Intelligent tutoring systems and adaptive platforms (e.g., Khan Academy, ALEKS) can diagnose students' specific difficulties in problem identification, mathematization, or procedural execution and provide personalized scaffolding [65]. These systems use algorithms to adjust task difficulty, offer hints at strategic moments, and track learning trajectories over time.
2. Interactive Problem-Solving Environments: Digital workspaces such as Desmos Activity Builder, GeoGebra Classroom, and Polypad allow students to manipulate mathematical objects, visualize

relationships dynamically, and test hypotheses through simulation. These environments support the transition from concrete to abstract representations, a critical bridge for mathematical literacy.

3. Collaborative Digital Tools: Platforms enabling synchronous and asynchronous collaboration (e.g., Microsoft Teams, Google Workspace, Padlet) can make students' problem-solving processes visible to peers and teachers. By externalizing reasoning, students develop metacognitive awareness and benefit from distributed expertise [66].
4. Learning Analytics and Formative Assessment Tools: Digital assessment platforms can capture process data, not just final answers, revealing where students struggle in the problem-solving sequence. Teachers can use these insights for targeted interventions, moving beyond summative scores to diagnostic, actionable feedback [11].
5. Gamification and Engagement Platforms: Tools like Kahoot, Quizizz, and Prodigy use game mechanics to increase motivation and provide low-stakes practice opportunities. While not sufficient alone, these can complement more substantive mathematical work by building fluency and confidence [60].

In the Indonesian context, the digital transformation of assessment through AKM's computer-based delivery adds another dimension. Students' varying digital literacy, their familiarity with navigating digital interfaces, using virtual annotation tools, and managing on-screen information, may interact with mathematical literacy measurement. This raises equity concerns, as the digital divide in device access, internet connectivity, and prior computer-based testing (CBT) experience could systematically advantage or disadvantage certain student populations [67]. Understanding these technology-related factors is essential for interpreting AKM results and designing effective, equitable interventions.

Moreover, the COVID-19 pandemic accelerated the adoption of digital learning tools in Indonesia, exposing both opportunities and challenges. While some students thrived with access to online resources and flexible learning modalities, others faced significant barriers due to inadequate infrastructure, lack of devices, and limited teacher preparedness for technology integration [68]. These disparities underscore the need for comprehensive strategies that address not only technology provision but also capacity building for teachers and students to use technology effectively for mathematical literacy development.

Research evidence suggests that technology is most effective when embedded in pedagogical designs that prioritize sense-making, inquiry, and authentic problem-solving [52], [55]. Technology should serve as a cognitive tool that amplifies students' mathematical thinking rather than replacing it. For example, dynamic geometry software is most powerful when students use it to explore conjectures and justify patterns, not merely to produce accurate diagrams. Similarly, spreadsheets support mathematical modeling when students design their own formulas to represent real-world relationships, not just when they follow step-by-step tutorials.

Therefore, effective technology integration for mathematical literacy requires a systemic approach: investment in infrastructure and devices, professional development for teachers in TPACK, curriculum resources that model productive technology use, and policies that ensure equitable access. Without attention to these interconnected dimensions, technology risks exacerbating rather than reducing educational inequalities.

2.3. Overview of Minimum Competency Assessment (AKM)

AKM is a fundamental assessment that improves the quality of learning and develops students' potential so they can participate positively in society. The aim of implementing AKM is to improve student's literacy skills, both numeracy and reading literacy and to strengthen students' character in Indonesia [69]. Meriana's opinion is supported by the statement that the aim of establishing AKM is to measure students' level of competency in Indonesia so that it is hoped that all students can achieve high competency [70]. Based on these goals, it is hoped that student's ability to solve literacy problems will increase and the quality of education in Indonesia will begin to improve, considering the low level of student ability and education in Indonesia today.

Looking at the statistical data from the PISA scores that have been carried out, it is clear that the achievements of Indonesian students in the international field still need to be higher. This is due to the low literacy skills of students in Indonesia. Therefore, the Indonesian government is trying to support increasing mathematical literacy by implementing the AKM policy as a substitute for the national exam since 2020 [71]. Two competencies are assessed in AKM: student reading literacy and numeracy [72]. There is support for this opinion from another opinion, which says there are two literacy skills in AKM: language and numeracy [10]. So, AKM tests numeracy skills and reading literacy skills.

Reading literacy skills are students' abilities to identify, apply, interpret, and reflect on written texts. Meanwhile, numeracy applies concepts, steps, facts, and mathematical tools to solve practical problems [10], [73]. Then, according to Hendrawati et al. [74], numeracy literacy ability is the use of students' reasoning to manipulate various mathematical components related to practical life. The AKM test has a composition of problems: content, context, and students' cognitive processes [10].

Content in language literacy includes fiction texts and information texts. The two texts have significant differences; information texts contain news or statements of fact, and fiction texts contain information that is purely imaginary or fictitious [75]. Meanwhile, the cognitive process of language literacy includes finding information, namely a person's ability to identify problems to obtain precise information data, then interpretation and integration the ability to interpret explicit or implied information, and then evaluation and reflection, namely the ability to judge based on what he has obtained. So that it is helpful in everyday life [10]. Meanwhile, in the context of language literacy, it consists of personal, namely problems related to personal problems; socio-cultural, namely practical problems related to conditions or situations in the surrounding community; and scientific, namely problems related to scientific facts [10].

The content, context, and cognitive process of numeracy in AKM, according to the Ministry of Education [10], are as follows. Numeracy content includes numbers, measurement and geometry, data and uncertainty, and algebra. Numbers include representation, sequence of numbers, and operations on numbers, including fractions, whole numbers, and decimals. Measurement and geometry include recognizing flat shapes and space, using area and volume in practical problems, and understanding the measurement of length, weight, time, volume and discharge, and area units using standard units. Data and uncertainty are the understanding, interpreting, and presenting data and opportunities. Moreover, algebra includes equations and inequalities, ratios, and proportions. The context of numeracy includes personal, socio-cultural, and scientific. Personal is a problem related to one's own or personal interests. Socio-cultural issues are related to the interests of individuals, groups, cultures, and communities. Meanwhile, science is a problem related to scientific issues, facts, or activities.

To address the call for a critical perspective on AKM's pedagogical and political context, it is important to note that AKM's rationale and design sit at the intersection of instructional improvement and system accountability. Pedagogically, as a low-stakes, system-level assessment, it is meant to yield diagnostic insights for school interventions, refocus teaching on essential competencies, and encourage formative practices. Its impact, however, hinges on teachers' assessment literacy, sustained follow-up support, and alignment between AKM descriptors and classroom tasks; without adequate professional development and resources, the feedback loop from assessment to instruction remains weak [10], [21]. Politically, AKM replaces the high-stakes National Examination to reduce test-driven pressure while supplying evidence for governance, equity monitoring, and resource allocation. This shift offers benefits, less "teaching to the test" and broader school-quality indicators, but risks symbolic compliance, uneven regional capacity to act on results, and AKM scores becoming de facto accountability targets [6], [10], [11], [21], [39].

2.4. Technology-Enhanced Mathematics Learning

Technology-enhanced mathematics learning refers to the purposeful use of digital tools and environments to support and deepen students' understanding of mathematical concepts, procedures, and problem-solving processes. Rather than functioning merely as a medium for delivering content, technology can serve as a cognitive and interactive environment that enables exploration, experimentation, and the construction of multiple representations [76]-[81]. Research has shown that when technology is integrated with clear pedagogical intentions, it can promote student engagement, support conceptual understanding, and foster the development of mathematical literacy, particularly in contexts that require students to connect mathematical ideas with real-world situations [57], [82]-[87].

Dynamic mathematics software and interactive digital environments, such as GeoGebra or Desmos, exemplify how technology can support representation, reasoning, and modeling in mathematics. These tools allow students to link symbolic, graphical, and numerical representations, manipulate parameters, and observe the effects of changes in real time, thereby strengthening their representational fluency and algebraic thinking [88], [89]. In the context of mathematical literacy as framed by PISA and national assessments, such environments can help students model real-life situations, visualize relationships between quantities, and test different scenarios, which are central to formulating, applying, and interpreting mathematics in authentic contexts [5], [11], [90]. For AKM-oriented tasks, these affordances are particularly relevant because they can support students in navigating complex, information-rich problems that mirror everyday decision-making situations.

Digital assessment and learning analytics form a complementary component of technology-enhanced mathematics learning by turning process data into actionable insights. Computer-based assessment allows for the collection of rich data traces, including response sequences, timing information, changes in answers, and the use of digital tools, which go far beyond what is visible from final scores alone [91], [92]. Learning analytics techniques can then be applied to identify patterns of misconception, persistent bottlenecks, and typical error trajectories, providing valuable feedback for both teachers and system designers [93]-[95]. In the context of AKM and the findings of this study, these approaches offer a powerful way to operationalize students' cognitive processes into indicators that can inform the design of digital assessments, intelligent tutoring interventions, and dashboards for teachers, ultimately supporting more precise, data-informed efforts to improve mathematical literacy.

2.5. Digital Assessment, Computer-Based Testing, and Mode Effects in Mathematical Literacy Measurement

An emerging methodological concern in contemporary assessment is the mode effect, systematic differences in student performance between paper-based and computer-based tests (CBT). Meta-analyses show that mode effects vary by item type: computational items show minimal differences, but complex modeling items (such as the AKM problem employed in this study) can exhibit larger effects due to differences in annotation affordances, screen navigation demands, and reading behaviors [96].

For AKM specifically, since the national implementation uses CBT with adaptive routing, students' digital literacy, familiarity with on-screen reading, digital notepads, formula editors, and navigation tools, becomes intertwined with numeracy measurement. Students accustomed to paper-based annotation (underlining, drawing arrows, jotting notes, behaviors observable in effective problem-solving) may face additional cognitive load when translating these strategies to digital interfaces [39]. Conversely, students proficient with digital tools may benefit from features such as embedded calculators, undo functions, and copy-paste capabilities that reduce working memory demands.

This interaction implies that reported AKM numeracy levels partially reflect digital literacy, not only mathematical competency. Research from PISA 2015, when the assessment transitioned from paper to CBT, documented significant mode effects in several countries, with performance differences attributable to students' familiarity with computers and their reading strategies on screens [97]. Similar concerns apply to AKM: students in well-resourced urban schools with regular computer access may demonstrate artificially inflated scores relative to their mathematical literacy, while students in under-resourced rural schools with limited technology exposure may be penalized not for mathematical deficits but for digital unfamiliarity.

Several specific aspects of digital assessment interfaces can influence mathematical problem-solving:

1. Annotation and Workspace Limitations: Paper allows spontaneous, flexible notation, circling key information, drawing auxiliary diagrams, and writing intermediate steps in margins. Digital platforms vary widely in their annotation tools; constrained workspaces may inhibit students' natural problem-solving strategies [98].
2. Navigation Complexity: Multi-step problems requiring movement between screens (e.g., stimulus on one page, questions on another) increase cognitive load and can disrupt problem coherence. Students must mentally integrate information across interfaces, a demand absent in paper formats.
3. Reading Behavior Differences: Research shows that on-screen reading is often more superficial, with less re-reading and reduced attention to detail [39]. For mathematical literacy items requiring careful parsing of contextual information, this can disadvantage students who have not developed effective digital reading strategies.
4. Technical Fluency: Basic operations, such as typing mathematical expressions, using drop-down menus, and dragging sliders, consume cognitive resources for less digitally fluent students, resources that could otherwise be devoted to mathematical thinking.

These mode effects have important implications for interpreting AKM results and for research methodology. First, comparisons between Indonesia's AKM performance and international PISA results must account for potential mode-related measurement discrepancies. Second, interventions aimed at improving mathematical literacy should explicitly address digital literacy development to ensure students can effectively demonstrate their competencies in CBT environments. Third, research studies employing AKM-style problems must be transparent about delivery mode and consider how mode choice may shape findings.

In light of these considerations, some researchers and policymakers have called for hybrid assessment approaches: developing parallel paper-based and CBT versions of literacy assessments, conducting mode-effect studies to quantify and adjust for differences, and providing students with adequate preparation and practice in CBT environments before high-stakes administration [21], [97]. Such strategies can help ensure that assessments measure intended constructs, mathematical literacy, with minimal contamination from construct-irrelevant factors like digital interface familiarity.

Future research should systematically investigate how assessment mode and digital literacy moderate students' demonstration of the six fundamental mathematical skills (communication, mathematization, representation, reasoning, strategy design, and tool use) identified by OECD [39]. Understanding these interactions will enable more valid interpretation of assessment results and more effective design of technology-enhanced learning environments.

2.6. Research Gap and Study Positioning: From Qualitative Insight to Technology Design

The literature reviewed above establishes a rich but fragmented landscape, within which three critical gaps remain. First, there is a disconnection between qualitative research and technology design. Most research on mathematical literacy follows one of two paths: qualitative or phenomenological studies that richly describe students' thinking processes but stop at description, offering only generic recommendations such as "teachers should provide scaffolding"; or technology intervention studies that test specific tools but are not grounded in a deep understanding of the precise cognitive processes the technology should support. This often results in a misalignment between technological affordances and actual learning needs. Very few studies systematically bridge qualitative patterns to concrete, operational technology design requirements.

Second, research that uses AKM problems as research instruments remains limited. Although AKM has been central to Indonesian mathematics assessment since 2020, the majority of mathematical literacy studies still rely on PISA items. Yet AKM problems have distinct characteristics: stronger cultural contextualization, specific alignment with the Indonesian curriculum, and design tailored for computer-based delivery. The lack of AKM-focused research constrains our understanding of how Indonesian students specifically engage with and struggle through AKM problems.

Third, there is insufficient attention to Indonesian contextual realities. Much of the international literature on technology-enhanced mathematics learning emerges from high-resource settings, characterized by reliable infrastructure, abundant devices, and extensive teacher professional development. Indonesian conditions differ markedly: a pronounced urban–rural digital divide, many schools with unstable electricity and connectivity, wide variation in teachers' digital competence, and post-pandemic trauma associated with emergency remote learning.

Against this backdrop, the present study positions itself as an integrative, context-sensitive response to these three gaps. It bridges qualitative research and technology design by employing hermeneutic phenomenology to develop a deep understanding of students' experiences and thinking processes, and then explicitly translating these findings into concrete technological design requirements. It centers AKM by using AKM-oriented algebra problems as research instruments, ensuring that the resulting insights speak directly to Indonesia's national assessment. Finally, it contextualizes the proposed technological framework by explicitly addressing connectivity constraints, device limitations, teacher capacity, and cultural appropriateness, so that the solutions proposed are not only technologically innovative but also feasible and educationally meaningful within the realities of Indonesian schooling.

3. RESEARCH METHOD

3.1. Research Design

To conduct an in-depth analysis of mathematical literacy that is both pedagogically and technologically meaningful, the researchers employed a qualitative approach with a hermeneutic phenomenological design. Rather than merely describing students' experiences, this approach seeks to interpret the meanings embedded in students' responses and actions as they solve AKM-oriented mathematical problems, acknowledging the researcher's active, reflective role in making sense of lived experience [99], [100]. Pedagogically, this design makes it possible to uncover how students actually experience and make sense of AKM items, how they read and interpret the problem, select information, choose representations, carry out solution strategies, and justify their reasoning, thereby revealing specific points where instruction and scaffolding are most needed. In line with Creswell's [101] view that qualitative research uncovers facts through participants' responses and activities without manipulation, the data in this study include students' solution methods, obtained answers, movements, and verbal expressions as they work on AKM-oriented problems. Technologically, these rich, step-by-step traces of students' cognitive and meaning-making processes can be translated into design requirements for digital learning environments: they inform how AKM-aligned digital assessments should log student actions, which error patterns intelligent tutoring systems should detect and respond to, and which indicators learning analytics dashboards should visualize to flag critical breakdowns in problem interpretation, mathematization, or representation.

3.2. Research Phases

To conduct a well-structured research study, the steps of the research process must be determined in advance. These steps include preparation, research implementation, and generating credible data to be publicly presented through scholarly works. In this study, we divided the research phases into three stages: the preparation phase, the research implementation phase, and the data validation phase.

3.2.1. Preparation phase

Activities in this phase include the development of research instruments and the selection of participants. First, regarding research instruments, in qualitative studies, the researcher acts as the vital instrument; thus, the success of the research heavily relies on the researcher. As researchers, we focused our research on students' mathematical literacy and have previously published several papers on mathematical literacy in various reputable journals, ensuring our competence in conducting this study. To facilitate the researchers as the key instrument, we also developed auxiliary instruments to obtain more comprehensive information about students' mathematical literacy. These instruments include a mathematical literacy test instrument and non-test instruments, such as guidelines for conducting in-depth interviews and observation sheets during the research process. The test instrument used refers to AKM problems focused on the algebra domain. More specifically, these problems include the subdomains of ratio and percentage, which are crucial components of mathematical literacy at the junior high school level. These problems have been revised to ensure they are relevant to the research objectives and can accurately measure students' competencies. The test instruments are illustrated in Figure 2.

Heri adalah seorang karyawan di sebuah perusahaan swasta dengan gaji bulanan 10 juta. Dari gajinya, ia bisa menyisihkan 3 juta setiap bulannya di luar dana untuk kebutuhan lain. Selain itu, ia memiliki tabungan sebanyak 450 juta dan sedang berencana untuk membeli rumah. Namun, Heri ingin memastikan jika harus mencicil, durasinya tidak lebih dari 15 tahun. Baru-baru ini, Heri mendapatkan tawaran dari Perumahan Sekar Suli. Oleh karena itu, ia memutuskan untuk menghubungi mereka untuk mendapatkan informasi lebih lanjut tentang skema kredit rumah yang mereka tawarkan.
Heri adalah seorang suami dan ayah dari tiga anak, serta memiliki seorang asisten rumah tangga. Mereka membutuhkan sebuah rumah yang sesuai dengan kebutuhan keluarga. Anak pertama Heri ingin memiliki kamar sendiri, sementara dua anaknya yang lain ingin berbagi kamar.

Dalam proses pencarian rumah, Heri mendapatkan dua opsi kredit dari perumahan:
1. Kredit selama 10 tahun dengan uang muka minimal 20% dari harga rumah dan angsuran bulanan dengan bunga tetap sebesar 0.5%.
2. Kredit selama 15 tahun dengan uang muka minimal 10% dari harga rumah dan angsuran tahunan dengan bunga tetap sebesar 7.5%.

Selain itu, penting bagi Heri untuk memastikan bahwa dari dana 3 juta yang ia sisihkan setiap bulannya, masih ada sisa untuk keperluan mendadak keluarga. Bantulah Heri menentukan rumah dan skema pembayaran yang paling sesuai dengan kebutuhan dan kemampuan finansial keluarganya.

Translation:
Heri is an employee at a private company with a monthly salary of 10 million rupiahs. From his salary, he can save 3 million rupiahs each month, aside from other necessary expenses. In addition, he has savings of 450 million rupiahs and is planning to buy a house. However, Heri wants to ensure that if he has to take out a loan, the duration should be at most 15 years. Recently, Heri received an offer from Sekar Suli Housing. Therefore, he contacted them to get more information about the housing credit scheme they offer.

Heri is a husband and a father of three children, and he also has a household assistant. They need a house that suits the needs of the family. Heri's eldest child wants to have their own room, while the other two children are willing to share a room.

In the process of searching for a house, Heri received two credit options from the housing complex:

A 10-year loan with a minimum down payment of 20% of the house price and a fixed monthly instalment with an interest rate of 0.5%.

A 15-year loan with a minimum down payment of 10% of the house price and a fixed annual instalment with an interest rate of 7.5%.

Additionally, it is essential for Heri to ensure that from the 3 million rupiahs he saves each month, there is still enough left for family emergencies. Help Heri determine the house and payment scheme that best suits the needs and financial capabilities of his family.

Figure 2. AKM oriented test instrument

The AKM-oriented algebra item set (ratios and percentages) was developed through expert review and limited piloting. Content validity was established via a two-round panel of three experts, one AKM assessment specialist, one mathematics education researcher, and one experienced junior-high mathematics teacher, who evaluated alignment to AKM content/process descriptors, cognitive demand, linguistic load, and authenticity. Item wording and data displays were revised accordingly. We then piloted the tasks with [n = 8–12] students from a comparable school to check clarity, time-on-task, and elicitation of target processes; minor revisions addressed ambiguous phrasing and reading load.

Interview and observation protocols were similarly expert-reviewed for construct coverage (problem identification, mathematization, representation, strategy, operations, reasoning) and clarity, and piloted alongside the items. The semi-structured interview guide included probes to elicit lived experience and meaning-making (how students recognized key data, why a strategy was chosen, when and how they verified). Observation sheets specified focal behaviors (marking/annotating, gesture indicating search for data, use of scratch work, verification moves). These instruments were refined after pilot feedback to enhance qualitative reliability. In the main study, we triangulated across written work, think-aloud/retrospective interview accounts, and observation notes to strengthen credibility and confirmability.

Second, regarding participants, we selected junior high school students as participants. Purposive sampling determined the research subjects whose responses would be further analyzed. A detailed explanation of the participants is discussed in section 3.4.

3.2.2. Research implementation phase

In this phase, tests, interviews, and observations were conducted with the predetermined participants and subjects. The activities began with administering the test instruments to all research participants, who were eighth-grade junior high school students. After the tests were given, we reduced their answers and selected several participants to be research subjects for further interviews about their answers. These confirmatory interviews served to reinforce the data obtained from the tests. Subsequently, observations were conducted to monitor students' movements during the tests and interviews. These responses were recorded and later used to strengthen the test and interview data. Documentation of the test and interview implementation is presented in Figure 3.

During test administration, students were seated individually in a quiet classroom environment to minimize distractions. They were provided with the AKM problem on paper, blank answer sheets, and scratch paper for calculations. Students were given 45 minutes to complete the problem and were encouraged to show all their work and thinking processes. Researchers observed from a distance, taking field notes on students' behaviors such as re-reading the problem, marking text, using scratch paper, pausing, and self-checking. These observations were later triangulated with written responses and interview data.

Interviews were conducted within 1-3 days after the test, while students' memory of their problem-solving process was still fresh. Each interview lasted 20-30 minutes and was audio-recorded with students' and parents' consent. The semi-structured interview protocol began with open-ended questions ("Walk me through how you approached this problem") and moved to specific probes based on the student's written work ("I see you circled this part, why did you mark it?" or "You calculated this amount, what does it represent in Heri's situation?"). Interviews were conducted in Bahasa Indonesia, transcribed verbatim, and translated for analysis.

(a)

(b)

Figure 3. Research Implementation Documentation: (a) Test-taking and (b) Interview Sessions Data validation phase

3.2.3. Data validation phase

Activities in this phase are conducted to justify the data obtained during the research implementation, forming the basis of the resulting theory. This phase involves testing the validity of the data. According to Moloeng (2019), data validity testing is conducted to verify whether the obtained data is valid. One method used for data validity testing is triangulation. Triangulation is the process of supporting research findings as evidence for the interpretation and analysis conducted by the researcher [102], [103]. Among various types of triangulation, method triangulation was chosen and conducted in two ways: verifying research findings using different techniques and verifying findings from the same data source [104]. Therefore, this study utilized various data collection techniques and different sources during the research process. Verification with different techniques was conducted through tests, interviews, and observations. Meanwhile, source verification was conducted using the same source, namely the student research subjects.

After ensuring data validity, the researchers sought further justification through existing theories or research findings to reinforce and support the obtained data. This effort was made to justify a finding as a theory later, according to Pritchard's [105] view on knowledge formation. Therefore, the researchers linked the obtained data with relevant theories, ensuring that the research results significantly contribute to knowledge development and students' mathematical literacy.

Researcher positioning was explicitly addressed. The team's familiarity with AKM and the school context eased access and rapport but risked framing student responses through AKM competencies. To counter this, one researcher moderated sessions and interviews while another observed and recorded gestures and annotations to reduce single-observer bias. We adopted a non-evaluative stance, clarifying that tasks were for research, not grading, to lower performance anxiety and impression management. Analytically, we rotated coders across cases, double-coded a subset of data, and documented adjudication decisions. Overall, we deferred assumptions about "correct" school procedures in favor of interpreting meaning-in-use, balancing insider expertise with interpretive openness and transparency about researcher influence.

3.3. Digital Tools and Research Transparency

To enhance the rigor, transparency, and systematic nature of the qualitative analysis, this study integrated several digital tools throughout the research process. Data collection was supported by digital audio recorders to capture verbal reasoning, high-resolution scanners to preserve students' written annotations as digital archives, and tablets for real-time field notes. For data management, all files were organized using a systematic naming convention and stored in a secure, encrypted cloud platform to ensure data integrity and facilitate team collaboration. The analysis phase utilized computer-assisted transcription software for verbatim records and NVivo 12 for systematic coding and thematic analysis. This software allowed the research team to consistently apply the indicator-response framework, maintain a clear audit trail, and utilize matrix queries to visualize patterns across literacy indicators.

While the national AKM implementation typically uses computer-based testing (CBT), this study intentionally administered problems in a paper-based format to better observe natural problem-solving behaviors, such as spontaneous annotation and marginal notes. This choice minimized construct-irrelevant variance caused by varying levels of digital literacy and reduced the cognitive load associated with navigating digital interfaces, allowing students to focus entirely on mathematical thinking. Although this paper-based context may differ from the actual CBT experience, it provided a rich, unobstructed view of the cognitive and metacognitive processes central to this phenomenological design. Ultimately, the integration of these digital tools and methodological choices facilitated rigorous triangulation across test responses, interview transcripts, and observation notes, thereby strengthening the credibility and confirmability of the findings.

3.4. Participants

This study involved several students from a junior high school in Surakarta as research participants. The selection This study involved Year 8 students from a state junior high school in Surakarta, selected because this level corresponds to the PISA target age and covers algebraic content relevant to social and everyday mathematics. Approximately 30–40 students completed an AKM-oriented algebra test, from which three focal participants were purposefully selected using purposive sampling [101], [106], [107]. The selection was based on the heterogeneity of their responses in terms of problem identification, mathematization, representation, strategy, symbolic operations, and reasoning, so that each chosen script represented a distinct trajectory of strengths and difficulties and maximized the variation of processes observed in the larger cohort. These three students were then treated as qualitative cases for in-depth analysis, prioritizing interpretive depth over statistical representativeness. The study followed institutional ethical protocols, obtained approval from the relevant university ethics committee and school foundation, secured written parental/guardian consent, and ensured students' voluntary participation and anonymity through the use of pseudonyms.

3.5. Data Analysis

The data analysis technique was conducted inductively according to the methodology described by Creswell [101]. This process began with collecting research data using various techniques, such as mathematical literacy tests, interviews, and observations with the subjects. Once the data was collected, the next step was to reduce the data by selecting relevant information aligned with the research indicators. This step aimed to ensure that the data used in the analysis reached an optimal level of saturation. Next, the researchers presented the reduced data effectively. The data was presented and grouped based on relevant categories, accompanied by an in-depth analysis to better understand the research results. Finally, the researchers drew conclusions from the analyzed data. This process involved comparing various sources to identify patterns and relationships within the data regarding differences and similarities. By following this process, the researchers ensured that the analyzed data was valid, well-organized, and supported findings that significantly contribute to existing theories or even develop new ones.

We analyzed the data inductively using the indicator–response matrix in Table 1. First, every excerpt from written work, interviews, and observations was assigned to one of six mathematical literacy indicators (I1–I6: communication, mathematization, representation, problem-solving strategies, symbolic operations, reasoning). Within each indicator, we coded the specific response characteristics using a fixed set of patterns (R1–R11) that capture how students actually worked—for example, how they marked information, transformed data, represented ideas, planned strategies, executed calculations, and verified results. Each student could display different R-codes across indicators; the table shows which patterns appeared where for each subject. We then integrated these codes to trace sequences across the solving process and distilled cross-case themes, for instance, how early misidentification propagated into weak strategies and execution, or how strong representation stabilized later steps.

Coding Reliability and Transparency. To enhance reliability, we implemented several procedures:

1. Codebook Development: We developed a detailed codebook defining each indicator (I1–I6) and response pattern (R1–R11) with exemplars from pilot data. This codebook was refined through team discussion until consensus was reached.
2. Independent Double-Coding: Two researchers independently coded a subset of the data (approximately 30% of all data sources). Inter-coder agreement was calculated using Cohen's kappa, yielding $\kappa = 0.82$, indicating strong agreement.
3. Adjudication Process: Discrepancies in coding were resolved through discussion between coders, with a third researcher consulted when consensus could not be reached. All adjudication decisions were documented in memos within NVivo.
4. Audit Trail: All coding decisions, analytical memos, and team discussions were documented systematically to create a transparent audit trail that enhances the study's confirmability and dependability.

Cross-Case Analysis: After coding individual cases, we conducted cross-case analysis to identify patterns and themes. Using NVivo's matrix query function, we visualized the distribution of response codes across students and indicators, revealing the "domino effect" pattern where early difficulties in communication and mathematization (I1, I2) cascaded into problems with representation, strategy, and operations (I3, I4, I5). This pattern emerged as the central finding of our study and is elaborated in Section 4.

4. RESULTS AND DISCUSSION

These findings outline the responses from the selected subjects, detailing how they solved the AKM problems through interviews and observations. These responses are then summarized in Table 1, with unique codes assigned to each response. Subsequently, these responses are analyzed deeply based on the established mathematical literacy indicators.

Table 1. Snowball sampling process

Research	Mathematical literacy indicators					
Subjects	I1	I2	I3	I4	I5	I6
Subject 1	R1	R3	R5	R7	R9	R11
Subject 2	R1	R4	R6	R8	R9	R11
Subject 3	R2	R3	R5	R7	R10	R11

Information:
I1 :Communication
I2: Mathematization
I3 : Representation
I4: Problem-Solving Strategies
I5: Language and Symbolic Operations
I6 : Reasoning
R1-R11 : Response 1 to response 11

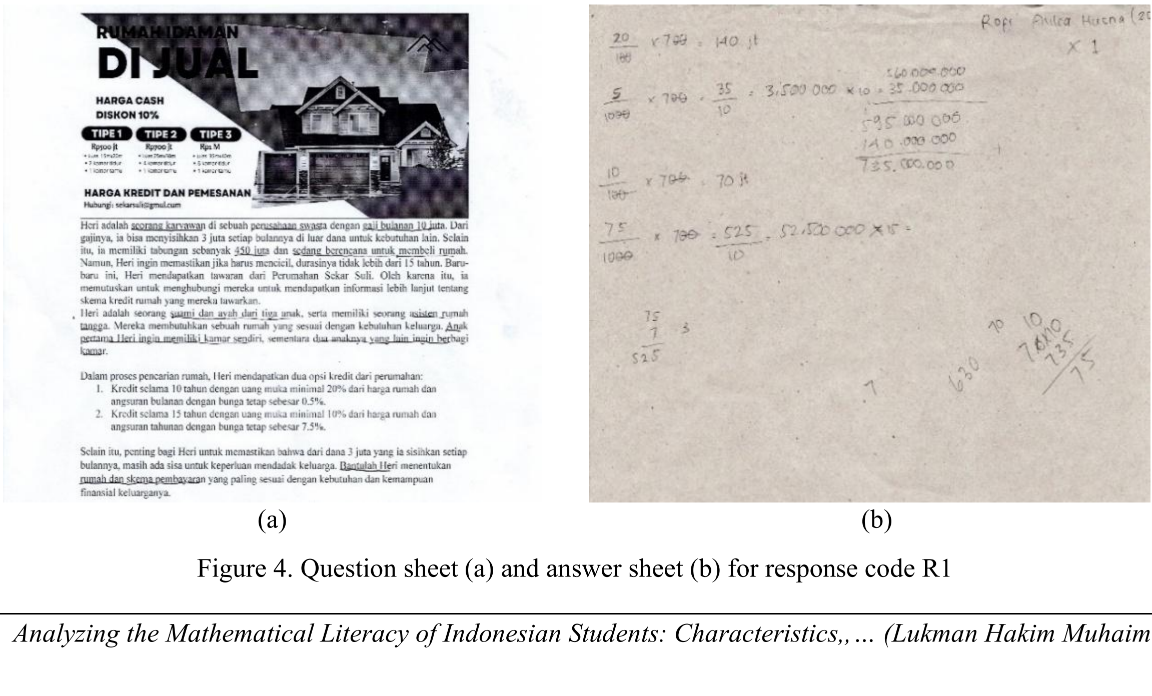
4.1. Communication

The first indicator is communication, which aims to observe how students read, interpret, and understand statements, questions, tasks, or objects. This enables individuals to form a mental model of the situation, which is crucial in comprehending, clarifying, and formulating a problem. Intermediate results may need to be summarized and presented during the problem-solving process. Once a solution is found, the problem solver may need to show the solution and provide an explanation or justification to others.

Referring to Table 1, there are two different responses: response code R1 and response code R2. During the formulation process, the subject with response code R1 begins by identifying the problem in the question. The subject is observed reading the information in the question multiple times and occasionally marking specific parts on the question sheet to understand the situation. After comprehending the information, the subject communicates the obtained data by writing down important information on the answer sheet, as shown in Figure 4. Through the interview, the subject explained that marking certain parts of the question was intended to focus on specific sections to facilitate understanding the problem.

This behavior aligns with effective problem-solving strategies documented in the literature. Active annotation (underlining, circling, drawing arrows) externalizes the comprehension process and reduces working memory load by creating external memory aids. Subject 1's deliberate marking of key information (Heri's salary, savings capacity, house requirements, credit options) demonstrates metacognitive awareness: the student recognizes the complexity of the problem and employs a strategy to manage information systematically.

In the implementation and interpretation process, the subject communicates the answer by calculating on scratch paper and then writing the calculations on the answer sheet. This is intended to minimize errors during the computational process, ensuring that the final answer is as accurate as expected. The subject confirmed this practice during the interview, where they revealed that performing calculations on scratch paper first helps keep the answer sheet neat in case of any calculation errors before transferring them to the answer sheet, thus minimizing mistakes in the final written answer.



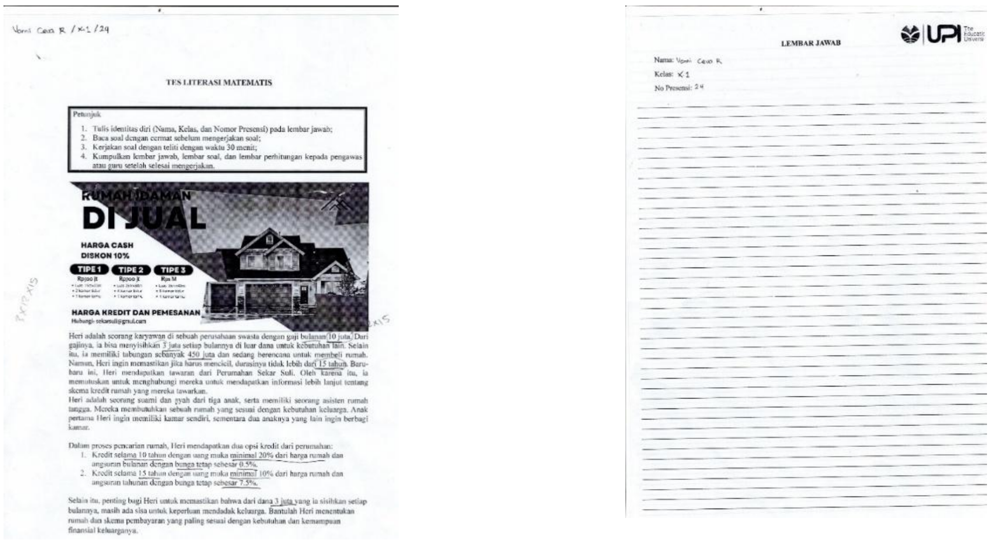
(a) (b)

Figure 4. Question sheet (a) and answer sheet (b) for response code R1

For response code R2, during the formulation stage, the subject identifies the problem by marking specific parts in the question. However, it is noteworthy that in this response, the subject does not proceed to write down any information or data on the answer sheet, as seen in Figure 5. A similar pattern can also be observed in the implementation and interpretation stages, where the subject only performs calculations documented on scratch paper without rewriting them on the answer sheet. This is also illustrated in Figure 5. When interviewed, the subjects revealed that they struggled to understand the problem and needed considerable time to comprehend it. Furthermore, the subject expressed hesitance in providing answers.

This response pattern suggests that the student recognized the problem's complexity (evidenced by marking behavior) but failed to achieve sufficient comprehension to proceed confidently. The gap between recognition and comprehension may stem from several factors: limited experience with complex, multi-constraint optimization problems; weak reading literacy affecting the ability to parse dense contextual information; or anxiety reducing working memory capacity. The absence of written summary or representation indicates that the student did not successfully construct a coherent mental model of the problem situation, a critical prerequisite for mathematical literacy (OECD, 2019a).

Importantly, in a digital assessment environment (as in the actual AKM CBT), students like Subject 2 might face even greater challenges. The ability to annotate flexibly, circling, underlining, drawing connections, may be constrained by digital interface limitations, potentially exacerbating comprehension difficulties for struggling students (Jerrim et al., 2018). This mode-related consideration underscores the importance of ensuring that digital assessment platforms provide robust annotation tools that do not disadvantage students who rely on these comprehension strategies.

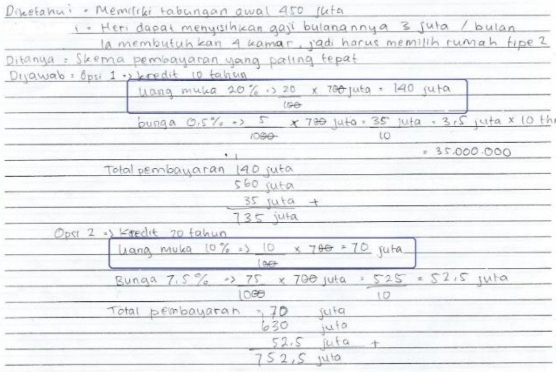


(a) (b)

Figure 5. Question sheet (a) and answer sheet (b) for response code R2

4.2. Mathematization

Mathematization is an indicator that assesses students' ability to transform real-world defined problems into mathematical forms. Once subjects successfully identify the problem within real-world contexts, they proceed by documenting the data they acquire. At this stage, accurate data documentation by the subjects plays a crucial role in transforming the information in the problem into mathematical expressions. This process forms the core of mathematization skills, where subjects connect real-world scenarios with mathematical language to address the issues at hand. Referring to Table 1, researchers identified two distinct responses in mathematization.



Diketahui : • Memiliki tabungan awal 450 juta
• Heri dapat menyisihkan gaji bulanannya 3 juta / bulan
Ia membutuhkan 4 kamar, jadi harus memilih rumah tipe 2
Ditanya : Skema pembayaran yang paling tepat
Dijawab : Opsi 1 => kredit 10 tahun
uang muka 20% => 20/~~100~~ x 7~~00~~ juta = 140 juta
bunga 0.5% => 5/10~~00~~ x 7~~00~~ juta = 35/10 juta = 3,5 juta x 10 th
= 35.000.000
Total pembayaran 140 juta
560 juta
35 juta +
735 juta
Opsi 2 => Kredit 20 tahun
uang muka 10% => 10/1~~00~~ x 7~~00~~ = 70 juta
Bunga 7,5% => 75/10~~00~~ x 7~~00~~ juta = 525/10 = 52,5 juta
Total pembayaran = 70 juta
630 juta
52.5 juta +
752,5 juta

Translation:

Given:

- Initial savings of 450 million IDR
- Heri can set aside 3 million IDR per month from his salary
- He needs 4 rooms, so he must choose a type 2 house

Question: What is the most appropriate payment scheme?

Answer:

Option 1: 10-year mortgage

- Down payment 20% → 20/100 x 700 million = 140 million IDR
- Interest 0.5% → 0.5/100 x 700 million = 3.5 million IDR x 10 years = 35 million IDR
- Total payment = 140 million IDR + 560 million IDR + 35 million IDR = 735 million IDR

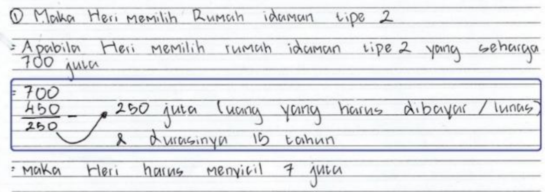
Option 2: 20-year mortgage

- Down payment 10% → 10/100 x 700 million = 70 million IDR
- Interest 7.5% → 7.5/100 x 700 million = 52.5 million IDR
- Total payment = 70 million IDR + 630 million IDR + 52.5 million IDR = 752.5 million IDR

Figure 6. Response sheet with code R3

Based on Figure 6, code R3 indicates that the subject struggled to comprehend information related to credit option selection. Theted for the lowest down payment, suggesting fixation on the specified options (20% and 10%). A larger down payment should have been chosen to reduce interest, allowing the subject to pay a maximum down payment of 450 million. During the interview, the subject explained that lack of focus hindered their understanding of the problem. Consequently, this lack of focus prevented them from optimally applying their knowledge to make informed decisions regarding the appropriate down payment choice. The interview highlighted that more than the problem is needed to improve subjects' ability to make sound decisions. The subject added that insufficient practice with literacy problems and using abstract textbooks were contributing factors. Unlike code response R4, where the subject demonstrated a better understanding of the issue, as seen in Figure 7, subjects with code R4 exhibited superior comprehension of the problem's essence, leading to more appropriate down payment decisions.

The differences between response codes R3 and R4 highlight the critical role of problem comprehension in mathematization. This suggests potential for technology-enhanced interventions: interactive problem environments that scaffold the identification of constraints and decision variables could support students in the mathematization process. For example, digital tools that prompt students to tag different information types (given data, unknowns, constraints, goals) before attempting calculations might prevent the premature fixation on superficial problem features observed in R3.



① Maka Heri memilih Rumah idaman tipe 2
= Apabila Heri memilih rumah idaman tipe 2 yang seharga 700 juta
= 700
450 −
250 → 250 juta (uang yang harus dibayar / lunas)
& durasinya 15 tahun
= Maka Heri harus menyicil 7 juta

Translation:

1. Therefore, Heri chooses his dream house, type 2.

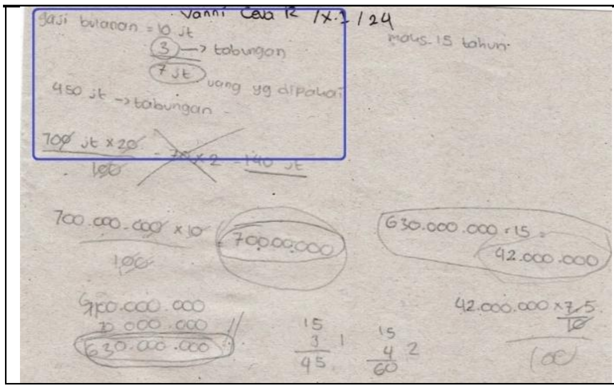
= If Heri chooses his dream house worth 700 million IDR:

= 700 million IDR - 450 million IDR = 250 million IDR that needs to be paid.
Thus, Heri needs to pay in installments of 7 million IDR.

Figure 7. Response sheet with code R4

4.3. Representation

In the indicator of representation, the ability of students to illustrate information in various representational forms to capture a concept is observed. Researchers identified two distinct responses in this indicator: codes R5 and R6. In code response R5, the subject represented information using various mathematical symbols, as depicted in the annotated sheet visualization in Figure 8. This figure displays a representative treatment of monthly salary information and savings schemes. Through this visualization, it is evident that the subject effectively illustrated information related to monthly salary and savings schemes. This demonstrates that the subject in code response R5 could articulate complex information using mathematical symbols, thereby facilitating a deeper understanding of the problem content. This understanding was complemented by the subject's ability to visually communicate the information through a depiction that aligns with the problem's context. In-depth interviews revealed that the mathematical symbols were used to summarize descriptive information in the problem, aiding the subject in approaching and solving related problems.

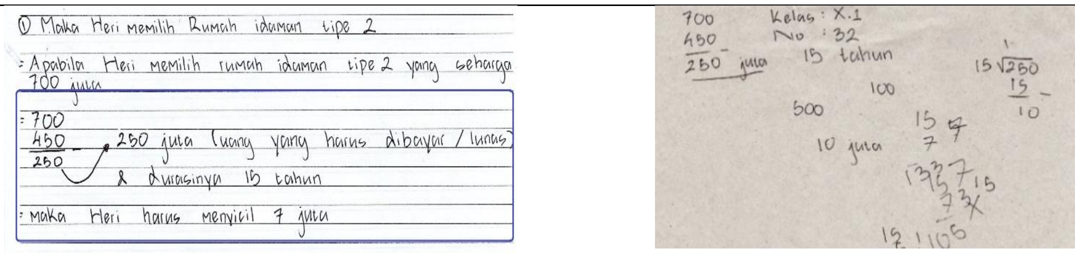


Translation:

Monthly salary = 10 million IDR - 3 million IDR (savings)
= 7 million IDR (money used)
400 million IDR → savings

Figure 8. Annotated sheet for code response R5

In code response R6, the subject did not engage in representing the information on the problem sheet, as visualized in Figure 9. Observing Figure 9, only calculations are visible without any accompanying representation. Researchers conducted interviews with involved subjects to gain deeper insights into this phenomenon. During these interviews, the subjects needed help understanding the issues on the problem sheet. Consequently, they performed calculations based solely on their understanding, leading to limited representation. Thus, the response in code R6 reflects that limited comprehension of the problem can hinder the subject's ability to generate visual representations that support a deeper understanding of the problem.



(a) (b)

Translation:

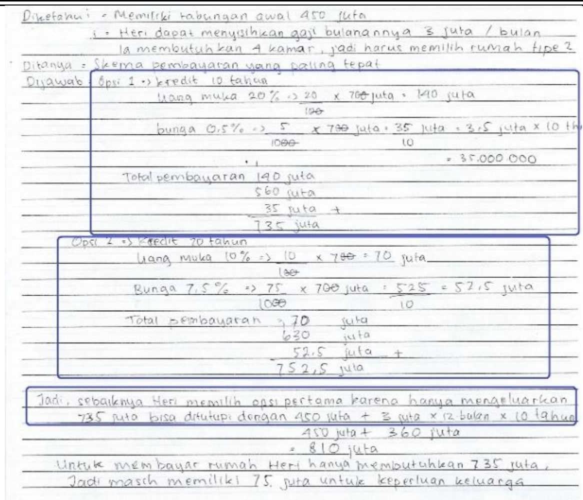
1. Therefore, Heri chooses his dream house, type 2.
= If Heri chooses his dream house worth 700 million IDR:
= 700 million IDR - 450 million IDR = 250 million IDR that needs to be paid.
Thus, Heri needs to pay in installments of 7 million IDR.

Figure 9. Response sheet (a) and annotated sheet (b) for code response R6

The representational differences between R5 and R6 are particularly relevant for technology integration. Dynamic digital environments (e.g., GeoGebra, Desmos) can support students in creating, manipulating, and linking multiple representations. For instance, a digital workspace might allow students to input textual information in structured fields, automatically generate visual representations (bar models, tables), and dynamically link these representations so that changes in one are reflected in others. Such tools can scaffold the representation process, making it more accessible to students who struggle like Subject in R6.

4.4. Problem-Solving Strategies

The indicator of problem-solving strategies assesses students' ability to select or design a plan or mathematical strategy to solve problems. This research identified two types of responses within this indicator. First, in code response R7, when planning problem-solving strategies, the subject planned to calculate various possibilities that would occur if they chose the credit options given on the problem sheet. This condition can be seen in the subject's response sheet in Figure 10.



Translation:

Given:

- Initial savings of 450 million IDR
- Heri can set aside 3 million IDR per month from his salary
- He needs 4 rooms, so he must choose a type 2 house

Question: What is the most appropriate payment scheme?

Answer:

Option 1: 10-year mortgage

Down payment 20% → 20/100 x 700 million = 140 million IDR

Interest 0.5% → 0.5/100 x 700 million = 3.5 million IDR x 10 years = 35 million IDR

Total payment = 140 million IDR + 560 million IDR + 35 million IDR = 735 million IDR

Option 2: 20-year mortgage

Down payment 10% → 10/100 x 700 million = 70 million IDR

Interest 7.5% → 7.5/100 x 700 million = 52.5 million IDR

Total payment = 70 million IDR + 630 million IDR + 52.5 million IDR = 752.5 million IDR

Therefore, Heri should choose the first option because it only requires a total payment of 735 million IDR, which can be covered by:

= 450 million IDR + 3 million IDR x 12 months x 10 years

= 450 million IDR + 360 million IDR

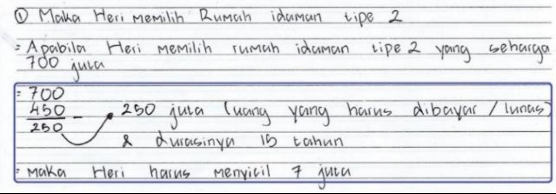
= 810 million IDR

To pay for the house, Heri only needs 735 million IDR, so he will still have 75 million IDR left for family needs.

Figure 10. Subject's response sheet for code response R7

Referring to Figure 10, it is clear that the subject in code response R7 devised a payment scheme that could have been more optimal. Errors in this mathematical aspect impacted the strategy they planned to use to solve the problem, ultimately leading to inaccurate answers. In code response R7, the scheme should have included details of monthly instalment payments and their costs, but the subject instead calculated the total overall payment. Thus, misunderstanding in this area directed the subject towards an inappropriate strategy in problem-solving. Additionally, there were errors in the down payment selection, which is the initial step in the mathematization process. This mistake also negatively affected the problem-solving strategy executed by the subject, as an incorrect down payment would influence all calculations and payment plans formulated. All of these aspects demonstrate that an inadequate understanding of mathematization can lead to inefficient problem-solving strategies and subsequently affect the accuracy of the answers provided. Thus, errors made by the subject at the initial stages of problem-solving can cascade into errors in subsequent stages.

The following code response is R8. The subject with code response R8 demonstrated the ability to devise a more appropriate payment scheme in the given problem-solving scenario. However, another aspect warrants attention: the formula used to calculate the credit instalments needed to be visible on the subject's response sheet. However, this formula is crucial in determining the monthly instalments, which are then compared to the monthly amount set aside from the income earned. During the interview, the subjects revealed they were unaware of the specific formula used; instead, they relied on another formula they understood to solve the problem. For further understanding of the subject's response with code R8, additional details from the subject's response sheet can be seen in Figure 11.

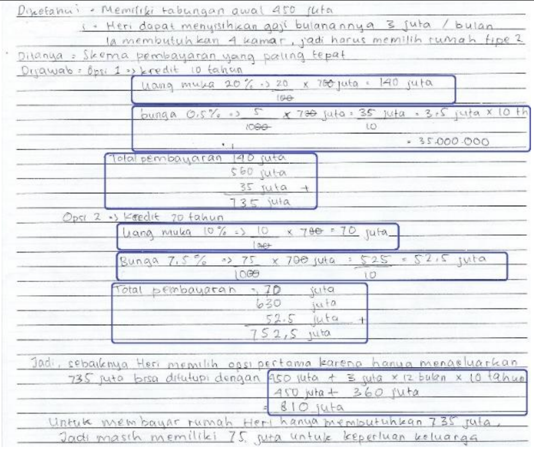

① Maka Heri memilih Rumah idaman tipe 2
= Apabila Heri memilih rumah idaman tipe 2 yang seharga 700 juta
= 700
450 -
250
→ 250 juta (uang yang harus dibayar / lunas) & durasinya 15 tahun
= Maka Heri harus menyicil 7 juta

Translation:
1. Therefore, Heri chooses his dream house, type 2.
= If Heri chooses his dream house worth 700 million IDR:
= 700 million IDR - 450 million IDR = 250 million IDR that needs to be paid.
Thus, Heri needs to pay in installments of 7 million IDR.

Figure 11. Subject's response sheet for code response R8

The cascading errors observed in R7, where misidentification in the mathematization phase led to inappropriate strategy selection, illustrate the domino effect that is central to our findings. This pattern has important implications for intelligent tutoring systems (ITS) design: effective ITS should monitor students' problem-solving trajectories and intervene at critical decision points (e.g., "Before calculating total payment, have you determined what Heri can afford for down payment?") to prevent cascading errors.

4.5. Language and Symbolic Operations


Diketahui : • Memiliki tabungan awal 450 juta
• Heri dapat menyisihkan gaji bulanannya 3 juta / bulan
Ia membutuhkan 4 kamar, jadi harus memilih rumah tipe 2
Ditanya : Skema pembayaran yang paling tepat
Dijawab : Opsi 1 => kredit 10 tahun
Uang muka 20% => $\frac{20}{100}$ x 700 juta = 140 juta
bunga 0.5% => $\frac{5}{1000}$ x 700 juta = $\frac{35}{10}$ juta = 3,5 juta x 10 th = 35.000.000
Total pembayaran 140 juta
560 juta
35 juta +
735 juta
Opsi 2 => Kredit 20 tahun
Uang muka 10% => $\frac{10}{100}$ x 700 = 70 juta
Bunga 7,5% => $\frac{75}{1000}$ x 700 juta = $\frac{525}{10}$ = 52,5 juta
Total pembayaran = 70 juta
630 juta
52.5 juta +
752,5 juta
Jadi, sebaiknya Heri memilih opsi pertama karena hanya mengeluarkan 735 juta bisa ditutupi dengan 450 juta + 3 juta x 12 bulan x 10 tahun
450 juta + 360 juta
= 810 juta
Untuk membayar rumah Heri hanya membutuhkan 735 juta,
Jadi masih memiliki 75 juta untuk keperluan keluarga

Translation:

Given:
- Initial savings of 450 million IDR
- Heri can set aside 3 million IDR per month from his salary
- He needs 4 rooms, so he must choose a type 2 house

Question: What is the most appropriate payment scheme?
Answer:
Option 1: 10-year mortgage
Down payment 20% → 20/100 x 700 million = 140 million IDR
Interest 0.5% → 0.5/100 x 700 million = 3.5 million IDR x 10 years = 35 million IDR
Total payment = 140 million IDR + 560 million IDR + 35 million IDR = 735 million IDR
Option 2: 20-year mortgage
Down payment 10% → 10/100 x 700 million = 70 million IDR
Interest 7.5% → 7.5/100 x 700 million = 52.5 million IDR
Total payment = 70 million IDR + 630 million IDR + 52.5 million IDR = 752.5 million IDR
Therefore, Heri should choose the first option because it only requires a total payment of 735 million IDR, which can be covered by:
= 450 million IDR + 3 million IDR x 12 months x 10 years
= 450 million IDR + 360 million IDR
= 810 million IDR
To pay for the house, Heri only needs 735 million IDR, so he will still have 75 million IDR left for family needs.

Figure 12. Subject's response sheet for code response R9

The indicator of language and symbolic operations examines students' ability to execute mathematical computations based on their previously planned strategies. Researchers identified two types of responses within this indicator, namely R9 and R10. In code response R9, the subject performed direct calculation computations on the answer sheet, as seen in Figure 12. Referring to this figure, the subject made several calculation errors, ranging from the down payment calculation and calculation of credit interest for each option to the total calculation. However, an incorrect problem identification led to an inappropriate problem-solving strategy, resulting in errors in the obtained answers despite the correct mathematical calculations. This condition confirms that errors at the beginning of problem-solving cascade into subsequent stages of problem resolution.

This response contrasts with code response R10, where calculations were not written on the answer sheet, and the subject only performed calculations on the provided annotation sheet, leaving their response sheet blank until the end. This can be observed in Figure 13. Response R10 indicates that the subject may have focused more on planning and strategizing mathematical calculations than executing them on the annotation sheet without writing them on the answer sheet. During interviews conducted by researchers to gather more information, subjects in this response revealed that they performed calculations but did not arrive at an answer, thus running out of time and leaving their answer sheet blank. Excerpts from these interviews confirm that time management is crucial in problem-solving, and a complete understanding of information and proper strategies can impact the accuracy of answers.

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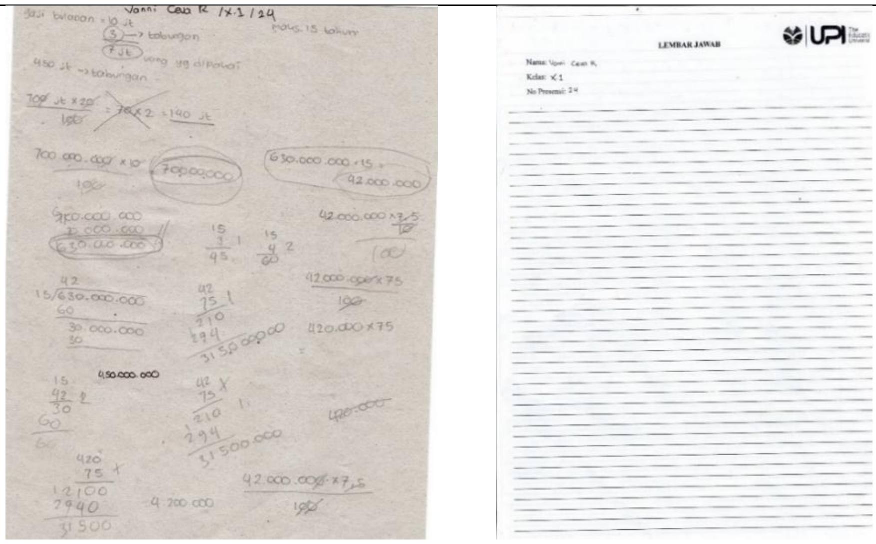

(a) (b)

Figure 13. Annotation sheet (a) and answer sheet (b) for code response R10

4.6. Reasoning

The final indicator, reasoning, evaluates students' ability to engage in logical thinking processes and connect problem elements to conclude, verify given justifications, or provide justifications for statements or solutions to the problem. The responses obtained by researchers for this indicator were consistent under code response R11, where subjects failed to recheck what they had obtained from each problem-solving stage. As a result, the conclusions provided by the subjects deviated significantly from what was required in the problem. Moreover, the answers could have been more accurate, leading to errors in the conclusions. During interviews, subjects expressed that they did not recheck their answers due to limited time and a lack of habit to verify all results obtained from each stage; they were only accustomed to checking calculations.

Based on these interviews, it appears crucial to undergo a comprehensive checking process at all stages of problem-solving, from problem identification to the final results in the form of answers or conclusions. This is necessary because focusing only on checking calculations poses the risk that errors may occur in the problem identification stage. In other words, even if mathematical calculations may be considered correct in procedural terms, if the problem has yet to be accurately identified, the verification process will be ineffective, and the resulting answers will still be incorrect. Therefore, the checking process should encompass all stages of problem-solving, including the initial stage of understanding the problem itself. This ensures that the problem identification is done correctly before proceeding to mathematical calculations. Thus, holistic checking will help avoid errors that may occur in various stages of problem-solving and ensure that the solutions provided are correct and accurate.

4.7. Technological Implications: Translating Qualitative Patterns into Digital Design Requirements

The qualitative patterns documented in Sections 4.1–4.6 reveal distinct and recurrent error trajectories in students' mathematical literacy processes. These patterns are not random or idiosyncratic; rather, they follow predictable sequences and display characteristic behavioral signatures. Such predictability opens up meaningful opportunities for technological intervention. When these patterns can be detected in real time through process logging, digital systems can provide adaptive scaffolding at critical junctures, while teachers receive actionable alerts to inform instruction. In this section, we translate these qualitative insights into concrete technological design requirements, organized by literacy indicator.

For the Communication indicator (I1), the qualitative findings show two dominant response patterns: R1 (partial or incomplete identification of relevant information) and R2 (no active marking and largely passive reading). Students who exhibit R1 and R2 tend to misunderstand key problem constraints, which then produce cascading errors in subsequent stages of problem solving. In a digital environment, the quality of students' communication and problem identification can be inferred from multiple behavioral signals. These include annotation metrics (for example, coverage defined as the proportion of information units that are annotated, and relevance defined as the proportion of annotations that target key information), reading behavior (such as dwell time on critical versus peripheral information), and temporal patterns (for instance, detecting when students proceed quickly to the next step without any annotation within a short time window). These signals can trigger tiered adaptive scaffolding, beginning with basic prompts to "identify all important information," followed by more guided questions, and, where necessary, worked examples. For teachers, a dashboard can visualize a class-level heatmap of annotation coverage, display individual timelines of interaction with the text, and generate real-time alerts when students exhibit high-risk patterns such as R1 or R2. To ensure feasibility in Indonesia, the system should provide a Bahasa Indonesia interface, operate in offline mode with later synchronization, be mobile-responsive, and function under low-bandwidth conditions.

For the remaining indicators (Mathematization, Representation, Problem-Solving Strategies, Symbolic Operations, and Reasoning; I2–I6), a similar logic of technological translation applies. For Mathematization (I2), systems can analyze the structure of students' formulas, map variables to the problem context, and offer modeling scaffolds when mismatches appear. For Representation (I3), algorithms can classify the types of representations students choose (such as tables, graphs, equations, or verbal explanations) and suggest alternative or complementary representations when appropriate. For Problem-Solving Strategies (I4), the system can prompt students to articulate their plans, detect when they are stuck or cycling unproductively, and provide metacognitive support. For Symbolic Operations (I5), automatic checking of calculations and recognition of common error patterns can help students correct themselves in real time. For Reasoning (I6), technology can track whether students verify their answers, perform reasonableness checks, and reflect on their solution paths, offering prompts when verification behaviors are absent. Each of these areas requires corresponding detection algorithms, layers of adaptive scaffolding, and dashboard specifications that are explicitly designed with Indonesia's infrastructural conditions and teacher capacity in mind.

A central implication of this study is the cascading nature of errors across indicators I1 to I6, in which early misinterpretation produces a "domino effect" that leads to subsequent failures in mathematization, representation, strategy selection, symbolic manipulation, and reasoning. This insight motivates the design of a "Domino Effect Dashboard" that provides early warnings when high-risk patterns in communication (such as R1 and R2) are detected, visualizes likely pathways of error propagation, and tracks the impact of interventions over time. By foregrounding these high-leverage points, the dashboard enables teachers to focus their efforts where they can most effectively disrupt the cascade of errors and support students' development of robust mathematical literacy.

Building on these findings, we propose a comprehensive technology-enhanced framework for mathematical literacy development aligned with AKM assessment. The framework consists of three integrated components that directly address the specific error patterns and cognitive processes identified in our qualitative analysis, while remaining feasible and appropriate for the Indonesian educational context.

4.7.1. Component 1: Intelligent Diagnostic Assessment System

The first component is an intelligent diagnostic assessment system designed to detect where students struggle in the problem-solving process through real-time process logging and pattern recognition. A process-logging dashboard tracks reading time, annotation patterns, calculation attempts, and answer changes, and then generates individual and class-level process profiles. Rule-based algorithms classify errors by literacy indicators (I1–I6) and map them onto the response patterns observed in the qualitative phase (R1–R11), while a real-time alert system flags high-risk trajectories and suggests timely interventions.

To support implementation in Indonesia, the system should be optimized for low-bandwidth environments (including 2G/3G connections), provide an offline mode with subsequent synchronization, use a Bahasa Indonesia interface, incorporate culturally relevant contexts, and integrate smoothly with AKM-style assessments. A mobile-first design and basic accessibility features will further enhance usability across diverse school settings.

4.7.2. Component 2: Adaptive Scaffolding Engine

The second component is an adaptive scaffolding engine that delivers context-sensitive, timely support based on the error patterns detected by the diagnostic system. This engine employs a tiered scaffolding approach, ranging from gentle prompts to more explicit guided steps and, when necessary, fully worked examples. Each qualitative response pattern (R1–R11) is linked to specific triggers and corresponding scaffolds, ensuring that support is tailored to the underlying cognitive difficulty rather than generic or one-size-fits-all.

The design of this component is guided by core pedagogical principles: scaffolds are temporary and fade as students gain competence; they aim to strengthen metacognitive awareness; they are culturally responsive; and they are aligned with constructivist views of learning that emphasize students' active construction of understanding. In technological terms, this engine can draw on architectures similar to cognitive tutors, adaptive learning systems, and conversational agents that employ natural language processing, as well as repositories of worked examples and tools such as dynamic visualization software.

4.7.3. Component 3: Teacher Analytics Dashboard

The third component is a teacher analytics dashboard that synthesizes complex student data into clear, actionable insights for classroom instruction, differentiation, and formative assessment. At the class level, the dashboard can provide heatmaps of performance across indicators I1–I6, distributions of error patterns, and trajectories of progress over time. At the individual level, it can display detailed learning profiles, including process logs that highlight how students interact with problems, where they hesitate, and how they respond to scaffolds.

Importantly, the dashboard offers actionable recommendations by suggesting instructional responses to recurring patterns and linking teachers to relevant teaching resources. It also incorporates the "domino effect" visualization, using interactive diagrams to show how early misunderstandings in communication propagate through mathematization, representation, strategy use, symbolic operations, and reasoning. Predictive alerts and data on the effectiveness of past interventions help teachers refine their strategies and allocate attention to students most in need. To build teacher capacity, the dashboard embeds professional learning resources, short video tutorials, and community features, and gradually reveals more advanced analytics as teachers' confidence and expertise grow.

4.7.4. Framework Integration and Implementation Roadmap

These three components are designed to function as a coherent, mutually reinforcing system. The intelligent diagnostic assessment captures rich process data; the adaptive scaffolding engine responds to this data in real time to support students; and the teacher analytics dashboard aggregates and interprets the data to guide instructional decision-making. Together, they form a hybrid human–AI system that leverages technology's strengths in monitoring, feedback, and pattern detection while preserving teachers' irreplaceable roles in relational support, contextual judgment, and motivation.

Implementation of this framework can proceed in phased stages. An initial design and development phase involves co-design sessions with teachers and local stakeholders, development of core features, construction of an Indonesian-language content library, and iterative usability testing. A subsequent pilot phase deploys the system in a small number of diverse schools, accompanied by intensive professional development for teachers and ongoing refinement based on effectiveness data. A final scale-up phase gradually expands adoption through train-the-trainer models, alignment with ministry initiatives, and the establishment of sustainable technical support structures.

Success can be evaluated through multiple metrics, including improvements in students' AKM performance and reduction in specific error patterns, levels of teacher adoption and perceived usefulness of the dashboard, system performance and reliability in low-resource contexts, and indicators of equity such as reductions in achievement gaps across regions or socioeconomic groups. Through this integrated and context-sensitive framework, the study demonstrates how qualitative insights into students' lived experiences with AKM problems can be systematically translated into a feasible, technology-enhanced pathway for strengthening mathematical literacy in Indonesia.

The results revealed there are five mathematical literacy indicators, which are communication, mathematician, representation, problem-solving strategies, language and symbolic operations, and reasoning. Furthermore, this research also identified three key problem-solving processes within mathematical literacy: formulation, implementation, and interpretation. Communication skills are essential in observing how students articulate these processes during problem-solving. Findings indicate that during the formulation process, students identify issues by marking specific parts. Muhaimin et al., [72] and Muhaimin & Kholid [4] reveal that using annotations in problems aids students in understanding the information presented, focusing their attention on pertinent details. Subsequently, during implementation and interpretation, students perform calculations on annotation sheets. Herholdt & Sapire [108] assert that performing calculations on annotation sheets reduces errors in calculations or planning problem-solving strategies. Thus, annotating problem sheets before transferring answers to response sheets constitutes a form of communication during problem-solving, enhancing students' understanding and minimizing calculation errors.

Additionally, the results revealed errors among students in understanding information, leading to data transformation mistakes in this mathematization indicator. Mathematical literacy involves everyday problem-solving [11], and problems are typically framed around daily life scenarios [109]. Therefore, it is crucial to record and comprehend relevant data accurately. Sometimes, problem statements may contain unnecessary additional information [110], necessitating the ability to sift through and focus on essential data a fundamental aspect of mathematical literacy. Moreover, clear and systematic data notation is essential [111] to aid in thinking processes and problem-solving. Errors in data recording can lead to inaccuracies in solutions. According to Sundayana & Parani [112], initial errors in problem-solving by students often stem from incomplete or inaccurate data gathered from the problem statement, affecting subsequent processes and potentially resulting in incorrect formulas and problem-solving strategies. Therefore, precision in this process is paramount. In mathematical literacy, these skills facilitate problem-solving and prove valuable in students' daily lives [3], [37].

Besides that, practical representation skills are crucial when students can provide comprehensive illustrations such as mathematical symbols, tables, and relevant diagrams about complex information. This is particularly important given that findings indicate distinct characteristics between the two responses. In this context, one response in R6 struggled with understanding the problem, resulting in their inability to provide appropriate representations of the problem. This finding aligns with statements in Minarni et al. [113] research, emphasizing the importance of a deep understanding of information in the representation process. Therefore, efforts to enhance students' representation skills should be supported by solid efforts to deepen their understanding of the material being studied.

Furthermore, the ability to devise problem-solving strategies is also found critical to mathematical literacy because it involves performing simple mathematical operations and analyzing, interpreting, and applying mathematics in various real-life situations [10], [11]. With clear strategies, individuals may be able to find efficient and effective solutions [114]. Many problems, especially in mathematics, require specific strategies for resolution [115]. Therefore, having the right strategy can expedite the problem-solving process and improve the accuracy of answers. However, we found that subjects made errors in selecting the formula for solving problems. Based on the findings from the formulation of problem-solving strategies, two issues emerged: inaccurate mathematization processes and lack of understanding of the material. Muhaimin & Kholid [4] stated that while conceptual understanding in recognizing problem patterns, identifying relationships between variables, and understanding basic mathematical concepts is crucial, this is only possible if students can transform information into relevant mathematical language. According to Cho & Nagle [116], a lack of deep understanding of the involved basic mathematical concepts causes students to make mistakes in choosing the formula to use, resulting in outcomes that may deviate from expectations. This statement is consistent with our findings that subjects needed to fully grasp the concepts of discounts and interest, leading to errors in strategy formulation and impacting calculation results.

It has been noted that errors made at the beginning of problem-solving will impact subsequent processes. Imagine if the foundation of a building needs to be stronger or more accurate. The building is at risk of collapsing under pressure. Similarly, in mathematical problem-solving, if the foundational understanding or strategy is inadequate during the formulation stage, the likelihood of obtaining correct answers in subsequent stages diminishes [117]. This condition is confirmed by code response R9, where it can be seen how initial errors in the formulation stage affect the results in the implementation stage. Our findings align with studies by Astutik & Purwasih [118] and Huu Tong & Phu Loc [119], indicating that earlier incorrect steps cause the most incorrect answers. Therefore, educators must ensure a solid understanding from the beginning so that students have a greater chance of obtaining correct answers in subsequent stages. Also, students need more time management to improve Broyden [120] revealed that the longer time spent on previous processes, the less time is available for subsequent stages.

Building on this, reasoning skills are imperative in solving mathematics problems, enabling subjects to reflect on their work and draw appropriate conclusions [121]. Researchers observed that subjects could not draw accurate conclusions due to their lack of habit in rechecking the information they obtained. Ideally, this checking process should be conducted at every problem-solving stage, not solely in calculation aspects [122]. This action aims to reduce the likelihood of errors occurring in the initial stages of the problem-solving process. Furthermore, when subjects reach this stage, they often have limited time remaining. Therefore, time management during work execution becomes crucial. Understanding the concepts is also critical in ensuring efficient and effective completion of tasks.

Students frequently cited “not enough time” and “lack of focus” on AKM problems. These are instructional design issues, not just individual deficits. Spending too long on identifying information and mathematizing reduces time for checking, consistent with cognitive load theory [123]. Instruction should front load sense making and representation, then reserve a brief verification phase; structured self explanations and short checks improve accuracy [124]. Practically, model quick annotation and require a “representation checkpoint” before computation, as encouraged by the PISA framework [5], [11], which reduces error propagation [108]. To curb focus loss from heavy text and vague goals, use progressive disclosure and clear sub goals, plus worked example pairs with fading and brief think alouds [125]. Finally, institutionalize timed “audit passes” and peer review aligned to the six indicators to sustain accuracy and reduce cascading errors [126].

The findings of this study provide a critical blueprint for both pedagogical and technological interventions aimed at improving mathematical literacy. Pedagogically, the evidence of cascading errors underscores the need for instructional routines that prioritize problem identification, data selection, and representation before computation. Teachers should implement structured “checkpoints” based on the six indicators of mathematical literacy (communication, mathematization, representation, problem-solving strategies, language and symbolic operations, and reasoning) to help students internalize a reflective problem-solving cycle and reduce error propagation. Technologically, these process-level patterns offer design requirements for AKM-aligned digital assessments, intelligent tutoring systems, and learning analytics. By logging intermediate actions, digital platforms can detect early warning signs such as incomplete data recording or the absence of representation and then trigger real-time scaffolds or visualize student trajectories on dashboards to inform targeted teacher interventions.

Despite these insights, the study is limited by its small, purposive sample of three focal cases from a single school, which prioritizes interpretive depth over statistical generalizability. The focus on a single AKM-oriented algebra problem also means that different content domains or item types might elicit different error trajectories. Furthermore, the use of a paper-based format may not fully capture the mode effects present in the actual computer-based AKM administration, such as navigation constraints and differences in digital annotation. Future research should therefore employ larger, more diverse samples and utilize authentic CBT environments with log-file or screen-capture data to validate the cascading-error patterns identified here. In addition, design-based research is needed to iteratively develop and test the proposed digital scaffolds, intelligent tutoring interventions, and learning analytics tools derived from the indicators and process patterns revealed in this study.

5. CONCLUSION

This study examines Indonesian students' mathematical literacy through qualitative analysis of AKM-oriented algebra tasks, revealing recurring error patterns across six literacy indicators that form a domino effect, where early misunderstandings lead to subsequent failures. Based on these findings, the study proposes a technology-enhanced framework consisting of an Intelligent Diagnostic Assessment System, an Adaptive Scaffolding Engine, and a Teacher Analytics Dashboard to support real-time error detection, contextual feedback, and informed teaching, while remaining aligned with Indonesian educational conditions. Technology is positioned as a pedagogical partner that strengthens, rather than replaces, the teacher's role. Although the framework is still theoretical and requires empirical validation, this study highlights the need for integrated efforts combining qualitative insight, thoughtful technological use, and sustained teacher development to improve mathematical literacy equitably in Indonesia.

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USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried **out** entirely by the authors without the assistance of AI-based technologies.

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