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DIGITAL LITERACY IN GEO-SHEET-ASSISTED ANALYTIC GEOMETRY LEARNING AMONG PRE-SERVICE MATHEMATICS TEACHERS

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Abstrak

Meningkatnya integrasi teknologi dalam pendidikan matematika menegaskan pentingnya memahami literasi digital mahasiswa dalam pembelajaran berbasis teknologi. Penelitian ini bertujuan untuk mendeskripsikan profil literasi digital calon guru matematika dalam pembelajaran geometri analitik berbantuan Geo-Sheet. Literasi digital dikonseptualisasikan ke dalam empat dimensi, yaitu sikap belajar, sosial-emosional, teknis, dan kognitif. Penelitian ini menggunakan pendekatan *mixed methods* dengan desain *explanatory sequential* melalui integrasi data kuantitatif dari angket literasi digital dan data kualitatif dari respons terbuka, observasi kelas, serta wawancara terhadap 31 calon guru matematika. Hasil penelitian menunjukkan bahwa skor literasi digital berada pada kategori tinggi hingga sangat tinggi pada keempat dimensi. Dimensi sikap belajar (M = 4,35; SD = 0,71), sosial-emosional (M = 4,45; SD = 0,62), dan kognitif (M = 4,41; SD = 0,57) termasuk dalam kategori sangat tinggi, sedangkan dimensi teknis berada pada kategori tinggi (M = 3,84; SD = 0,90). Temuan kualitatif menunjukkan Geo-Sheet mendukung proses verifikasi visual yang membantu mahasiswa membandingkan representasi, mengidentifikasi ketidaksesuaian, dan menyempurnakan solusi yang diperoleh. Mahasiswa juga memanfaatkan Geo-Sheet untuk menginterpretasikan, mengevaluasi, dan memvalidasi representasi matematis, yang menunjukkan keterlibatan bermakna dalam penggunaan teknologi digital. Namun demikian, performa pada dimensi teknis masih bervariasi yang dipengaruhi oleh penguasaan fitur, keterbatasan perangkat, dan kualitas koneksi internet. Temuan penelitian ini menunjukkan bahwa literasi digital dalam pembelajaran matematika tidak hanya berkaitan dengan kemampuan teknis menggunakan teknologi, tetapi juga berhubungan erat dengan proses penalaran melalui kegiatan interpretasi, perbandingan, dan validasi representasi matematis. Oleh karena itu, pembelajaran berbasis teknologi perlu dirancang untuk mendukung pengembangan literasi digital sekaligus penalaran matematis dalam pendidikan calon guru.

Kata kunci: Geometri analitik; Literasi digital; Geo-Sheet; Calon guru matematika; Pembelajaran berbasis GeoGebra

Abstract

The increasing integration of technology in mathematics education highlights the importance of understanding students' digital literacy in technology-supported learning. This study aims to describe the digital literacy profile of pre-service mathematics teachers in Geo-Sheet-assisted analytic geometry learning. Digital literacy was conceptualized into four dimensions: learning attitude, social-emotional, technical, and cognitive. A mixed-methods approach with an explanatory sequential design was employed by integrating quantitative data from a digital literacy questionnaire and qualitative data from open-ended responses, classroom observations, and interviews involving 31 pre-service mathematics teachers. The results indicate high to very high scores across the four dimensions of digital literacy. The learning attitude (M = 4.35, SD = 0.71), social-emotional (M = 4.45, SD = 0.62), and cognitive dimensions (M = 4.41, SD = 0.57) were categorized as very high, whereas the technical dimension was categorized as high (M = 3.84, SD = 0.90). Qualitative findings reveal that Geo-Sheet supports visual verification processes that help students compare representations, identify discrepancies, and refine their solutions. Students also used Geo-Sheet to interpret, evaluate, and validate mathematical representations, indicating meaningful engagement with digital tools. However, technical performance varied according to feature mastery, device limitations, and internet connectivity. The findings suggest that digital literacy in mathematics learning extends beyond technical competence and is closely associated with students' engagement in reasoning processes involving the interpretation, comparison, and validation of mathematical representations. This study highlights the importance of designing technology-supported learning environments that foster both digital literacy and mathematical reasoning in teacher education.

Keywords: Analytic Geometry; Digital Literacy; Geo-Sheet; Pre-Service Mathematics Teachers; Geogebra-Based Learning

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INTRODUCTION

In mathematics education, the increasing use of digital representations has fundamentally transformed how mathematical concepts are explored, visualized, and understood. In particular, domains such as analytic geometry require the coordination of algebraic and geometric representations, making digital environments an essential medium for supporting students' understanding, interpretation, and evaluation of mathematical representations. Consequently, technology integration in mathematics learning is no longer limited to facilitating instruction but plays a critical role in supporting conceptual understanding as well as the interpretation, evaluation, and validation of mathematical representations.

Within this context, digital literacy has become an essential competence for prospective mathematics teachers. Digital literacy extends beyond operational proficiency and encompasses the ability to critically interpret digital representations, analyze mathematical relationships, evaluate the validity of solutions, and construct meaning from abstract concepts in digital environments (Dewi et al., 2025; Hasyim & Kurniawati, 2021; Rahmawati et al., 2022; Reddy et al., 2020; Septia & Wahyu, 2023; Yani T. et al., 2025). However, previous studies indicate that pre-service teachers often view digital literacy mainly as technical proficiency rather than as a critical practice involving interpretation and evaluation of digital representations (Labor & Escandallo, 2024; List, 2019). This limited perspective may hinder the meaningful integration of digital tools in mathematics learning.

It is important to distinguish between digital literacy and digital competence, as these terms are often used interchangeably. Digital competence generally refers to a broader set of knowledge, skills, and attitudes required for the effective use of technology, including technical, pedagogical, and ethical dimensions (UNESCO, 2018). In contrast, digital literacy emphasizes individuals' ability to critically engage with, interpret, and evaluate digital information. In mathematics education, this distinction is particularly significant, as digital literacy involves the ability to connect visual and symbolic representations and to support evaluation and validation of mathematical representations within digital environments (Althubyani, 2024; Gbormittah et al., 2024; Hillmayr et al., 2020; Techataweewan & Prasertsin, 2018).

Several digital literacy frameworks have been proposed, including DigComp (Vuorikari et al., 2022), JISC Digital Capabilities (JISC, 2022), and UNESCO's ICT Competency Framework (UNESCO, 2018). While these frameworks provide comprehensive descriptions of digital competence across educational and professional contexts, they are designed to assess broad digital skills. In contrast, this study focuses on how pre-service mathematics teachers engage with digital representations in analytic geometry through Geo-Sheet, requiring a framework that emphasizes operational, cognitive, collaborative, and attitudinal aspects of technology use.

Accordingly, this study adopts the framework of Techataweewan & Prasertsin (2018), which comprises four domains: operation, thinking, collaboration, and awareness skills. Although originally developed for Thai undergraduates, these domains align closely with GeoGebra-supported mathematics learning. Operation skills relate to using GeoGebra tools, thinking skills to interpreting and validating mathematical representations, collaboration skills to digital interaction, and awareness skills to students' attitudes toward technology-supported learning. To fit the context of Indonesian pre-service mathematics teachers in analytic geometry, these domains were operationalized as four dimensions: technical, cognitive, social-emotional, and learning attitude. This adaptation enables digital literacy to be examined in relation to students' interpretation, evaluation, and validation of mathematical representations in a dynamic digital environment.

Despite its importance, empirical evidence indicates that digital literacy remains suboptimal. Studies show that students' digital literacy levels are generally moderate and are often constrained by limited experience in using digital tools for meaningful learning and problem solving (Herlina et al., 2023; Purnamasari et al., 2021; Purwanto & Rusmining, 2024; Taheri & Pennington, 2024). For instance, (Purnamasari et al., 2021) reported that students' digital literacy has not been optimally developed due to insufficient integration of technology in student-centered learning environments. Furthermore, studies involving pre-service mathematics teachers reveal that digital literacy does not necessarily correlate with mathematical literacy, suggesting that the ability to use digital tools does not automatically translate into meaningful understanding or the ability to interpret and evaluate mathematical representations (Yani T. et al., 2025). These findings indicate that digital literacy, when not explicitly connected to disciplinary practices, may remain superficial and disconnected from meaningful engagement with mathematical concepts.

To address the gap between digital literacy and meaningful engagement with mathematical representations, learning environments that integrate visualization and analytic processes are required. One way to achieve this is through the use of digital technologies that support interactive engagement with mathematical representations, such as GeoGebra. GeoGebra is widely recognized as an effective tool for learning analytic geometry, as it enables dynamic interaction with mathematical objects and supports the coordination of multiple representations (Salsanabila et al., 2024; A. Yildiz et al., 2017; E. Yildiz & Arpaci, 2024). Previous studies have shown that GeoGebra enhances conceptual understanding, visual representation skills, and student engagement, as well as supports the development of students' mathematical literacy in classroom settings (Herlina et al., 2023; Himmi et al., 2024; Zutaah et al., 2023). However, its use is often limited to exploratory or demonstrative functions, and its potential to support deeper engagement in interpreting, comparing, and validating mathematical representations is not always fully realized. This suggests that the effectiveness of GeoGebra depends not merely on its use as a technological tool, but on how it is pedagogically integrated to support students' interaction with and evaluation of mathematical representations.

Moreover, several studies have explored the use of GeoGebra-assisted learning to improve students' mathematical literacy and learning outcomes. While these studies demonstrate the potential of digital tools in supporting mathematics learning, they predominantly emphasize effectiveness and achievement, with comparatively limited attention to students' cognitive engagement during interaction with digital environments (Hillmayr et al., 2020; Maulidiya & Aziza, 2024; Sunzuma, 2023). This indicates the need for more process-oriented investigations that examine how learners construct meaning, verify solutions, and engage in the interpretation and evaluation of mathematical representations within digital contexts.

Unlike previous studies that primarily focus on improving students' mathematical literacy and learning outcomes through GeoGebra-assisted instruction, the present study examines how digital literacy is reflected in students' cognitive engagement, particularly in processes of interpretation, comparison, and visual verification within dynamic digital environments. Despite the growing body of research on GeoGebra integration, empirical evidence remains limited regarding how GeoGebra-based learning materials contribute to the development of digital literacy in relation to students' interaction with mathematical representations. Existing studies tend to emphasize technology adoption, effectiveness, or user perceptions, rather than examining how digital engagement supports interpretation, comparison, and validation processes (Liu et al., 2025; Musasa et al., 2025; Sudihartinih et al., 2025; Susanto et al., 2023; Yohannes & Chen, 2023). Furthermore, research on structured digital materials such as GeoGebra-based worksheets, including Geo-Sheets, is still relatively scarce, particularly in the context of analytic geometry learning (Rahim et al., 2023).

In response to this gap, the present study investigates the use of GeoGebra-based learning materials, referred to as Geo-Sheet. Geo-Sheet is a GeoGebra-based interactive web worksheet designed to support students' exploration, visualization, and verification in analytic geometry learning. Geo-Sheet are designed to facilitate students' interaction with dynamic mathematical representations, enabling them to explore geometric relationships, compare representations, and verify analytic solutions within a digital environment. This study adopts a mixed-methods approach to examine how digital literacy is manifested through pre-service mathematics teachers' engagement with digital representations, with a particular focus on processes of interpretation, evaluation, and visual verification.

Based on the above background, the research questions of this study are formulated as follows:

RQ1. How is digital literacy manifested across the technical, cognitive, social-emotional, and learning attitude dimensions among pre-service mathematics teachers in Geo-Sheet-assisted analytic geometry learning?

RQ2. How do pre-service mathematics teachers use Geo-Sheet to interpret, compare, and validate mathematical representations within a digital learning environment?

METHOD

This study was conducted at Universitas PGRI Madiun, East Java, Indonesia, during the even semester of the 2024-2025 academic year. The study employed a mixed-methods approach with an explanatory sequential design to examine pre-service mathematics teachers' digital literacy in analytic geometry learning using Geo-Sheet (Creswell & Clark, 2017). The overall research procedure following the explanatory sequential mixed-methods design is illustrated in Figure 1.

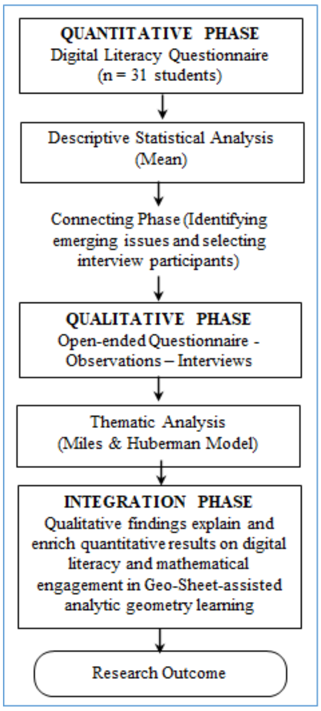

Figure 1. The Explanatory Sequential Mixed-Methods Design

Figure 1 illustrates the research flow of the explanatory sequential mixed-methods design adopted in this study. Following the quantitative analysis, qualitative data were collected sequentially through open-ended questionnaire responses, classroom observations, and semi-structured interviews. The open-ended responses were used to identify students' experiences and challenges when using Geo-Sheet. Classroom observations were subsequently conducted to examine how these experiences were manifested during learning activities and to identify participants for further exploration. Finally, semi-structured interviews were conducted to obtain a deeper understanding of students' engagement with digital tools and mathematical representations.

The learning material used in this study was Geo-Sheet, a GeoGebra-based interactive web worksheet designed to support students' analytic exploration and visual verification in analytic geometry learning. The Geo-Sheet was validated by four experts in mathematics education and instructional media, focusing on content suitability, presentation, language, and alignment with teaching material development principles. The validation results indicated that the Geo-Sheet was in the "valid" category and suitable for instructional use (Masfingatin et al., 2026).

The Geo-Sheet intervention was conducted over five sessions during a period of five weeks. Each session lasted approximately 2 x 50 minutes and was integrated into regular analytic geometry instruction.

The digital literacy indicators used in this study were adapted from (Techataweewan & Prasertsin, 2018), who conceptualized digital literacy through operation, thinking, collaboration, and awareness skills. In the context of analytic geometry learning supported by GeoGebra, these indicators were operationalized into four dimensions: technical, cognitive, social-emotional, and learning attitude. These dimensions were used to capture students' digital engagement and learning experiences when interacting with digital learning environments. To operationalize the framework in this study, the mapping between the original digital literacy components and the adapted dimensions is presented in Table 1.

Table 1. Mapping of Digital Literacy Framework

No.	Original Skills	Adapted Dimensions	Description
1.	Operation	Technical	Ability to operate GeoGebra and digital tools effectively
2.	Thinking	Cognitive	Ability to analyze, interpret, and verify mathematical representations
3.	Collaboration	Social-emotional	Ability to interact and collaborate responsibly in digital environments
4.	Awareness	Learning attitude	Motivation and disposition toward using technology for learning

The participants were 31 pre-service mathematics teachers enrolled in an analytic geometry course at Universitas PGRI Madiun. All students in one intact class participated in the study. The class was selected because it represented a technology-supported learning environment in which Geo-Sheet was systematically integrated into instruction. Specifically, the course incorporated Geo-Sheet as part of the learning design, students had prior experience using GeoGebra, and the learning activities focused on analytic geometry topics requiring coordination between algebraic and geometric representations.

Quantitative data were collected using a Likert-scale questionnaire designed to measure students' digital literacy in technology-supported learning. The instrument was developed based on the digital literacy framework consisting of learning attitude, social-emotional, technical, and cognitive dimensions adapted from Techataweewan & Prasertsin (2018). The questionnaire comprised five items representing the four dimensions of the framework. To establish content validity, the instrument was reviewed by two experts in mathematics education and educational technology, who evaluated the relevance, clarity, and representativeness of each item in relation to the intended dimensions. Revisions were made based on their feedback. The overall internal consistency of the questionnaire was assessed using Cronbach's Alpha, yielding a coefficient of $\alpha = 0.855$, indicating satisfactory reliability for descriptive research purposes.

Quantitative data were analyzed using descriptive statistics by calculating mean scores for each digital literacy indicator (Boone & Boone, 2012). The results were categorized into five levels: very low (1.00–1.79), low (1.80–2.59), sufficient (2.60–3.39), high (3.40–4.19), and very high (4.20–5.00) (Pepito & Acledan, 2022). The quantitative results were used to guide the selection of interview participants. Students were grouped into digital literacy levels based on their questionnaire scores, and those categorized as high and very high were purposively selected for the qualitative phase. This approach is consistent with the explanatory sequential design, where qualitative data are used to provide deeper insights into the patterns identified in the quantitative findings.

Qualitative data were obtained through semi-structured interviews, classroom observations documented in field notes, and an open-ended questionnaire to explore students' learning experiences and challenges when using Geo-Sheet. The interview and observation protocols were developed based on the research objectives and the digital literacy framework. To ensure content validity, these qualitative instruments were also reviewed by two experts in mathematics education, and revisions were made to improve the clarity and relevance of the guiding questions. Semi-structured interviews were conducted with three students selected based on classroom observations to represent different patterns of engagement with Geo-Sheet-assisted learning. The selected students demonstrated varying experiences in interacting with digital tools, interpreting mathematical representations, and addressing challenges encountered during learning. The observation data enabled the researcher to identify students who exhibited diverse patterns of interaction with Geo-Sheet and different responses to technology-supported learning tasks. Nevertheless, because the interview participants were selected from a limited number of observed cases, the qualitative findings may not fully represent the experiences of all students, particularly those who may encounter greater difficulties when using digital learning tools.

Qualitative data were analyzed thematically using the Miles and Huberman model (Miles et al., 2014), which consists of three stages: data reduction, data display, and conclusion drawing. Integration was achieved by connecting quantitative results with qualitative findings. The quantitative data were used to identify patterns of digital literacy levels, while qualitative data were used to explain these patterns by examining students' cognitive processes during interaction with Geo-Sheet.

Ethical approval for this study was obtained from Universitas PGRI Madiun. All participants provided informed consent prior to data collection. Anonymity and confidentiality were maintained throughout the study.

RESULT AND DISCUSSION

This section presents the results and discussion of the study by integrating quantitative and qualitative data to describe the digital literacy of pre-service mathematics teachers in Geo-Sheet-based analytic geometry learning. Quantitative data from questionnaires provide an overview of students' digital literacy levels, while qualitative data from open-ended responses, interviews, and classroom observations are used to deepen the interpretation of how digital literacy is manifested in students' engagement with digital representations.

The results are organized into four interconnected dimensions of digital literacy: overall digital literacy profile, learning attitude and social-emotional dimensions, technical dimensions, and cognitive dimensions. This organization enables a comprehensive understanding of how Geo-Sheet supports students' engagement, interaction, technical operation, and the interpretation, evaluation, and validation of mathematical representations. The discussion in each subsection connects empirical findings with relevant perspectives in digital literacy and mathematics education.

This subsection presents an overall profile of pre-service mathematics teachers' digital literacy based on their experiences using Geo-Sheet in analytic geometry learning. The profile was constructed through the integration of quantitative data from digital literacy questionnaires and qualitative evidence derived from open-ended responses, classroom observations, and interviews. The questionnaire results are summarized in Figure 2.

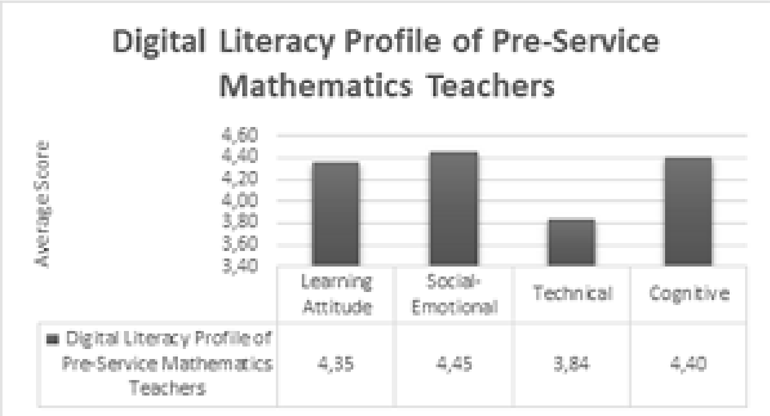

Figure 2. Digital Literacy Profile of Pre-Service Mathematics Teachers Using Geo-Sheet

Figure 2 provides an initial overview of the digital literacy profile, indicating that learning attitude, social-emotional, and cognitive dimensions achieved very high scores, while the technical dimension was comparatively lower, though still within the high category. To provide a more detailed quantitative representation, mean scores, standard deviations (SD), and category levels for each dimension are presented in Table 2.

Table 2. Digital Literacy Levels by Dimension

No.	Dimension	Description	Mean	SD	Category
1.	Learning attitude	Motivation to use GeoGebra in learning	4.35	0.71	Very High
2.	Social-emotional	Collaboration and peer interaction	4.45	0.62	Very High
3.	Technical	Ability to operate GeoGebra tools	3.84	0.90	High
4.	Cognitive	Ability to analyze and verify mathematical representations	4.41	0.57	Very High

As shown in Table 2, all dimensions of digital literacy achieved mean scores within the high to very high categories. The learning attitude, social-emotional, and cognitive dimensions demonstrate very high mean scores, indicating strong engagement, collaboration, and meaningful use of digital tools for interpreting and evaluating mathematical representations. In contrast, the technical dimension, although still categorized as high, obtained a comparatively lower mean score and slightly higher variability, suggesting differences in students' operational familiarity with GeoGebra. However, these variations should be interpreted with caution, as each dimension was measured using a limited number of indicators.

The relatively higher standard deviation in the technical dimension indicates greater variation among students, reflecting differences in prior experience, technological familiarity, and access to digital tools. Previous studies have shown that students' digital skills are influenced by practical exposure, repeated interaction with technology, and the availability of technological resources, which together contribute to disparities in ICT competence (González-Laguna et al., 2026; Hillmayr et al., 2020; Onyema et al., 2026). In contrast, the lower variability observed in the cognitive dimension suggests more consistent engagement in processes of interpretation, evaluation, and visual verification, as supported by studies highlighting the role of dynamic mathematical environments in strengthening conceptual understanding and evaluative thinking (Althubyani, 2024; Gbormittah et al., 2024; Khalil et al., 2019).

These findings align with previous research in digital literacy and technology-supported learning, which indicates that pre-service teachers generally exhibit strong digital competence in environments that support problem solving, communication, collaboration, and information literacy (Rahim et al., 2023). Similarly, Prachagool et al. (2022) reported that pre-service teachers demonstrate high levels of digital literacy across dimensions such as social responsibility, team-based learning, information management, and digital integrity. Positioned within this broader literature, the present results reinforce the view that digital literacy among future teachers develops through meaningful engagement with digital learning contexts.

These quantitative findings are further explained through qualitative data, which provide insight into how digital literacy is manifested in students' learning processes during analytic geometry learning. Students consistently described Geo-Sheet as a digital learning medium that supported conceptual understanding through visualization and interaction. Many responses emphasized that visual representations helped make abstract concepts more accessible and easier to interpret. As one student noted, "*In my opinion, the use of GeoGebra-based Geo-Sheets makes it very easy to learn analytical geometry because the visualization makes the concept clearer*." This indicates that visualization functions not only as a representational aid but also as a support for meaning-making and conceptual validation in analytic geometry.

Students also demonstrated a tendency to use Geo-Sheet as a verification tool for confirming analytic solutions. Participants frequently reported using GeoGebra visualizations to compare and evaluate the correctness of their work. For example, one student stated, "*With Geo-Sheet, I can check if my answer is correct or not through the image in GeoGebra*." This pattern suggests that students engaged in an evaluative use of digital tools, where visualization supported the interpretation and validation of mathematical representations rather than more procedural execution.

Classroom observations further revealed that students remained actively engaged despite these constraints. When encountering technical or conceptual difficulties, students frequently sought peer assistance or experimented with alternative constructions. This adaptive behavior suggests that the overall digital literacy profile is supported by positive learning attitudes and social-emotional interactions that help mitigate technical limitations.

Taken together, the findings portray digital literacy among pre-service mathematics teachers as a multifaceted construct encompassing dispositional readiness, collaborative engagement, and evaluative use of digital tools, while technical proficiency varies according to experience and learning infrastructure. This overarching profile establishes an empirical foundation for understanding digital literacy as an integrated construct, which is further elaborated through the detailed examination of each dimension in the following subsections.

The learning attitude and social-emotional dimensions describe how students engage affectively and interpersonally in Geo-Sheet-based learning. The learning attitude dimension achieved a mean score of 4.35 (SD = 0.71), while the social-emotional dimension reached 4.45 (SD = 0.62), both categorized as very high. These results indicate strong motivation, persistence, and collaborative engagement among students.

Qualitative evidence shows that students perceived GeoGebra visualization as making analytic geometry learning more engaging and accessible. Several students consistently reported that visualization reduced the abstract nature of symbolic representations, enabling them to explore concepts more actively. This finding is consistent with previous research reporting that GeoGebra-enhanced learning environments increase students' interest and motivation in analytic geometry (Listiani et al., 2024; Raisatunnisa et al., 2025; Sugandi et al., 2021; Uwurukundo et al., 2024). In this context, visualization functions not only as a representational tool but also as a cognitive entry point that facilitates early understanding, which in turn strengthens motivation and sustained engagement.

Furthermore, Geo-Sheet appears to support exploratory and reflective learning attitudes. Students reported that, despite initial difficulties, particularly among those with limited prior experience, they remained engaged because Geo-Sheet allowed them to verify their solutions through visual representations. Such findings align with studies showing that inquiry-based and technology-supported learning environments can strengthen emotional engagement and persistence (Hadi & Faradillah, 2022), as well as improve learning effectiveness through ICT integration (Sudihartinih et al., 2025). More specifically, prior research has demonstrated that the use of GeoGebra not only enhances engagement but also contributes to improved mathematical achievement through interactive exploration and conceptual understanding (Zulnaidi et al., 2020). Although the present study does not directly measure achievement, these findings suggest that increased engagement and persistence may function as supporting conditions for more effective learning processes.

From a social-emotional perspective, Geo-Sheet promoted collaborative learning through peer interaction. Classroom observations revealed that students frequently engaged in discussions when interpreting visual outputs, comparing constructions, and resolving discrepancies between analytic and graphical representations. These interactions provided social support, reduced anxiety, and facilitated shared understanding.

This pattern indicates that digital literacy in this context extends beyond individual competence to include meaningful participation in collaborative digital environments, in line with broader conceptualizations proposed by UNESCO (2018) and OECD (2022). This interpretation is further supported by research showing that communication and collaboration are significant predictors of digital practices in teaching, highlighting the central role of social interaction in digital literacy development (Zhang et al., 2024). In this sense, the present study highlights that collaborative engagement is not merely a supporting factor, but an integral component of digital literacy that shapes how students construct and apply mathematical understanding through digital tools.

However, it is important to consider alternative explanations for these findings. The high self-reported scores in learning attitude and social-emotional engagement may be influenced by social desirability bias, as students may tend to report positive perceptions of technology-enhanced learning environments (Boone & Boone, 2012). Additionally, the observed engagement may partially reflect a Hawthorne effect, where students increase their participation due to awareness of being observed. Therefore, while the findings indicate strong affective and social engagement, they should be interpreted with caution and in conjunction with qualitative evidence.

The technical dimension of digital literacy in this study refers to students' ability to operate Geo-Sheet and GeoGebra features effectively during analytic geometry learning. The questionnaire results indicate that the technical dimension achieved a mean score of 3.84 (SD = 0.90), categorized as high, but lower than the learning attitude, social-emotional, and cognitive dimensions.

The relatively high standard deviation (SD = 0.90) indicates considerable variability among students, suggesting uneven levels of prior experience and operational familiarity with digital tools. This finding implies that while most students were able to use Geo-Sheet to support learning activities, technical proficiency was not uniformly distributed across participants. A small number of students reported lower confidence when using specific GeoGebra features, particularly during initial interactions, indicating differences in technological readiness rather than a lack of engagement.

Qualitative data further clarify these patterns. Students consistently reported experiencing initial difficulties when using certain GeoGebra tools embedded in Geo-Sheet, particularly due to limited prior exposure to the software. This pattern was also confirmed during interviews, where one participant (S2) explained that they needed additional time to become familiar with construction commands before being able to use the tools confidently. Rather than indicating persistent barriers, these challenges were typically transitional, suggesting that technical digital literacy develops progressively through interaction with the learning environment.

In addition to individual familiarity, technical challenges were influenced by external factors such as internet connectivity and device limitations. Several students noted that unstable connections occasionally disrupted dynamic visualization, while smaller mobile screens reduced precision when manipulating geometric objects. These constraints occasionally affected efficiency but did not prevent students from engaging with mathematical tasks. This pattern indicates that technical performance is shaped not only by individual competence but also by infrastructural conditions.

Classroom observations further revealed that students demonstrated adaptive behaviors when encountering operational difficulties. Instead of disengaging, students explored alternative commands, repeated constructions, and sought assistance from peers until the intended visualization was achieved. Such behaviors reflect a form of technical resilience, where students actively negotiate challenges within digital environments. Importantly, these interactions also show that technical engagement is closely linked to collaborative processes, reinforcing the social-emotional dynamics identified in the previous subsection.

Beyond basic operation, students increasingly used Geo-Sheet strategically to support learning. In particular, they employed digital tools to verify analytic results and confirm geometric relationships, indicating that technical competence functioned as an enabling condition for deeper mathematical engagement. In this sense, technical digital literacy is not limited to procedural skills, but extends to purposeful and goal-directed use of digital tools within problem-solving contexts.

These findings align with previous research indicating that students are generally capable of using digital media in mathematics learning, but may initially face challenges in transforming software use into meaningful learning support (Herlina et al., 2023). Similarly, (Soeparno & Ismaniati, 2022) highlight that technical challenges are often shaped by external factors such as connectivity and device availability. The present study extends these perspectives by demonstrating that technical digital literacy emerges from the interaction between individual skills, learning context, and technological infrastructure.

However, it is important to interpret these findings with caution. The technical dimension is based partly on self-reported data, which may not fully capture actual operational competence. In addition, observed improvements in technical performance may be influenced by repeated exposure to Geo-Sheet during the learning sessions, rather than representing stable proficiency. Therefore, while the results indicate generally high levels of technical engagement, they should be understood as context-dependent and subject to situational factors.

As technical barriers diminished over time, students were able to shift their focus toward interpreting geometric relationships and verifying analytic solutions. This transition suggests that technical competence plays a foundational role in enabling deeper cognitive engagement, which is further discussed in the following subsection.

Building on the affective, social, and technical dimensions described earlier, the cognitive dimension focuses on how students use digital tools to evaluate, interpret, and validate mathematical representations through the integration of analytic reasoning and GeoGebra-based visualization within Geo-Sheet. Questionnaire results indicate that this dimension achieved a mean score of 4.41 (SD = 0.57), categorized as very high. This suggests that students perceived digital tools not merely as computational aids, but as resources that support evaluation and validation of mathematical representations and validation processes.

Qualitative evidence provides deeper insight into how this cognitive dimension manifested during learning activities. A consistent pattern observed across tasks was students' use of Geo-Sheet to verify analytic solutions obtained through manual calculations. When discrepancies emerged between symbolic results and visual outputs, students revisited their procedures, identified errors, and refined their reasoning until consistency was achieved. This pattern was also reflected in interview data, where one participant (S1) explained that when the visual result did not match the analytic solution, they returned to their calculations to check for mistakes and ensure alignment between representations. This iterative process indicates that digital tools supported reflective evaluation rather than passive acceptance of results.

A similar pattern appeared when students encountered differences in algebraic representations. In several cases, students did not immediately interpret such discrepancies as errors; instead, they evaluated whether different equations represented the same geometric object by comparing their visual representations. Another participant (S3) noted during the interview that even when equations appeared different, they focused on whether the resulting geometric constructions were equivalent. Through this process, students demonstrated representational fluency and the ability to recognize conceptual equivalence, indicating more developed evaluative and representational engagement supported by digital tools.

Classroom observations further showed that students engaged in analytic reasoning when constructing geometric objects that required coordination between algebraic and geometric perspectives. During tasks involving power of a point and radical axis constructions, students occasionally encountered unexpected visual outputs. Rather than relying on trial-and-error adjustments, they analyzed the underlying relationships and modified their constructions accordingly. This interplay between symbolic reasoning and visual interpretation illustrates how Geo-Sheet mediated the refinement of mathematical ideas through continuous validation.

Importantly, these findings indicate that visualization did not replace analytic reasoning; rather, it reorganized how students evaluated mathematical validity. Digital representations encouraged students to question results, examine inconsistencies, and justify conclusions, thereby supporting reflective awareness during problem-solving processes. The very high cognitive score therefore reflects students' capacity to use digital tools for testing assumptions, detecting errors, and consolidating understanding.

These results are consistent with previous studies identifying GeoGebra as a form of digital scaffolding that supports mathematical thinking through interaction with dynamic representations (Khalil et al., 2018, 2019). The present study extends this perspective by showing that such scaffolding not only facilitates visualization, but also supports evaluative reasoning and representational judgment, particularly in contexts requiring alignment between analytic and visual representations.

Building on the affective, social, and technical conditions described in the previous subsections, the cognitive dimension captures how students use digital tools to evaluate and validate mathematical understanding.

Taken together, the findings suggest that digital literacy in Geo-Sheet-based analytic geometry learning operates as an integrated and interdependent construct. Positive learning attitudes and supportive social-emotional interactions create the conditions that enable students to engage productively with digital tools, while technical competence provides the operational foundation for participation. Within this framework, the cognitive dimension reflects students' ability to evaluate, interpret, and validate mathematical representations through the coordinated use of analytic reasoning and visualization.

This interrelationship indicates that the role of digital tools extends beyond facilitating access or efficiency, toward shaping how students engage with, interpret, and verify mathematical ideas. In this context, digital literacy can be understood as a cognitive–socio-technical practice in which students use digital tools not only to perform procedures, but also to support reflective evaluation and conceptual understanding.

CONCLUSION

This study examined the digital literacy of pre-service mathematics teachers in Geo-Sheet-assisted analytic geometry learning through four interrelated dimensions: learning attitude, social-emotional, technical, and cognitive. The findings indicate that digital literacy in technology-supported mathematics learning extends beyond the operational use of digital tools. Rather, it involves students' ability to interpret, compare, evaluate, and validate mathematical representations while engaging with dynamic digital environments.

A key contribution of this study is the demonstration that digital literacy in mathematics education should be understood as a context-dependent construct that is closely intertwined with mathematical reasoning processes. While previous studies have often emphasized technical competencies and general digital skills, the present findings show that the cognitive dimension of digital literacy emerges through students' engagement with multiple mathematical representations and their use of digital tools to verify and refine solutions. This suggests that digital literacy and mathematical reasoning develop in a mutually supportive manner within technology-enhanced learning environments.

For mathematics teacher education, the findings imply that digital tools should be integrated not merely as visualization aids but as resources for promoting interpretation, comparison, and validation of mathematical ideas. Teacher educators may therefore design learning activities that require pre-service teachers to move between algebraic and geometric representations, evaluate inconsistencies, and justify solutions using dynamic visual feedback. Such experiences can help future teachers develop both digital literacy and meaningful pedagogical uses of technology in mathematics classrooms.

Several limitations should be acknowledged. First, the questionnaire was designed to provide a descriptive profile of digital literacy and was supported by expert-reviewed content validity; however, evidence of construct validity through factor-analytic procedures was not examined because of the small sample size and the use of single-item indicators for several dimensions. Second, the qualitative phase involved only three interview participants selected based on observed classroom engagement, all of whom subsequently fell within the high and very high questionnaire score categories. Consequently, the findings may not fully represent the experiences of students with less positive digital literacy profiles or those who encounter greater technical difficulties when using digital learning tools. Future research should involve larger and more diverse participant groups, employ more comprehensive measurement instruments, and examine digital literacy across different mathematical topics and technology-supported learning environments.

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