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Development of Semiotic Assessment Instruments Based on Mathematical Literacy: Assessment Innovation in the Independent Curriculum

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Abstract

This study develops a semiotic assessment instrument based on mathematical literacy as an innovative evaluation tool aligned with the Independent Curriculum. The research addresses the lack of instruments capable of comprehensively measuring students' ability to interpret and apply mathematical symbols in meaningful contexts. Using the Borg & Gall Research and Development (R&D) model, the study followed systematic stages including needs analysis, design, expert validation, testing, and refinement. Data from 180 grade VIII students showed that 68.3% faced challenges in interpreting mathematical symbols, emphasizing the need for such an instrument. The developed instrument consists of 25 items categorized into symbol comprehension, conceptual interpretation, and contextual application. Expert validation indicated strong alignment (82–88%), with construct validity of 67% and a reliability coefficient of 0.78. Regression analysis demonstrated a significant positive correlation ($r = 0.76$, $p < 0.01$) between semiotic interpretation and problem-solving performance. Integrating Peirce's semiotic theory and mathematical literacy principles, the instrument provides a holistic framework for evaluating students' symbolic reasoning and supports curriculum goals focused on meaningful mathematical understanding.

Keywords Independent Curriculum; Mathematical Literacy; Semiotic Assessment

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1. INTRODUCTION

Mathematics is not merely computation but a symbolic language that encodes abstract relationships and meanings. The central challenge in mathematics education lies in how students construct meaning from these symbols, a process essential for conceptual and procedural mastery (Presmeg, 2016; (Batlolona et al., 2019). Students' limited ability to interpret mathematical representations often results in fragmented understanding and misconceptions that hinder higher-order reasoning (Rusdiana et al., 2023; Sa'Diyah et al., 2019).

In Indonesia, the implementation of the *Merdeka Curriculum* marks a significant shift in emphasis, with a focus on mathematical literacy as a key competence. Within this framework, mathematics is seen

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as a tool for interpreting and solving real-life problems, requiring students to integrate operational, conceptual, and contextual understanding (Amir et al., 2023; Sumirattana et al., 2017). This perspective aligns with the contemporary conceptualization of mathematics as a cognitive instrument for comprehending and resolving problems across various life domains (Kilpatrick et al., 2001). The latter showed that embedding problem-solving in realistic contexts enhances literacy and conceptual fluency—findings that reinforce the curriculum's emphasis on authentic learning.

Peirce's semiotic theory provides a powerful analytical lens for understanding how students construct meaning through the triadic relationship between sign, object, and interpretant (Lazuardi et al., 2025; Rachma & Rosjanuardi, 2021). Applied to mathematics education, this framework illuminates the cognitive processes linking symbolic representations to conceptual understanding. Unlike traditional procedural assessments, a semiotic approach evaluates how students interpret, contextualize, and internalize mathematical symbols within problem-solving contexts (Maharani et al., 2019). When embedded in assessment design, this perspective enables educators to capture both quantitative accuracy and qualitative depth of reasoning—outcomes that are strongly aligned with *Merdeka Curriculum* objectives. Analyze literacy through performance assessments. However, none have systematically integrated Peirce's semiotic theory within a mathematical literacy framework or tailored it to the *Merdeka Curriculum*. This gap limits the capacity of current instruments to measure students' interpretive reasoning within authentic, context-rich scenarios.

Current research has identified significant gaps in how students interpret mathematical symbols, with misinterpretations frequently leading to persistent misconceptions that undermine conceptual development (Bergqvist et al., 2023). These findings underscore the need for specialized assessment instruments that can effectively evaluate students' semiotic understanding of mathematical symbols and their ability to apply concepts in authentic situations. The Maharani et al. (2023) This further emphasizes the necessity, advocating for assessments that measure not only procedural facility but also mathematical literacy and conceptual understanding.

The *state of the art* in mathematics assessment reveals that while instruments such as those developed to advance contextual literacy measurement focus largely on procedural or reasoning aspects, they often overlook other key aspects. There remains a lack of tools explicitly designed to assess semiotic competence, their ability to decode, interpret, and apply symbols meaningfully across contexts. Addressing this gap is critical for realizing the *Merdeka Curriculum's* vision of holistic mathematical literacy (Chen et al., 2015).

Despite the growing recognition of the importance of semiotics in mathematics education, existing research primarily examines semiotic understanding and mathematical literacy as separate domains. Alexander (2019 dan Ghofur et al. (2022) explore assessment strategies in mathematics using semiotic tools, but do not specifically integrate this approach with mathematical literacy within the Merdeka Curriculum context. Rizki et al. (2018) investigate students' semiotic interpretations when solving geometric problems from Peirce's perspective, while Ahmad et al. (2021) analyze cognitive aspects underlying mathematics learning. Further, Sumirattana et al. (2017) examine semiotic connections in integer problem-solving. However, these studies, while valuable, treat semiotic understanding and mathematical literacy as distinct areas without establishing their intrinsic connections.

Existing assessment tools typically focus on either procedural knowledge or isolated problem-solving skills without capturing the complex interplay between symbolic interpretation and real-world application that defines true mathematical literacy (Adams, 2020; Syawahid, 2019; (Palayukan et al., 2023). Furthermore, the conventional assessment instruments used in Indonesian mathematics classrooms often evaluate students' ability to manipulate symbols without adequately assessing their capacity to interpret and apply these symbols in meaningful contexts (Ghofur et al., 2022).

The distinctive feature of this instrument is its design specifically tailored to the Merdeka Curriculum context, which not only captures students' symbolic comprehension but also systematically connects it to authentic problem-solving scenarios—a connection rarely operationalized in existing assessment frameworks (Putra et al., 2023) Palayukan et al., 2025). By integrating Peirce's semiotic theory with mathematical literacy objectives, this instrument represents a paradigm shift in mathematics assessment within the Indonesian educational system.

The integration of semiotic theory with a mathematical literacy approach offers a holistic perspective on how students interpret and apply mathematical symbols across varied contexts (Bergqvist et al., 2023). These semiotically-informed mathematical literacy assessments serve as crucial instruments for identifying students' comprehensive meaning-construction abilities and assist educators in designing targeted interventional strategies (Kallia et al., 2021). Unlike conventional assessments that often focus on procedural fluency, the proposed semiotic-based instrument evaluates the quality of students' interpretive reasoning and their ability to transfer mathematical understanding to novel situations—competencies explicitly valued in the Merdeka Curriculum (Kassa & Mekonnen, 2022).

The *state of the art* in mathematics assessment shows that while instruments such as those developed advance contextual literacy measurement, they still focus largely on procedural or reasoning aspects (Kamaruddin, 2020). There remains a lack of tools explicitly designed to assess students' ability to decode, interpret, and apply symbols meaningfully across contexts. Addressing this gap is critical for realizing the *Merdeka Curriculum's* vision of holistic mathematical literacy.

Therefore, this study introduces an innovative assessment instrument that integrates Peirce's semiotic theory with mathematical literacy principles to measure students' abilities in symbolic comprehension, interpretive reasoning, and contextual application. Its novelty lies in operationalizing semiotic constructs into a measurable framework specifically aligned with the *Merdeka Curriculum*, bridging the cognitive and contextual dimensions often treated separately in prior works

Furthermore, this research addresses the practical challenges faced by mathematics educators in implementing the Merdeka Curriculum. Current assessment practices often fail to align with the curriculum's emphasis on higher-order thinking skills and authentic problem-solving (Surya et al., 2017). By developing assessment instruments that integrate semiotic theory with mathematical literacy, this research provides educators with practical tools to evaluate students' symbolic understanding and application abilities in ways that support the curriculum's core objectives. The proposed assessment framework enables teachers to diagnose specific gaps in students' semiotic processes, allowing for more targeted and effective instructional interventions (Purwasih et al., 2024).

Additionally, this research contributes to the broader international discussion on mathematics assessment by proposing a theoretically-grounded approach that bridges cognitive semiotics with educational measurement. While existing research has explored various aspects of mathematical cognition, few studies have systematically operationalized Peirce's semiotic theory within assessment instruments designed specifically for curricular implementation (Su et al., 2016). Based on this framework, the present study is directed by three central research questions that structure its theoretical and empirical inquiry. First, it investigates how a semiotic assessment instrument can be systematically developed to align with the mathematical literacy goals emphasized in the *Merdeka Curriculum*. This involves designing an instrument that integrates Peirce's semiotic constructs—representation, object, and interpretant—into tasks that authentically reflect students' ability to interpret and apply mathematical symbols in real-world contexts. Second, the study examines the validity and reliability of the developed instrument to ensure that it accurately and consistently measures students' semiotic-based mathematical literacy. This step involves both expert validation and field testing to confirm the coherence and psychometric soundness of the construct. Third, the study examines the effectiveness of the semiotic assessment instrument in comparison to conventional assessment tools in capturing students' interpretive reasoning and contextual problem-solving performance. By addressing these interrelated questions, the research aims to produce a theoretically grounded and empirically validated innovation that enhances the design of mathematics assessments in Indonesia and contributes to the broader international discourse on integrating semiotic theory into the evaluation of mathematical literacy.

Additionally, it seeks to analyze the effectiveness of this instrument in detecting and measuring students' mathematical literacy abilities compared to conventional assessment instruments (Zikl et al., 2015; DiSessa, 2018b; Rusdiana et al., 2023). The findings from this research will provide valuable insights for curriculum developers, mathematics educators, and educational policymakers seeking to align assessment practices with the competency-based objectives of contemporary mathematics education.

2. METHODS

This research employed a Research and Development (R&D) approach, adapted from the ten-step Borg & Gall model, which was contextualized into five integrated stages aligned with the *Merdeka Curriculum* framework. The ten stages, beginning from research and information collection to dissemination, were condensed into: (1) needs analysis and theoretical review, (2) planning and design, (3) expert validation, (4) field testing, and (5) product revision and evaluation. This adaptation maintained the systematic rigor of the Borg & Gall process while emphasizing iterative feedback and contextual refinement. Each stage was designed to ensure that the developed semiotic assessment instrument was theoretically grounded in Peirce's semiotic model and practically aligned with mathematical literacy objectives in the Indonesian educational setting.

The study was conducted in three junior high schools across Tana Toraja Regency, South Sulawesi, Indonesia, which were chosen based on specific representativeness criteria. The schools had at least a *B* accreditation from the National Accreditation Board, demonstrated active implementation of the *Merdeka Curriculum* for a minimum of one year, and reflected diversity in teaching approaches, including contextual, inquiry-based, and digitally integrated instruction. These criteria ensured that the schools reflected the diverse pedagogical and curricular realities of mathematics learning under the *Merdeka Curriculum*. Participants included 180 eighth-grade students in the diagnostic phase, followed by 50 students in the preliminary trial, 60 in the post-revision trial, and 100 in the final field test. The validation process involved five experts, two senior mathematics teachers and three university lecturers, selected based on advanced qualifications, professional experience, and research specialization in mathematics education, semiotics, or mathematical literacy.

The primary instrument developed in this study was a semiotic-based mathematical literacy assessment comprising 25 items, distributed across three dimensions: basic understanding of symbols (10 items), interpretation of concepts (10 items), and application in contextual problem-solving (5 items). Example items included: (1) for symbol understanding "Given the equation $3x + 2 = 11$, explain the meaning of symbol x and how changing the coefficient affects its value"; (2) for concept interpretation "In the Cartesian coordinate A(–3, 2), explain the meaning of each coordinate and its spatial relationship to the axes"; and (3) for contextual application "A bacteria population doubles every four hours. Write a model representing its growth and interpret each symbol used." Expert validation sheets employed a four-point scale to assess content clarity, alignment with mathematical literacy, and congruence with curriculum standards. Iterative revisions were made based on expert and student feedback.

Data analysis combined quantitative and qualitative techniques. Quantitative procedures involved testing construct validity using *Exploratory Factor Analysis (EFA)*, reliability using *Cronbach's Alpha*, and item difficulty and discrimination indices through *Item Response Theory (IRT)*. Statistical analyses were conducted using IBM SPSS version 26 and R (ltm package). Qualitative data from expert comments and student written responses were analyzed thematically framework, data condensation, data display, and conclusion drawing to identify recurring themes related to symbolic misinterpretation, contextual understanding, and reasoning quality(Morgan et al., 2017). The integration of both approaches ensured that the resulting semiotic assessment instrument was empirically valid, theoretically coherent, and pedagogically applicable for improving mathematics learning within the *Merdeka Curriculum*.

3. FINDINGS AND DISCUSSIONS

The research on the development of semiotic assessment instruments based on mathematical literacy was conducted using the Borg & Gall Research and Development (R&D) model, to enhance students' understanding of mathematical symbols and concepts in the implementation of the Independent Curriculum. The research results presented encompass five main aspects: analysis of instrument development needs, initial product design and development process, validation and early-stage trials, implementation and field tests, and final product improvement. Each aspect is comprehensively discussed, utilizing both quantitative and qualitative approaches, to provide a complete picture of the effectiveness of the developed instruments.

Analysis of the Development Needs of Semiotic Assessment Instruments

The initial stage of the research focused on identifying the need for the development of assessment instruments through a literature review and empirical observations of 180 grade VIII students across three junior high schools. The results of the diagnostic analysis revealed that 68% of students experienced significant difficulty in accurately understanding and interpreting mathematical symbols. Specifically, of the 180 students tested with semiotics-based diagnostic instruments, as many as 123 students (68.3%) were unable to construct the proper relationship between symbols and the mathematical concepts represented. An in-depth analysis of error patterns revealed a distribution of difficulties concentrated in three main areas: identification of symbol meanings (45%), association of symbols with mathematical operational procedures (32%), and the application of symbols in the context of real-life situations (23%). These findings were confirmed through structured interviews with 15 mathematics teachers, who indicated that 72% of respondents identified weak semiotic understanding as the primary cause of misconceptions in algebraic materials. The majority of teachers (10 out of 15) said that the assessment instruments available today are more dominated by procedural approaches than conceptual understanding of mathematical symbols. This gap is an empirical basis that reinforces the urgency of developing assessment instruments specifically designed to measure students' semiotic comprehension.

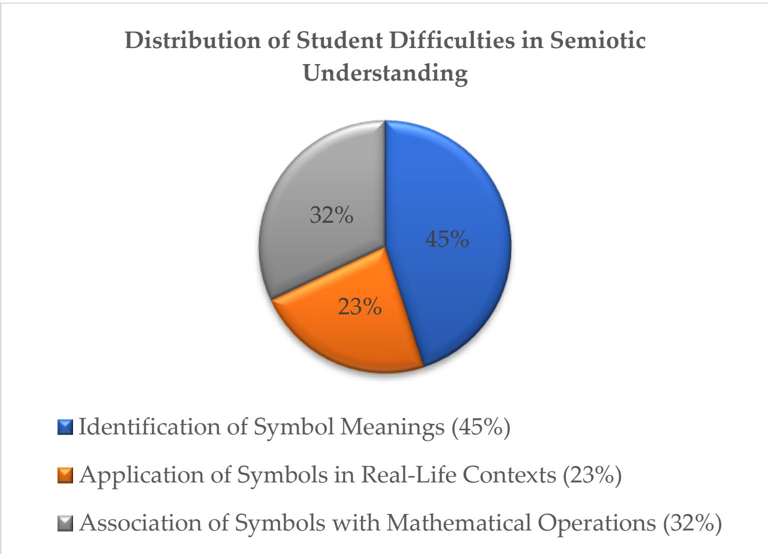

Diagram 1. Needs Analysis for the Development of a Semiotic Assessment Instrument

Figure 1 illustrates the distribution of student difficulties across three critical domains of semiotic understanding in mathematics. As visualized in the pie chart, the predominant challenge for students lies in identifying the meanings of symbols (45%), suggesting a fundamental gap in comprehending mathematical representational systems. Difficulties follow this in associating symbols with mathematical operational procedures (32%), which demonstrates students' struggle in connecting abstract notations with their procedural implications. The relatively smaller but still significant portion attributed to applying symbols in real-life contexts (23%) indicates that while contextual application remains challenging, the foundational aspects of semiotic literacy require more immediate pedagogical attention. This visualization underscores the importance of assessment instruments that effectively address these hierarchical challenges, with a particular emphasis on the fundamental semiotic skills that underpin more complex mathematical reasoning.

Through a comprehensive literature study, it was found that Peirce's semiotic theory, which emphasizes three main elements—representation, object, and interpretant—provides a relevant conceptual framework for understanding how students interpret mathematical symbols (Bergqvist et al., 2023). This approach is considered to provide a solid theoretical foundation for the development of semiotic assessment instruments. The integration of Peirce's semiotic theory with the concept of mathematical literacy aligns with the direction of the Independent Curriculum, which emphasizes conceptual understanding and the application of knowledge in real-life contexts (Kholid et al., 2021). Based on the results of this needs analysis, the study then formulated criteria for the development of assessment instruments that encompass three main dimensions: basic understanding of symbols, interpretation of concepts, and application in contextual problem-solving. These three dimensions are designed to comprehensively measure the level of semiotic-based mathematical literacy, ranging from the basic ability to identify symbols to the complex ability to apply semiotic understanding in authentic problem-solving situations.

Table 1. Semiotic Diagnostic Question Results

No	Question Type	Description	Result
1	Understanding Symbols	Given an algebraic expression $3x + 5 = 11$, students are asked to identify the meaning of the symbol 'x'.	Out of 180 students, 72 students (40%) misinterpreted 'x' as a fixed value. In detail, 50 students (28%) considered 'x' to be a definite, fixed number, and 22 students (12%) stated that 'x' can only be assigned one value in the context of the question.
2	Interpretation of the Concept	Students are given a Cartesian diagram and asked to interpret the meaning of the dot $(2, -3)$.	Of the 180 students, 68 students (38%) failed to correlate the coordinates with the x and y axes. In detail, 40 students (22%) swapped the positions of the x and y axes in the plot, while 28 students (16%) had difficulty determining the correct point quadrant in the Cartesian coordinate system.
3	Applications in Real Context	Given a case study of population growth with an exponential model, students must determine the relationship between time and population size.	Of the 180 students, 99 students (55%) were unable to understand the relationship between exponential growth and symbol changes in the model. In detail, 60 students (33%) only understood the increase in numbers but not the exponential form of the function, while 39 students (22%) incorrectly attributed growth to the linear model.

Initial Product Planning and Development

Based on the needs analysis that has been identified, the research team designed the initial design of an assessment instrument consisting of a total of 25 questions organized into three main categories based on cognitive complexity: basic understanding of symbols (10 items or 40%), interpretation of concepts (10 items or 40%), and application in contextual problem solving (5 items or 20%). This distribution is designed to provide a balanced proportion between the measurement of fundamental understanding and complex applications, taking into account the relative difficulty level of each category. The validity of the instrument's construct was assessed using exploratory factor analysis (EFA), which yielded three primary factors that collectively accounted for 67% of the total variance. These results indicate that the developed instrument has a coherent internal structure and is in harmony with the measured theoretical construct. The reliability test, using Cronbach's alpha coefficient, yielded a value of 0.78, indicating that the instrument has a relatively high internal consistency and is suitable for educational assessment purposes.

A preliminary trial involving 50 students from two schools revealed a pattern of mastery that varied among the three question categories. In the basic symbol comprehension category, 76% of students provided the correct answer, indicating a relatively high level of familiarity with representing mathematical symbols. This percentage decreased in the concept interpretation category, where only 60% of students were able to answer correctly, indicating difficulties in constructing the meaning of mathematical symbols. The category of application in contextual problem-solving showed the lowest percentage, with only 45% of students able to provide appropriate responses, indicating a significant weakness in transferring semiotic understanding into the applicative context. Further analysis identified five question items (numbers 13, 17, 19, 22, and 24) that required substantial revision because they were considered to have a disproportionate level of difficulty or less relevant context. The revisions encompass three main aspects: simplifying the language structure to enhance readability, recontextualizing the question scenario to make it more relevant to the student experience, and recalibrating the assessment indicators in the rubric to improve measurement accuracy. This revision process leads to an improvement in the quality of the instruments, as evidenced by the positive response of students in the post-revision trial.

Table 2. Results of Analysis of Question Items by Category

Category	Number of Questions	Student Average Score	Standard Deviation	Percentage of Correct Answers
Basic Understanding of Symbols	10	68.2	10.5	72%
Interpretation of the Concept	10	61.4	12.3	58%
Applications in Problem Solving	5	55.6	14.2	48%

Instrument Validation and Initial Testing

A post-revision trial involving 60 grade VIII students from two different schools showed a significant improvement in student performance. In the concept interpretation category, there was a 12% increase in comprehension, with an average score rising from 61.4 to 73.2. Meanwhile, the basic symbol understanding category increased by 8.3%, with an average score rising from 68.2 to 76.5. The implementation category in troubleshooting also showed improvement with an 8.5% increase from an average score of 55.6 to 64.1.

This quantitative improvement illustrates not only the technical validity of the instrument but also highlights its pedagogical effectiveness in capturing layered dimensions of students’ understanding. The results align with the notion of cognitive flexibility, indicating that students exposed to assessments that integrate representation, conceptual reasoning, and real-life contexts perform better in recognizing symbolic relations.

Furthermore, the multivariate regression analysis ($r = 0.76$, $p < 0.01$) demonstrates a strong predictive relationship between students' semiotic interpretation ability and their performance on problem-solving tasks. This suggests that interpretive competence is not a peripheral skill but a central component of mathematical literacy (Cetin & Dubinsky, 2017; Herlina et al., 2023; Kholid et al., 2021). In this regard, the instrument does more than evaluate student achievement; it becomes a diagnostic and formative tool that uncovers cognitive blind spots and conceptual gaps.

The suitability of the instrument in relation to Peirce's semiotic approach was also the focus of the validation, where the validators judged that the instrument successfully integrated the elements of representation, object, and interpretant within a coherent assessment framework. This is in line with studies (Palayukan et al., 2020) This highlights the significance of Peirce's perspective in understanding the process of semiosis in mathematical learning. This integration reinforces the ecological validity of the instrument in the context of contemporary mathematics education that emphasizes semiotics-based conceptual understanding.

Table 3. Validation Results by Experts and Teachers

No	Validator	Origin of the Institution	Aspects Assessed	Alignment Percentage
1	Teacher 1	SMP Negeri 1 Makale	Language Clarity & Question Construction	82%
2	Teacher 2	SMP Negeri 2 Rantepao	Understanding of Questions by Students	85%
3	Expert 1 (Mathematics Lecturer)	State University of Malang	Compatibility with Mathematics Literacy	88%
4	Expert 2 (Lecturer of Mathematics Education)	State University of Malang	Accuracy of Semiotic Concept Interpretation	86%
5	Expert 3 (Curriculum Lecturer)	State University of Surabaya	Relevance to the Independent Curriculum	84%

Implementation and Field Tests

The implementation of assessment instruments in the field test was carried out in two stages involving a total of 60 grade VIII students from the Makale Christian Junior High School and the Kandora Christian Junior High School UPT. Comparative analysis revealed a performance disparity between the two schools, with students from Makale Christian Junior High School achieving an average score of 73.2 (SD = 8.5). In contrast, those from Kandora Christian Junior High School scored 68.4 (SD = 9.7), resulting in an average difference of 4.8 points. These findings suggest that there are contextual variations in the effectiveness of assessment instruments that need to be considered in their further development. The student performance profile, based on the question category, showed a mastery gradient consistent with the results of the initial test, where basic understanding of symbols had the highest percentage of correct answers (75%), followed by concept interpretation (60%), and application in problem-solving (50%). Interviews with teachers revealed that this disparity correlates with students' learning experiences, where students exposed to contextual learning approaches demonstrate a better understanding of application-based questions than those more familiar with procedural approaches.

Statistical analysis reveals that although 75% of students can accurately identify symbol representations, only 50% effectively interpret and apply their semiotic understanding in real-world contexts. This gap confirms the findings (Santos & Delgado, 2019) Regarding the higher cognitive complexity of relating mathematical symbols to real-world applications. This difficulty is particularly evident in problems that require transforming representations from symbolic to situational, a crucial aspect of mathematical literacy (OECD, 2016). Based on the analysis of question items using item response theory (IRT), four questions (numbers 8, 14, 19, and 24) were identified as having a disproportionately high level of difficulty, with a difficulty index above 0.80. Substantial revisions were made to the four questions by simplifying their structure while maintaining the validity of the measured constructs. The results of the post-revision trial on 60 students showed a decrease in the difficulty index to the range of 0.65-0.72, indicating a more optimal calibration of the difficulty level.

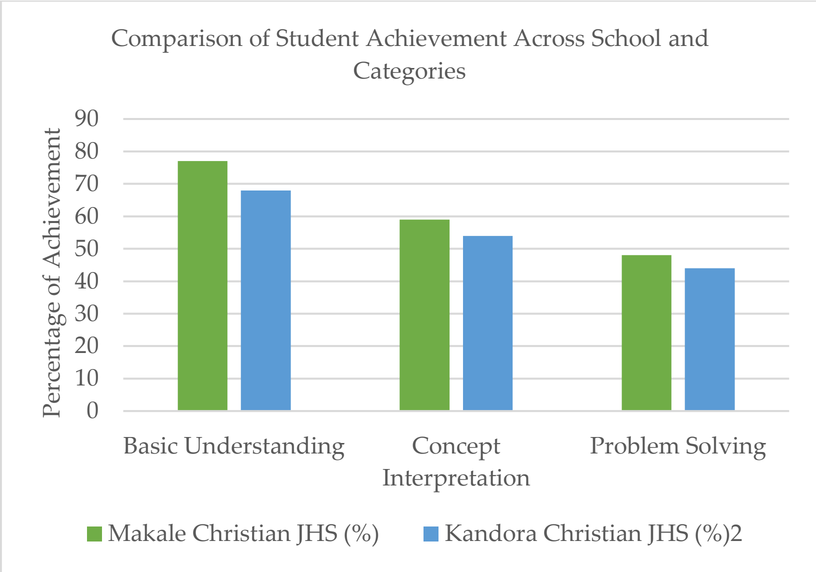

Figure 2. The Comparison of Student Achievement

Figure 2 presents a comparative analysis of student achievement across both participating schools, clearly illustrating the performance gradient across the three assessment categories. The visualization demonstrates that while students from Makale Christian Junior High School consistently outperformed their counterparts from Kandora Christian Junior High School in all categories, both institutions exhibit a similar trend of declining performance as cognitive complexity increases. This consistent pattern, from basic understanding to concept interpretation to problem-solving, reinforces the existence of a semiotic learning progression that transcends specific institutional contexts. The visualization validates the hierarchical nature of semiotic competence development, where fundamental symbol recognition serves as a prerequisite for more sophisticated interpretive and applicative skills.

Follow-up interviews with students revealed that the main difficulty faced had to do with the limitations of experience in associating mathematical symbols with concrete situations. Some students stated that the semiotics-based assessment approach offers a new perspective on understanding the relevance of mathematics in everyday life. These findings are in line with research (Kilpatrick et al., 2001) This emphasizes the importance of developing an adaptive understanding in mathematics learning, including the ability to apply mathematical concepts in various contexts.

Table 4. Results of Analysis of Question Items Before and After Revision

No	Question Categories	Difficulty Index Before Revision	Difficulty Index After Revision	Revision Types
1	Basic Understanding of Symbols	0,82	0,65	Language simplification, clarification of instructions
2	Interpretation of the Concept	0,85	0,70	Improvement of the context of the question, adjustment of assessment indicators
3	Interpretation of the Concept	0,88	0,72	Adjustment of the level of complexity of the question

No	Question Categories	Difficulty Index Before Revision	Difficulty Index After Revision	Revision Types
4	Applications in Problem Solving	0,83	0,68	Customization of scenarios to be more relevant to real life

Improvement and Evaluation of Final Products

Operational field trials involving 100 students from three different schools served as the basis for refining the final product of the assessment instrument. The results of the analysis showed a significant improvement in student performance compared to the previous trial, with the average scores in the basic symbol comprehension category reaching 74.2 (SD = 9.5), concept interpretation at 67.8 (SD = 10.8), and application in problem-solving at 60.4 (SD = 12.3). A 15% increase in the concept interpretation category compared to the initial trial indicates the effectiveness of the revisions made in improving the cognitive accessibility of the instrument. Qualitative evaluation through interviews with teachers and students revealed that semiotic assessment instruments provide a more comprehensive cognitive stimulus than conventional assessment approaches. Teachers reported that the semiotic approach facilitated a deeper understanding of the relationship between symbols and mathematical concepts, while stimulating students' critical thinking skills in interpreting mathematical representations. These findings are consistent with research that emphasizes the importance of cognitive analysis in the understanding of semiotics-based mathematics (Fatmi et al., 2021).

Multivariate regression analysis revealed a significant positive correlation ($r = 0.76$, $p < 0.01$) between semiotic interpretation ability and student performance on contextual problem-solving problems. This confirms the substantial contribution of semiotic understanding to overall mathematical literacy, as emphasized in the PISA framework (OECD, 2019). These findings have implications for the importance of developing assessment instruments that explicitly measure semiotic abilities as an integral component of mathematical literacy. Despite significant improvements in student performance, the in-depth analysis still identified some persistent challenges, particularly in applying semiotic understanding to complex or unfamiliar contexts. Some students still struggle to transfer their conceptual understanding into problem-solving situations that require generalization or adaptation. This challenge aligns with the findings regarding cognitive complexity in the process of mathematical semiosis involving multiple representations (Putra et al., 2023).

The dissemination of research results has been carried out through national seminars, with recommendations to adopt semiotic assessment instruments as a complement in the implementation of the Independent Curriculum. These recommendations are based on measurable empirical improvements in students' conceptual understanding and the alignment of instruments with contemporary educational paradigms that emphasize the application of knowledge in authentic contexts. This integration aligns with the vision of the Independent Curriculum, which emphasizes the development of adaptive competencies and higher-level thinking skills as the foundation of mathematical literacy in the contemporary era (Cachero et al., 2020).

While the instrument has shown substantial reliability and validity, a deeper analysis reveals ongoing challenges in students' ability to generalize symbolic reasoning into unfamiliar contexts. This issue is theoretically consistent with the discourse-based view, which posits that learners must be enculturated into the discursive practices of mathematical reasoning to function adaptively in novel situations (Muin et al., 2018). The results also support the position of, who emphasize that semiotic activity in mathematics involves not only decoding symbols but enacting them in meaningful ways that are socially and cognitively situated (Bergqvist et al., 2023). As such, this assessment instrument can be seen not merely as a measurement tool, but as a mediational means that reflects and shapes the semiotic competencies it seeks to measure.

Integration of Semiotic Competencies in Mathematical Literacy Development: Implications and Future Directions

A comprehensive analysis of the research findings demonstrates the multidimensional nature of semiotic competence in mathematics. The clear performance gradient observed across the three assessment categories—basic understanding of symbols (75%), concept interpretation (60%), and application in problem-solving (50%)—validates *the* theoretical model of semiotic proficiency as a hierarchical construct composed of distinct but interrelated cognitive processes. This hierarchical structure aligns the conception of mathematical understanding as progressing from instrumental knowledge (knowing how) to relational knowledge (knowing why), with semiotic competence serving as the bridge between these types of knowledge.

The significant correlation ($r = 0.76$, $p < 0.01$) between semiotic interpretation ability and performance on contextual problem-solving tasks provides empirical Cachero et al. (2020) *Sociocultural* perspective on mathematical learning, which positions symbols as cultural tools that mediate between abstract mathematical concepts and their applications in authentic contexts. This relationship underscores the central role of semiotics in developing the adaptive reasoning component of mathematical proficiency, as conceptualized revised framework of mathematical competence.

Furthermore, the observed disparity between schools (Makale Christian Junior High School: 73.2 vs. Kandora Christian Junior High School: 68.4) highlights the contextual sensitivity of semiotic development, that institutional and instructional factors significantly influence students' ability to navigate between representational systems. This finding has important implications for educational equity, suggesting that inconsistent exposure to semiotic-focused instruction may contribute to achievement gaps in mathematical literacy.

The findings of this research provide both theoretical and practical insights into the role of semiotic competence in fostering mathematical literacy within the Merdeka Curriculum. Theoretically, the study confirms that Peirce's semiotic triadic model—comprising representation, object, and interpretant—can be operationalized into measurable components that reflect students' cognitive processes in interpreting mathematical symbols. The consistent performance gradient from basic symbol recognition to contextual application indicates that semiotic competence develops hierarchically, supporting the notion that understanding symbolic meaning is foundational to higher-order reasoning. This aligns with Bergqvist et al. (2023) and DiSessa (2018)*; however, the present study extends these frameworks by demonstrating how semiotic reasoning can be directly embedded into assessment practice, rather than being* treated as an abstract cognitive construct. Practically, the positive correlation between semiotic interpretation and problem-solving performance ($r = 0.76$, $p < 0.01$) highlights that interpretive reasoning is not ancillary but central to mathematical literacy—an implication that calls for explicit inclusion of semiotic elements in classroom assessments and instructional design.

Despite its success in establishing a valid and reliable semiotic assessment instrument, this study acknowledges certain limitations that warrant further exploration. One significant limitation lies in the contextual dependency of students' semiotic performance—particularly their difficulty transferring symbolic understanding to novel or unfamiliar problems. This may stem from structural factors in Indonesia's mathematics curriculum, which still tends to emphasize procedural mastery over interpretive depth, as well as from teachers' limited exposure to semiotics-based pedagogy. Furthermore, while the *Merdeka Curriculum* encourages autonomy and contextual learning, many schools have yet to translate these goals into concrete assessment practices. The discrepancy observed between schools (Makale and Kandora) suggests that teacher expertise and learning culture have a significant impact on the development of semiotic reasoning. Comparative studies, such as those by Rizki et al. (2018) and Ahmad et al. (2021), have also noted similar contextual variability, yet they did not investigate its pedagogical roots. This study thus contributes a more nuanced explanation by linking these performance gaps to differences in instructional emphasis and assessment literacy among teachers.

The implications for educational practice are substantial. Teachers can integrate the semiotic assessment instrument as both a formative and diagnostic tool, allowing immediate feedback on students' symbolic reasoning during learning activities. For instance, teachers may administer short, semiotic-based tasks at the end of a lesson to identify whether students interpret symbols conceptually or procedurally, enabling them to provide targeted remedial support. Moreover, the instrument can guide differentiated instruction, where students who struggle with interpretation receive scaffolded visual or contextual representations before progressing to abstract reasoning. Incorporating this instrument into classroom-based assessments also fosters reflective teaching, enabling educators to monitor how instructional strategies impact students' semiotic growth over time. On a broader scale, curriculum developers and teacher educators can employ this instrument as a model for designing future assessments that capture deeper learning processes—bridging the gap between curriculum goals and classroom realities while strengthening Indonesia's movement toward authentic, meaning-centered mathematics education.

The effectiveness of the revised assessment instrument in improving student performance across all categories (basic understanding: +8.3%, concept interpretation: +12%, application: +8.5%) demonstrates the potential of semiotically-oriented assessments to serve not only evaluative but also formative functions. The argument is that well-designed assessment tools can function as "bridge-builders" between procedural fluency and conceptual understanding by making explicit the connections between symbols, concepts, and applications. Research on mathematical modeling, which identified interpretive activities as critical mediating processes between abstract mathematical structures and their real-world instantiations (Sanford & Naidu, 2017).

The research also revealed persistent challenges in students' ability to transfer semiotic understanding to unfamiliar contexts, *an* observation that the application of symbolic knowledge in novel situations represents the highest level of mathematical literacy (Amir et al., 2023). This challenge *highlights the need for* instructional *approaches that explicitly scaffold students' ability to generalize their understanding of semiotics* across diverse contextual domains.

4. CONCLUSION

This study concludes that the developed semiotic assessment instrument based on mathematical literacy is valid, reliable, and effectively aligned with the goals of the *Merdeka Curriculum*. The integration of Peirce's semiotic theory provides a strong framework for assessing students' ability to interpret and construct mathematical meaning. The instrument enhances students' conceptual understanding, interpretive reasoning, and contextual problem-solving skills. For teachers, it serves as a formative diagnostic tool to identify misconceptions and design targeted remedial strategies. For curriculum developers, the findings underscore the importance of integrating semiotic competence as a central learning trajectory in mathematics education. Policymakers can utilize these results to promote authentic assessment models that value both interpretive reasoning and procedural accuracy. The study also recommends future expansion across different grade levels and the integration of digital-based assessment for broader accessibility. Overall, this research contributes to transforming mathematics assessment toward a more meaning-centered and competency-based paradigm.

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