ijonse International Journal on Studies in Education
www.ijonse.net

The Regulating and Mediating Roles of Digital Competencies on Science Literacy in PISA: The Impacts of ICT Use within and beyond School

Mehmet Haldun Kaya [1] *, Mehmet Akın Bulut [2], Volkan Hasan Kaya [3]

[1] İzmir University of Economics, Türkiye, 0000-0002-0276-4886
[2] Ibn Haldun University, Türkiye, 0000-0002-7506-8750
[3] Ministry of National Education, Türkiye, 0000-0002-8991-0187
* Corresponding author: Mehmet Akın Bulut (akin.bulut@ihu.edu.tr)

Article Info

Article History

Received:
29 October 2025

Revised:
27 February 2026

Accepted:
14 March 2026

Published:
22 March 2026

Keywords

PISA
ICT literacy
Digital literacy
Science literacy

Abstract

Although information and communication technologies (ICT) in education has been widely studied, the specific ways digital competencies and varying ICT use patterns influence science literacy remain insufficiently underexplored. The rapid evolution of the digital age has made ICT an essential component of learning, yet effective digitalization requires more than technological access, it demands the development of students' digital competencies, encompassing skills in information access, analysis, communication, and problem-solving. These competencies are vital not only for academic success but also for participation in a technology-driven society. Science education offers a critical setting for exploring this relationship, as it inherently fosters both digital competencies and science literacy, defined as the capacity to understand, evaluate, and apply scientific knowledge in real-world contexts. International assessments such as the Programme for International Student Assessment (PISA) demonstrate the importance of digital tools in enhancing scientific reasoning and conceptual understanding. However, the extent to which different ICT use contexts, within school, beyond school, and across time, mediate or regulate the impact of digital competencies on science literacy remains unclear. This study investigates (1) the direct effects of students' digital competencies on science literacy, (2) the mediating roles of digital inquiry-based learning (ICTINQ) and subject-related ICT use (ICTSUBJ), and (3) the regulating roles of extracurricular ICT use (ICTECA), regulated school use (ICTREG), and temporal use patterns (ICTWKDY, ICTWKEND). By clarifying these relationships, the research addresses a critical gap in understanding how digital engagement supports scientific reasoning and problem-solving in modern education.

Citation: Kaya, M. H., Bulut, M. A., & Kaya, V. H. (2026). The regulating and mediating roles of digital competencies on science literacy in PISA: The impacts of ICT use within and beyond school. *International Journal on Studies in Education (IJonSE), 8*(3), 575-598. https://doi.org/10.46328/ijonse.5954

Introduction

The fast space of the digital age made the effective use of ICT compulsory, not a luxury for anyone. Digitization in education not only refers to the use of technologies but also developing students ‘digital competencies and integrating such competencies into instructional processes (Voogt & Roblin, 2012). Digital competencies could be identified as a set of multidimensional skills involving the basic abilities of accessing and analyzing information, solving problems and communicating effectively (Ferrari, 2013). The importance of such competencies cannot be downgraded to academic success only as they are key to becoming an effective individual in almost every aspect of today’s modern life (Adiguzel et al., 2023; Adıgüzel et al., 2023).

Science education improves students’ science literacy and digital competencies through the opportunities provided in this digital age. Science literacy refers to individuals’ comprehension, evaluation and implementation of scientific knowledge in living conditions (Bybee, 2010; Göçemen, 2023). The integration of digital technologies into science education helps to improve students’ scientific reasoning skills and to comprehend scientific concepts better (Fraillon et al., 2014). Thus, the interplay between digital competencies and science literacy has been growing more important in educational studies and research (Birgili et al., 2025; Bulut et al., 2026).

This interplay between digital competencies and science literacy is clearly evident in testing models like Programme for International Student Assessment (PISA). PISA is an OECD-run test that assesses the capabilities of 15-year-old students in mathematics, science, and reading. PISA not only evaluates student performance but also analyzes how this knowledge can be implemented when solving real-life problems (Yeniçeri & Bulut, 2023). PISA's assessments of scientific literacy also emphasize the role that digital skills possess in this process. Digital tools help students to access scientific information more quickly and use it effectively. The contributions of digital technologies, particularly in inquiry-based learning and problem-solving processes, are clearly obvious in analyses carried out within the PISA framework (Nasırcı & Kerkez, 2023), which highlights the necessity of supporting science education in the digital age with digital literacy skills. Research has shown that use of digital tools to promote inquiry-based learning interactions (ICTINQ) and subject-matter access (ICTSUB) could have a strong effect on science literacy, both directly and indirectly (Scherer & Siddiq, 2015).

How frequent digital tools are utilized in education transpires as another important factor in understanding their effects on science literacy. For example, the use of ICT in extracurricular activities (ICTECA) helps students develop their abilities to access digital information and integrate it into their daily lives. The regulated use of ICT within school settings (ICTREG) encourages the effective utilization of digital tools for pedagogical purposes. Meanwhile, use of ICT tools during weekdays (ICTWKDY) and weekend (ICTWKEND) emerges as a temporal variable determining the intensity of this process. This research aims to investigate the impact of the frequency of digital tool use on scientific literacy within the context of PISA, focusing on analyzing the 'regulating roles' of these variables. In addition, it seeks to examine the impact of students' digital competencies on science literacy and investigate the 'mediating roles' of digital tools in this relationship. The connections between digital literacy and science literacy are critical so as to comprehend the way students develop scientific thinking and problem-solving skills.

Research Questions

This study aims to answer the following key questions:

1. What is the impact of students' digital competencies on science literacy?
2. How do the mediating roles of digital inquiry-based learning activities (ICTINQ) and the use of subject-related digital tools (ICTSUBJ) affect science literacy?
3. How do the regulating roles of digital tool use (ICTECA, ICTREG, ICTWKDY, ICTWKEND) affect science literacy?
4. How do the connections between digital literacy and science literacy shape students' scientific thinking and problem-solving skills?

Literature Review

Definition and Significance of Digital Competencies

Digital competence refers to an individual's ability to use digital technologies creatively, ethically, and effectively across various contexts (Göçen & Bulut, 2024). This multidimensional concept includes many diverse skills such as the capacity to access, manage, and critically analyze digital information, solve problems in innovative ways, and participate in technology-mediated collaborative work (Ferrari, 2013). As an indispensable component of 21st-century skills, digital competence has been required to address the needs of the evolving global world (Binkley et al., 2012). The integration of digital competencies into educational settings is of paramount importance to make students ready to navigate contemporary society effectively (Bulut et al., 2025; Karanfiloğlu & Bulut, 2025). Particularly, science education presents itself as a model platform to promotes these competencies. Through digital tool integration, students can access and critically engage with scientific information in meaningful ways, enhancing both their conceptual understanding and their capacity for scientific inquiry and problem-solving (Ertmer & Ottenbreit-Leftwich, 2013). Research shows that digital competencies facilitate inquiry-based learning approaches and help students to explore hypotheses and test ideas, which contributes to comprehensive conceptual understanding (Voogt & Roblin, 2012).

The significance and impact of digital competencies go beyond formal instructional contexts as its scope encompasses lifelong learning settings as well. The capacity to access, analyze, and synthesize digital information substantially enhances individuals' abilities to engage in problem-solving, inference-drawing, and research throughout their lives (Vuorikari et al., 2016). For instance, professionals utilizing digital tools for continuous development can more effectively participate in interdisciplinary collaboration and adapt to technological advancement. Furthermore, these competencies are crucial for informed decision-making in daily life, such as evaluating online source credibility and engaging in digital citizenship activities (Carretero et al., 2017).

Science Literacy

Science literacy involves an individual's capacity to comprehend, evaluate, and incorporate scientific knowledge into decision-making processes and daily life, integrating critical thinking and problem-solving capabilities

(Bybee, 2010). This concept extends beyond mere access to scientific information as it also involves the ability to contextualize and apply such knowledge in practical and social frameworks. The significance of science literacy manifests in its empowerment of individuals to make informed decisions regarding crucial societal challenges, including healthcare, environmental sustainability, and energy conservation. For instance, epidemiological understanding enables informed assessment of vaccine efficacy, while knowledge of renewable energy technologies facilitates advocacy for sustainable practices.

As the use of digital technologies gets more widespread, science literacy has turned into a framework integrated with digital skills. Digital competencies are pivotal in fostering students' scientific literacy. For instance, digital tools enable students to access scientific information more quickly and efficiently (Janssen et al., 2013). They also provide tools for critical evaluation of scientific data and engagement in evidence-based reasoning (Rocard et al., 2007). Interactive learning environments, simulations, and visualization tools foster comprehension of complex scientific principles through dynamic, experiential learning processes. These digital resources support inquiry-based learning methodologies, enabling students to explore hypotheses and develop sophisticated problem-solving capabilities (Fraillon et al., 2014).

The PISA acknowledges the multidimensional composure of science literacy through comprehensive evaluations across three domains: content knowledge (of biology, physics, and chemistry), process skills (including scientific methodology comprehension and application), and contextual understanding (connecting scientific principles to real-world scenarios) (Göçemen, 2023). Research indicates these assessments effectively measure conceptual understanding and problem-solving capabilities across diverse educational contexts. Moreover, the integration of digital tools in pedagogical practices, particularly in inquiry-based learning activities in science education, demonstrates significant enhancement of students' critical thinking and application skills (Nasırcı & Kerkez, 2023).

The Mediating Roles of Digital Competencies

The use of digital technologies in education mainly relies on the way these technologies are integrated and the pedagogical contexts in which they are utilized. Especially in science education, the effective use of digital tools increases students' active participation in scientific processes. The two main ways of using digital technologies in education are hard to miss in inquiry-based learning activities (ICTINQ) and processes related to accessing subject-specific knowledge (ICTSUBJ).

Use of ICT In Inquiry-Based Learning (ICTINQ)

Inquiry-based learning (INQ) in science education is a pedagogical method which turns students into active learners who determine scientific problems, create hypotheses, and analyze data through critical thinking and problem-solving. This method emphasizes hands-on experiences and learner-centered inquiry to develop a deeper understanding of scientific concepts and processes (Hmelo-Silver et al., 2007).

ICT tools and platforms, such as laboratory simulations, interactive experiments, and data visualization platforms, play a crucial role in inquiry-based learning by enabling learners to actively explore, test hypotheses, and visualize abstract scientific concepts, thereby making them more concrete and comprehensible. These technologies allow students to experiment with and visualize data in ways that would be difficult to replicate in traditional INQ learning environments (Bell et al., 2010; Linn et al., 2014). Digital tools and environments also enable collaboration as students get assistance when analyzing data and testing hypothesis in their group work. These tools and platforms both enhance individual and collective learning and improve teamwork and problem-solving skills (Hämäläinen et al., 2018). Recent studies confirm that ICT integration improves research skills, digital literacy, and engagement in STEM and STEAM education (Hiğde & Aktamış, 2023; Sánchez & Cortés Orduna, 2024). ICTINQ plays a critical role in the development of critical thinking skills and prepares students for a technology-driven world. By blending inquiry with digital tools, educators can cultivate deeper scientific understanding and digital competency, advancing 21st-century educational goals.

Integration of ICT in Subject Teaching (ICTSUBJ)

The integration of ICT in subject teaching (SUBJ) facilitates students' access to information and enables them to comprehend scientific concepts. The use of ICT allows students to effectively engage with the target topics. ICT tools and platforms accelerate the process of accessing scientific information by enabling them to utilize this knowledge in various contexts. These practices enhance both digital literacy and scientific literacy, preparing students for the demands of an increasingly interconnected and technologically driven world (Scherer & Siddiq, 2015). Additionally, ICT makes the learning pace appropriate for individual learners, which helps them to progress at their own speed. This way, these tools address the diverse needs of learners and yield more satisfactory educational outcomes (Kozma, 2011; Scherer & Siddiq, 2015).

Interactive educational ICT supports learners' understanding of complicated scientific concepts by making abstract ideas visual. For instance, the 3D visuals of biological processes or the virtual demonstrations of physics experiments present concrete representations that help students comprehend target concepts better. Moreover, real-time feedback systems actively engage students in the learning process, enabling them to identify and address gaps in their understanding promptly. This approach fosters active participation and self-regulation in learning (Looi et al., 2011). This approach based on individualized data both contributes to personalized learning and improves autonomous learning skills. The ability to access and utilize digital resources fosters a culture of self-directed learning, which is critical in contemporary education (Ertmer & Ottenbreit-Leftwich, 2013).

PISA includes interactive tasks to evaluate learners' skills in organizing information, communicating in digital environments, and demonstrating digital literacy skills. This process measures both the passive use of ICT and their active role in problem-solving and creative thinking. PISA's digital tasks aim to make learners ready for real-world scenarios by assessing their ability to collect, analyze, and present information in an organized way from online sources (Milner-Bolotin, 2023). The process of measuring digital competence is not different from 21st-century skills like communication, collaboration, creativity, and innovation. PISA tests present a comprehensive framework that assesses learners' skills to manage group work scenarios and create solutions (Maxim, 2023).

The Regulating Roles of Digital Competencies

The use of ICT has an effective regulatory role in students' learning processes. The impact of this role changes depending on the frequency and contexts where learners use these digital tools. The use of ICT in extracurricular activities (ICTECA) enhances students' development of individual learning and their interdisciplinary thinking skills. Janssen et al. (2013) point out that use of ICT this way can improve students' complex competencies like scientific literacy. ICTECA enables learners to learn at their own pace and contributes to their problem-solving processes.

Regulated in-school use of ICT (ICTREG) also supports learning processes through planned activities guided by teachers. In this context, the integration of ICT for instructional aims makes goal-oriented learning experiences richer and more meaningful. Passey (2014) states that regulated use of digital tools in schools enhances learners ‘achievement of instructional objectives and serves as an effective medium to improve science literacy.

The regulatory role of ICT is also related to ‘time’. Weekday ICT use (ICTWKDY) aims to reinforce course content and support in-class learning activities. On the other hand, weekend ICT use (ICTWKEND) helps learners focus on personal exploration and learning activities. Fraillon et al. (2014) underline the importance of regular and balanced use. Likewise, Looi et al. (2011) also highlight that excessive use cold have a negative impact on learning motivation and focus.

In this context, the regulatory role of ICT is structured by its frequency and context of use. That role could have a positive influence on learning processes when structured in alignment with students' learning needs. This shows that ICT might serve as an effective instrument to achieve targeted learning objectives.

Connections Between Digital Literacy and Science Literacy

The literature shows that there are strong connections between digital and science literacy. Digital literacy helps learners improve their abilities to access information, have a critical lens, and find creative solutions to problems. Science literacy contributes to the implementation of these skills within scientific settings. The effective use of digital tools in these processes improves learners’ scientific reasoning skills and problem-solving abilities (Hinostroza et al., 2016).

Blending digital skills with science education presents students with rich and meaningful learning experiences. It is highlighted that digital and science literacy are complementary (Tondeur et al., 2016). On the one side of the coin, digital technologies contribute to science education by optimizing learning processes and improving student performance. For example, digital simulations used in laboratory experiments enable students to better understand intricate concepts and support the tangible application of these concepts (Bell et al., 2010). On the other side of the coin, the focus on teaching STEM subjects has necessitated the development of digital teaching materials and platforms that improve digital literacy by encouraging critical thinking and problem-solving. This two-way relationship shows that the needs of science education catalyze innovations in digital tools and increase digital literacy standards (Rahman et al., 2023).

Moreover, digital tools enhance opportunities for collaborative learning, enabling students to develop teamwork skills. These tools provide students with the necessary support to better grasp scientific concepts and apply this knowledge to generate creative solutions. The pedagogically sound integration of digital technologies into science education improves its quality and bolsters students' academic success.

Methodology

Research Design

This study employs a quantitative research design to examine the relationship between students' digital competencies (ICTEFFIC) and their science literacy (SCILIT) through mediating and moderating effects analysis. A mediation and moderation analysis framework was applied using data from PISA 2022, a large-scale international assessment that evaluates student competencies in reading, mathematics, and science. The PISA dataset includes detailed responses to context questionnaires, allowing for an in-depth exploration of students' engagement with digital tools in different learning contexts.

The study adopts a structural equation modeling (SEM) approach, employing multiple regression analysis to estimate direct, indirect, and interaction effects. A bootstrapping technique was used to validate the significance of mediation pathways, ensuring robust inferential validity. A regression analysis based on the bootstrap method was employed to test the hypotheses.

Specifically, the PROCESS macro developed by Hayes (2022) was utilized for analyzing the mediation and moderation effects. Bootstrapping was used to estimate the confidence intervals (CI) for the indirect effects, with the criterion that the 95% CI should not include zero to support the hypotheses (MacKinnon et al., 2004). This approach was particularly effective in examining serial mediation models and comparing the magnitude of different indirect effects.

Participants

The study sample consists of 6,566 students from diverse educational backgrounds in Eastern Europe, selected from the PISA 2022 database. The dataset provides a representative cross-section of students with varying levels of economic, social and cultural status (ESCS) and digital engagement. Science literacy scores, derived using Plausible Values (PVs), serve as the primary outcome measure, ensuring a reliable estimation of students' proficiency levels.

Data Collection Tool and Measures

The *ICT Familiarity Questionnaire* is an internationally optional instrument within the PISA 2022 assessment, designed to measure students' access to, use of, and attitudes toward information and communication technology

(ICT).

IRT-Scaled Derived Variables

- **ICTSCH** and **ICTHOME:** Frequency-based indices measuring ICT availability in and outside school, respectively.
- **ICTSUBJ:** Extent of ICT integration in subject-specific lessons.
- **ICTENQ:** Use of ICT for inquiry-based learning activities (e.g., multimedia creation, project tracking).
- **ICTOUT:** ICT use for school-related tasks outside the classroom (e.g., checking grades, teacher communication).
- **ICTWKDY** and **ICTWKEND:** Frequency of ICT-based leisure activities during weekdays and weekends, respectively.
- **ICTREG:** Students' attitudes toward regulated ICT use at school (e.g., device restrictions, Internet filters).
- **ICTEFFIC:** Self-efficacy in digital competencies, assessing confidence in performing ICT-related academic and practical tasks.

Each scale employed multi-item Likert-type or frequency-based response formats, with items recoded as needed for analysis. Reliability (Cronbach's α) and item parameters were reported for international comparability, and non-administered or suppressed scales were coded systematically (e.g., "97" or "99" in datasets). The study incorporates a total of six independent, dependent, mediating, and moderating variables, each derived from PISA 2022 context questionnaires and performance assessments (PISA, 2022). The independent variable in this study is students' self-efficacy in digital competencies (ICTEFFIC), which measures their confidence in using digital tools for learning and scientific problem-solving. The dependent variable is science literacy (SCILIT), measured using PISA's Item Response Theory (IRT)-scaled assessment scores, which evaluate students' ability to apply scientific knowledge in real-world contexts.

Two mediating variables are included: ICT use in inquiry-based learning activities (ICTENQ), which assesses students' engagement with digital tools for research and exploration, and subject-related digital tool use (ICTSUBJ), which captures the extent to which students utilize digital technologies in subject-specific learning activities. The moderating variables include ICT use frequency on weekdays (ICTWKDY), weekends (ICTWKEND), school-related ICT use outside the classroom (ICTOUT), and students' perceptions of regulated ICT use in school (ICTREG). These variables provide insight into how different digital engagement patterns influence the relationship between ICT competencies and science literacy. To control for potential confounding effects, the study also includes students' socioeconomic status (ESCS) and gender as control variables.

Data Analysis

The study employs multiple regression analysis using the PROCESS macro (Model 6 and Model 1) developed by Hayes (2022) to test the mediation and moderation hypotheses. The analysis is conducted in SPSS 28.0, allowing for the estimation of direct, indirect, and moderated effects. Before conducting the analyses, the dataset was prescreened to ensure compliance with key assumptions:

- Linearity was assessed through scatterplots of residuals.
- Normality was verified using the Kolmogorov-Smirnov and Shapiro-Wilk tests.
- Homoscedasticity was checked through residual plots.
- Multicollinearity was examined using the Variance Inflation Factor (VIF) criterion, ensuring that all predictors had VIF values below 5.

To test the mediation effects, regression models were run to determine whether ICTENQ and ICTSUBJ significantly mediate the relationship between ICTEFFIC and SCILIT. The bootstrapping method with 10,000 resamples was used to estimate bias-corrected 95% confidence intervals (CI) for indirect effects. A mediation effect was considered statistically significant if the CI did not include zero. For the moderation effects, interaction terms were created between ICTEFFIC and each moderating variable (ICTWKDY, ICTWKEND, ICTOUT, and ICTREG). The significance of the interaction terms was assessed using hierarchical regression models, with statistically significant interactions indicating that the effects of ICTEFFIC on SCILIT vary depending on ICT usage context.

Results

Direct and Indirect Effects (H)

The regression analysis using bootstrap confidence intervals revealed that students' digital self-efficacy (ICTEFFIC) had a statistically significant indirect effect on science literacy (SCILIT) through both ICTENQ and ICTSUBJ:

H1: ICTEFFIC Positively Affects SCILIT through ICTENQ

H2: ICTEFFIC Positively Affects SCILIT through ICTSUBJ

Specifically, the indirect effect through ICTENQ was -2.369 with a confidence interval of [-2.870, -1.913], while the indirect effect through ICTSUBJ was 1.237, with a confidence interval of [0.841, 1.648]. Since the confidence intervals did not include zero, H1 and H2 were supported, confirming that both digital inquiry-based learning and subject-related ICT use play significant roles in mediating the relationship between digital self-efficacy and science literacy.

H1: ICTEFFIC Positively Affects SCILIT through ICTENQ

The analysis showed a significant positive effect of ICTEFFIC on SCILIT through ICTENQ, supporting H1. The indirect effect of ICTEFFIC on SCILIT via ICTENQ was -2.369, with a confidence interval of [-2.870, -1.913], confirming the mediating role of digital inquiry-based learning. This indicates that students who are confident in their digital skills are more likely to engage in ICT-driven inquiry-based learning, which, in turn, improves their science literacy.

H2: ICTEFFIC Positively Affects SCILIT through ICTSUBJ

The analysis also supported H2, as the indirect effect of ICTEFFIC on SCILIT via ICTSUBJ was 1.237, with a confidence interval of [0.841, 1.648]. This suggests that students with high digital self-efficacy actively use subject-specific digital tools, which positively impacts their science literacy. Unlike inquiry-based learning, which fosters critical thinking, subject-related digital tool use enhances students' ability to apply scientific knowledge within structured curricula.

Serial Mediation Effect (H)

The results further demonstrated that ICTENQ and ICTSUBJ functioned as serial mediators between ICTEFFIC and SCILIT. The serial indirect effect was 0.600, with a confidence interval of [0.469, 0.742], supporting H3. This suggests that students who feel more confident in their digital skills are more likely to engage in ICT-based inquiry learning, which in turn may facilitate their use of subject-specific digital tools, anticipated to enhance their science literacy.

Comparison of Indirect Effects (H)

A comparison of the mediated pathways revealed that the indirect effect of ICTEFFIC on SCILIT via ICTENQ was significantly different from its effect via ICTSUBJ. The difference between the two indirect effects was -3.6062, with a confidence interval of [-4.2625, -2.9742], supporting H4. Further analysis indicated that the indirect effect of ICTEFFIC on SCILIT via ICTENQ differed significantly from the serial indirect effect via both ICTENQ and ICTSUBJ. The difference was -2.9691, with a confidence interval of [-3.5482, -2.4134], supporting H5. Similarly, the indirect effect via ICTSUBJ was different from the serial indirect effect, with a difference of 0.6371 and a confidence interval of [0.2415, 1.0490], supporting H6.

Moderating Effects (H)

The moderation analyses assessed the role of ICT usage patterns in shaping the relationship between ICTEFFIC and SCILIT. The results indicated that as the frequency of ICT use on weekdays (ICTWKDY) and weekends (ICTWKEND) decreased, the positive effect of ICTEFFIC on SCILIT increased. These findings supported H7 and H8, suggesting that students who use digital tools less frequently outside of school may derive greater benefits from structured digital learning environments. Similarly, H9 and H10 were supported, as lower levels of ICT use outside of school (ICTOUT) and perceptions of regulated ICT use (ICTREG) strengthened the relationship between ICTEFFIC and SCILIT. This implies that flexible and less-restrictive ICT policies in schools might enhance the positive impact of digital competencies on science literacy.

Hypothesis Testing and Analysis

The study examined ten hypotheses (H1-H10) concerning the relationships between students' digital self-efficacy (ICTEFFIC), science literacy (SCILIT), ICT use for inquiry-based learning (ICTENQ), subject-related ICT use (ICTSUBJ), and the moderating effects of ICT usage frequency (ICTWKDY, ICTWKEND, ICTOUT) and regulation (ICTREG). The results from mediation and moderation regression analyses are presented in Table 1.

Table 1. Regression Analysis Results for Mediation Test (N=6566)

	Outcome Variables								
	M 1 (ICTENQ)			M2 (ICTSUBJ)			Y (SCI-LIT)(Outcome)		
Estimated Variables		*b*	SH		*b*	SH		*b*	SH
X (ICTEFFIC)	*a1*	*.191****	*.013*	*a2*	.081***	.012	*c'*	10,653***	.874
M 1 (ICTENQ)	-	-	-	-	-	-	*b1*	-12.42***	.833
M2 (ICTSUBJ)	-	.-	-	-	-	-	*b2*	15,233***	.934
Still	I_{M1}	-.484***	.049	I_{M2}	.550***	.042	I_R	503,975***	
	R2 = .048			*R2 = .045*			*R2 = .187*		
	F (3,6562)= 110.2830, p<.001			F (3,6562)= 103.0828, p<.001			F (5,6560)= 300.9215 p<.001		

Note. * p<.05, ** p<.01, *** p<.001; SE: Standard Error. Unstandardized beta coefficients (b) are reported. Control Group (s): ESCS GENDER

The confidence intervals are obtained with the bootstrap technique.

H1: ICTEFFIC Positively Affects SCILIT through ICTENQ

The analysis showed a significant positive effect of ICTEFFIC on SCILIT through ICTENQ, supporting H1. The indirect effect of ICTEFFIC on SCILIT via ICTENQ was -2.369, with a confidence interval of [-2.870, -1.913], confirming the mediating role of digital inquiry-based learning. This indicates that students who are confident in their digital skills are more likely to engage in ICT-driven inquiry-based learning, which, in turn, improves their science literacy.

H2: ICTEFFIC Positively Affects SCILIT through ICTSUBJ

The analysis also supported H2, as the indirect effect of ICTEFFIC on SCILIT via ICTSUBJ was 1.237, with a confidence interval of [0.841, 1.648]. This suggests that students with high digital self-efficacy actively use subject-specific digital tools, which positively impacts their science literacy. Unlike inquiry-based learning, which fosters critical thinking, subject-related digital tool use enhances students' ability to apply scientific knowledge within structured curricula.

H3: ICTEFFIC, SCI LIT, ICTENQ, and ICTSUBJ Act in a Serial Mediation Process

A serial mediation analysis confirmed that ICTENQ and ICTSUBJ together mediate the relationship between ICTEFFIC and SCILIT. The serial indirect effect was 0.600, with a confidence interval of [0.469, 0.742], supporting H3. This finding suggests that digital self-efficacy does not directly enhance science literacy; rather, it fosters engagement in inquiry-based ICT learning, which then leads to greater use of subject-specific digital tools, ultimately improving science literacy outcomes.

H4: The Indirect Effect of ICTEFFIC on SCILIT via ICTENQ Is Different from the Indirect Effect via ICTSUBJ

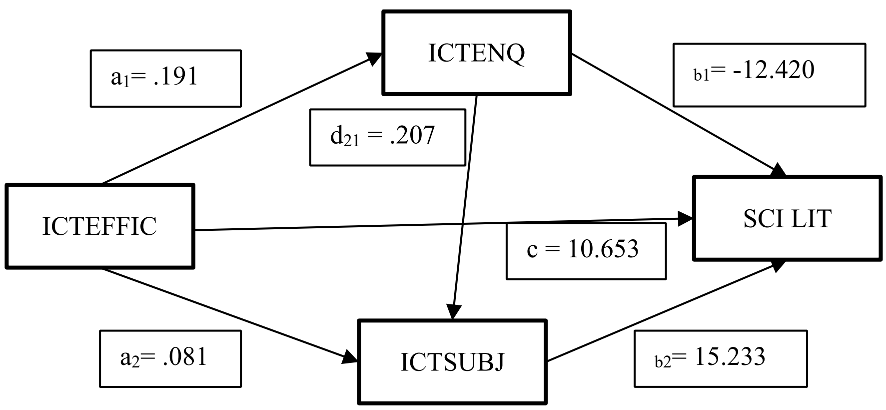
Hypothesis H4 tested whether the indirect effects of ICTENQ and ICTSUBJ differed in their contributions to SCILIT. The difference between the two indirect effects was -3.6062, with a confidence interval of [-4.2625, -2.9742], confirming statistical significance. This suggests that ICTENQ has a stronger influence on science literacy than ICTSUBJ, as engagement in digital inquiry-based learning contributes more significantly to critical thinking and problem-solving skills than subject-specific ICT use.

H5: The Indirect Effect of ICTEFFIC on SCILIT via ICTENQ Is Different from the Serial Indirect Effect (ICTENQ → ICTSUBJ → SCILIT)

The results showed that the indirect effect of ICTEFFIC on SCILIT via ICTENQ alone was significantly different from the serial indirect effect involving both ICTENQ and ICTSUBJ. The difference was -2.9691, with a confidence interval of [-3.5482, -2.4134], supporting H5. This suggests that while ICTENQ alone contributes to science literacy, the sequential combination of inquiry-based learning and subject-related ICT use produces a more robust impact on students' scientific thinking skills.

H6: The Indirect Effect of ICTEFFIC on SCILIT via ICTSUBJ Is Different from the Serial Indirect Effect (ICTENQ → ICTSUBJ → SCILIT)

Hypothesis H6 was also supported, with a difference of 0.6371 and a confidence interval of [0.2415, 1.0490], indicating that ICTSUBJ alone does not fully account for the impact of ICTEFFIC on science literacy. Instead, students first engage in ICT-based inquiry learning before incorporating subject-specific ICT tools, reinforcing the layered impact of digital self-efficacy on science literacy.



Direct effect (c') = 10.653 $p < .001$
Indirect effect (serial mediation effect)=.600, %95 GA [.469, .742]

Control Group (s): ESCS GENDER

Figure 1. Serial Mediation Effect Analysis

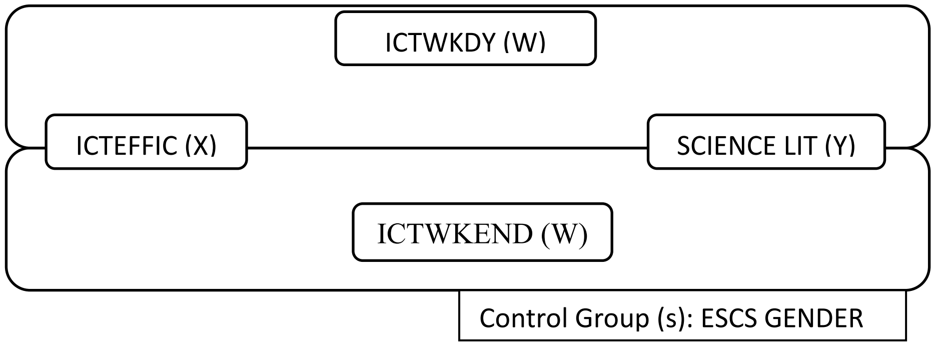


Figure 2. Conceptual Representation of the Moderation Effect Model (Hypotheses H7 and H8)

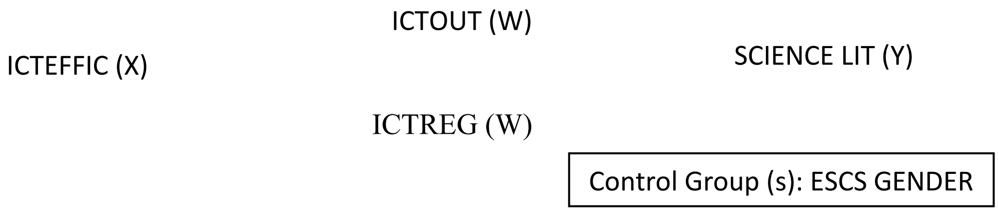


Figure 3. Conceptual Representation of the Moderation Effect Model (H9 and H10 Hypotheses)

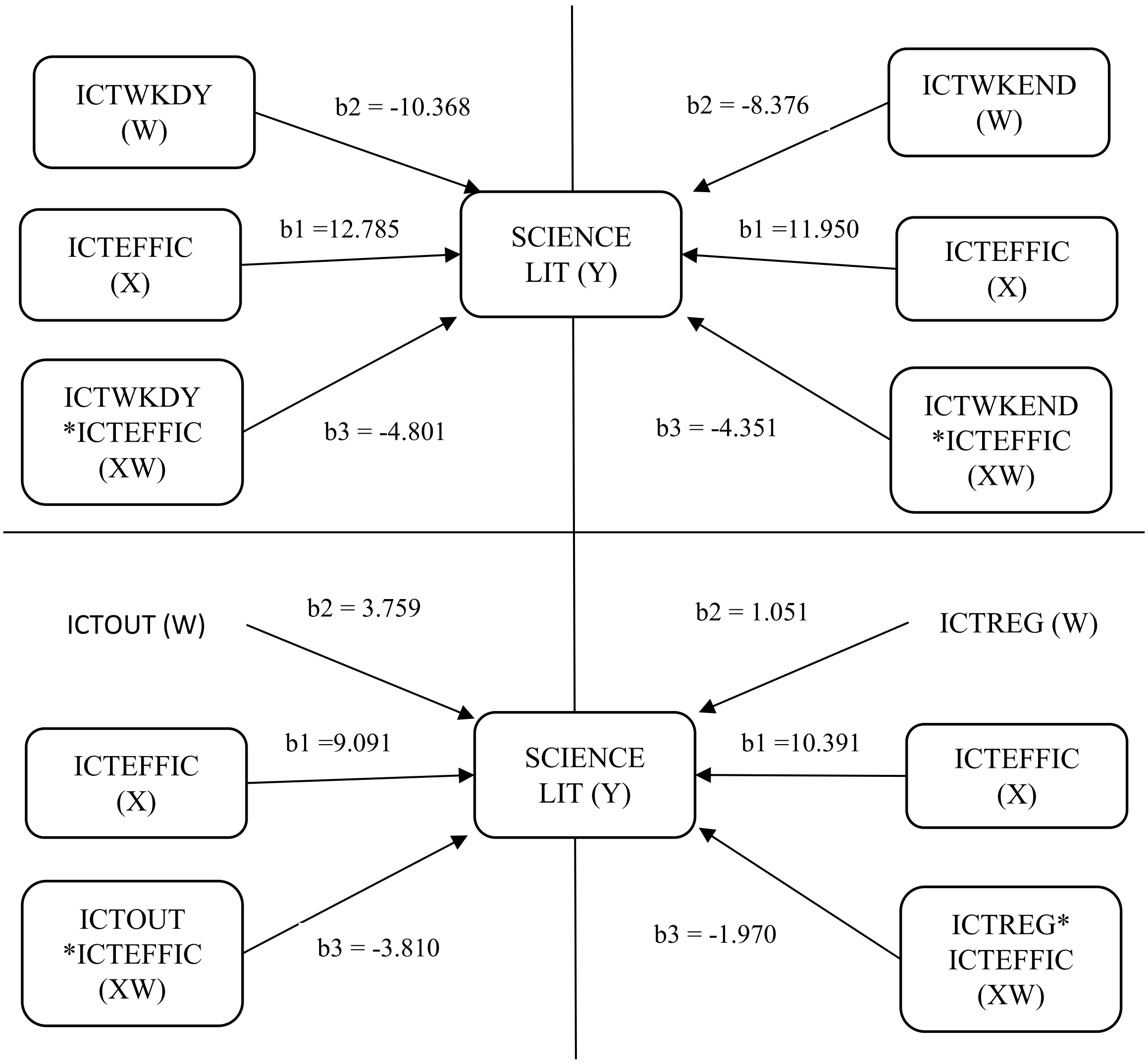


Figure 4. Displaying Results on Statistical Diagram

According to the analysis results carried out with Model 1 analysis as seen in Figure 1-2-3-4, as the durations of ICTWKDY, ICTWEKEND, ICTOUT and ICTREG decrease, the positive effect of ICTEFFIC on SCIENCE LIT increases. Therefore, the effect of ICTEFFIC on SCIENCE LIT is higher in students who use ICTWKDY, ICTWEKEND, ICTOUT and ICTREG at low levels (compared to those who use them at high levels).

H7: ICTWKDY Moderates the Relationship Between ICTEFFIC and SCILIT

A significant moderation effect was found for ICTWKDY, supporting H7. The results indicate that the positive effect of ICTEFFIC on SCILIT is stronger among students who use ICT less frequently on weekdays. This suggests that excessive ICT use during school days may not necessarily enhance science literacy and that structured, moderate engagement may be more effective.

H8: ICTWKEND Moderates the Relationship Between ICTEFFIC and SCILIT

Similarly, H8 was supported, showing that the impact of ICTEFFIC on SCILIT is stronger for students who use ICT less frequently on weekends. This indicates that students who rely on ICT for academic purposes rather than excessive leisure-based digital engagement benefit more from their digital competencies in science education.

H9: ICTOUT Moderates the Relationship Between ICTEFFIC and SCILIT

The findings also support H9, confirming that students who use ICT less frequently for school activities outside the classroom show a stronger effect of ICTEFFIC on SCILIT. This suggests that students who develop structured digital learning habits within the school environment benefit more from their ICT competencies than those who rely heavily on self-directed digital learning outside formal education settings.

H10: ICTREG Moderates the Relationship Between ICTEFFIC and SCILIT

Finally, H10 was supported, showing that ICTEFFIC has a greater positive impact on SCILIT when students perceive lower levels of ICT regulation in schools. This indicates that overly restrictive ICT policies may limit students' ability to fully leverage their digital competencies, whereas more flexible digital learning environments foster a stronger connection between ICTEFFIC and science literacy.

Discussion

The findings of this study provide valuable insights into the complex relationship between students' digital competencies (ICTEFFIC) and science literacy (SCILIT), highlighting the mediating roles of inquiry-based ICT use (ICTENQ) and subject-related digital tool use (ICTSUBJ), as well as the moderating effects of ICT use frequency in different contexts (ICTWKDY, ICTWKEND, ICTOUT, and ICTREG). The results indicate that students who exhibit higher self-efficacy in digital skills tend to achieve better science literacy outcomes, but this relationship is not direct. Instead, it is largely facilitated by engagement in ICT-based inquiry learning and the use of subject-specific digital tools during instruction.

A key finding of the study is that ICTENQ and ICTSUBJ act as significant mediators, meaning that students with strong digital self-efficacy are more likely to engage in inquiry-driven digital learning, which subsequently increases their use of subject-specific digital tools, ultimately leading to higher science literacy scores. This aligns with prior research indicating that digital inquiry-based learning promotes critical thinking and scientific reasoning by enabling students to explore scientific concepts through interactive digital platforms (OECD, 2023). Moreover, the serial mediation effect suggests that digital tools used for exploratory and inquiry-driven purposes serve as a gateway to deeper engagement with science subjects, reinforcing the argument that technology should be embedded in pedagogically meaningful ways rather than used as an isolated tool. The impact of digital skills on students' understanding of complex scientific concepts is significant, as evidenced by various studies that highlight the role of technology in enhancing learning outcomes. Digital tools, such as cognitive maps and immersive environments, facilitate deeper engagement with scientific content, leading to improved conceptual understanding and reasoning skills. The use of digital cognitive maps in teacher education has shown to enhance meaningful learning of scientific concepts, as students who engaged in collaborative construction of these maps demonstrated improved representation strategies for complex scientific knowledge (Turmo, 2023). The visual scaffolding provided by these maps supports students in resolving socio-scientific challenges, indicating that digital skills can foster critical thinking and problem-solving abilities. Similarly, virtual environments designed for learning complex topics, such as Newtonian mechanics, have been found to improve students' mastery of abstract concepts, as these immersive experiences engage multiple senses, which can enhance understanding (Dede et al., 1996). Usability studies indicate that while challenges exist, the potential for improved learning outcomes through these environments is substantial. Adaptive web-based learning systems, like the Scientific Concept Construction and Reconstruction (SCCR), have demonstrated significant improvements in students' scientific reasoning and conceptual change, as students using this system outperformed their peers in traditional settings (She & Liao, 2010; Liao & She, 2009). The findings suggest that digital skills are crucial for facilitating conceptual change, as students with higher scientific reasoning abilities were better able to integrate new knowledge with existing frameworks. Conversely, while digital skills can enhance understanding, there is a concern that reliance on technology may lead to superficial learning if not integrated thoughtfully into the curriculum. Balancing digital engagement with traditional pedagogical methods remains essential for comprehensive scientific education.

The study also reveals the importance of ICT usage regulation and frequency in shaping the effectiveness of digital self-efficacy on science literacy. The moderation analysis demonstrates that the impact of ICTEFFIC on SCILIT is stronger when students' ICT use outside of school (ICTOUT) and their perceptions of regulated ICT use in school (ICTREG) are lower. This suggests that overreliance on technology outside the classroom may not necessarily translate to academic benefits, emphasizing the need for structured and purposeful digital engagement within school settings. Similarly, the findings regarding ICT use on weekdays (ICTWKDY) and weekends (ICTWKEND) indicate that students who use digital tools less frequently outside structured learning environments derive greater academic benefits from their ICT competencies. This supports the notion that digital literacy should be nurtured within a balanced framework that prioritizes quality over quantity of ICT exposure.

Inquiry-based digital learning fosters active engagement, critical thinking, and self-regulation, with key principles including technology integration, scaffolding, and gamification. Digital tools enhance inquiry activities by enabling interactive exploration (Mamun, 2022), while e-learning platforms provide virtual labs and simulations that accommodate diverse learning styles (Sotiriou et al., 2020). Scaffolding frameworks, such as the extended POEE model, guide students through inquiry phases and promote self-regulated learning (Mamun, 2022). Additionally, scaffolding fosters positive emotions and engagement, which are essential for effective inquiry-based learning (Mamun, 2022). Gamification elements further enhance motivation and enjoyment, leading to improved perceived learning outcomes (Zhang et al., 2024) and encouraging exploration and experimentation (Zhang et al., 2024). However, challenges such as student readiness and the need for teacher training remain barriers to implementation, requiring targeted solutions for maximizing the benefits of inquiry-based education (Sam, 2024). These findings have important implications for educational policymakers, school administrators, and curriculum developers, as they highlight the necessity of well-integrated ICT policies that support scientific inquiry and subject-based digital learning while ensuring appropriate regulation of digital engagement. Given the increasing reliance on technology-driven education models, the results of this study suggest that structured, inquiry-driven ICT use within classrooms may be more beneficial for science literacy development than unregulated or excessive ICT use in non-academic settings.

The results of this study provide compelling evidence that students' digital self-efficacy plays a crucial role in shaping their science literacy, particularly through inquiry-based and subject-related ICT use. The findings confirm that students who are confident in their digital skills tend to engage more effectively in technology-driven learning activities, which, in turn, enhances their ability to think critically and apply scientific concepts. Digital self-efficacy among youth is increasingly recognized as a crucial factor in their ability to navigate online information and make informed health decisions. Research suggests that digital interventions enhance self-efficacy, particularly in health-related contexts, empowering adolescents to resist negative behaviors like smoking and critically engage with health information. Digital health games have been effective in improving smoking refusal self-efficacy among early adolescents, demonstrating that engaging formats can help them resist peer pressure ("Effectiveness of a Digital Health Game Intervention on Early Adolescent Smoking Refusal Self-Efficacy.", 2024). Similarly, digital mental health interventions have improved adolescent access to care, enhancing their self-efficacy in managing mental health challenges (Szigethy et al., 2023). Despite high self-efficacy in accessing online health information, many adolescents overestimate their digital health literacy, highlighting the need for better critical health literacy to assess the reliability of sources (Taba et al., 2022). Given that many rely on social media for health advice, misinformation can lead to anxiety and poor decision-making without proper evaluation skills (Taba et al., 2022). Internet self-efficacy, shaped by prior experience and positive outcome expectations, plays a role in reducing the digital divide among youth (Eastin & LaRose, 2006). Training programs aimed at improving self-efficacy have led to reductions in anxiety and hopelessness, reinforcing the importance of digital self-efficacy in mental well-being (Rohde et al., 2024). While digital self-efficacy is vital for youth empowerment in health contexts, addressing the challenges of misinformation and implementing comprehensive digital literacy interventions are crucial for ensuring informed decision-making.

One of the most significant findings is that ICTENQ has a stronger impact on science literacy than ICTSUBJ, highlighting the importance of inquiry-based digital learning in fostering problem-solving and analytical skills. This aligns with prior research suggesting that students who use digital tools to explore scientific concepts and conduct virtual experiments develop deeper conceptual understanding compared to those who use ICT merely as a supplementary subject-based tool. Inquiry-based digital learning (IBL) plays a crucial role in enhancing problem-solving and analytical skills by fostering critical thinking, creativity, and active student engagement. This pedagogical approach encourages learners to explore, question, and construct their own understanding, which is fundamental for developing these competencies. Research indicates that IBL promotes critical thinking by requiring students to analyze information, evaluate evidence, and synthesize ideas, ultimately leading to improved problem-solving abilities (Sam, 2024). Moreover, IBL positively impacts students' motivation and academic performance, which are essential factors for effective problem-solving (Sam, 2024). Technology integration further strengthens the effectiveness of IBL by enhancing collaborative learning and analytical reasoning. Studies highlight that digital tools, such as collaborative conversational agents, improve student dialogue and reasoning, significantly enhancing their analytical skills (Araujo et al., 2024). Additionally, e-learning platforms that facilitate inquiry-based activities contribute to better learning outcomes, particularly in problem-solving skill development (Sotiriou et al., 2020). Assessment and feedback mechanisms also play a vital role in guiding students through their inquiry processes, as collaborative problem-solving and critical thinking thrive when effective feedback structures are in place (Ba et al., 2024). The use of epistemic network analysis helps visualize the progression of student thinking, allowing educators to better support students' analytical growth (Ba et al., 2024). Despite the proven benefits of IBL, challenges such as varying student readiness and the need for adequate instructional support persist. Ensuring that students receive appropriate guidance and scaffolding is essential for maximizing the effectiveness of inquiry-based approaches in education (Sam, 2024). Addressing these challenges will help educators fully leverage IBL's potential to develop critical thinking, problem-solving, and analytical competencies in students.

Another key finding is that students who engage in both inquiry-based ICT use and subject-related digital learning achieve the highest science literacy scores, reinforcing the argument that a balanced approach to digital engagement is essential for maximizing learning outcomes. Schools should therefore focus on integrating both exploratory and structured ICT-based learning strategies to ensure that students not only develop technical proficiency but also gain the ability to apply scientific knowledge in diverse contexts.

The moderation effects further indicate that excessive ICT use outside structured learning environments may not necessarily lead to better academic outcomes. Specifically, students who use ICT less frequently on weekdays and weekends showed stronger science literacy gains, suggesting that structured, high-quality digital engagement is more beneficial than excessive screen time. Moreover, students who perceive lower ICT regulation in schools benefit more from their digital self-efficacy, implying that schools should adopt more flexible ICT policies that empower students rather than impose restrictive digital usage guidelines.

These findings have important implications for educators, policymakers, and curriculum developers, emphasizing the need to balance ICT access, regulation, and structured learning opportunities. Future research should further explore how emerging technologies, such as artificial intelligence (AI) and virtual reality (VR), can enhance science education in digital learning environments. Additionally, longitudinal studies are needed to examine how digital self-efficacy develops over time and its long-term impact on scientific literacy and career pathways.

The results of this study underscore the transformative potential of digital learning in science education, emphasizing that technology should not be used passively but as an active tool for inquiry-driven learning and scientific exploration. Schools should therefore prioritize strategic ICT integration, teacher training, and digital literacy programs to equip students with the skills they need to thrive in an increasingly technology-driven world. The integration of technology in education differs significantly between school and out-of-school environments, shaping how youth engage with science. Research suggests that technology use outside of school can enhance motivation and interest in STEM, but its effectiveness depends on factors such as context and educator support. Informal science education programs have been shown to positively influence students' attitudes toward STEM, though their impact varies based on program type and student demographics (Xia et al., 2024). Additionally, engagement in making and tinkering activities fosters creativity and problem-solving skills, providing students with hands-on scientific experiences in a less structured, exploratory environment (Simpson et al., 2020).

Inside the classroom, technology use presents unique challenges due to traditional teacher-student dynamics. While in-school technology programs aim to enhance learning, rigid educational structures can sometimes diminish student motivation compared to more flexible after-school settings (McDavid et al., 2020). The assumption that students, as digital natives, are inherently more skilled with technology than teachers has also been questioned, as research indicates that teachers often struggle with technology integration due to inadequate training, leading to a disconnect between student expectations and instructional practices (Wang et al., 2014). While outside-school technology use fosters engagement and creativity, it often lacks the structured support and guidance that formal education provides. Conversely, in-school technology programs benefit from structured learning objectives but can sometimes limit student motivation and autonomy. These findings highlight the need for a balanced approach where technology is used in both formal and informal learning environments, ensuring that students receive both the freedom to explore and the structured guidance necessary for meaningful learning experiences.

Conclusions

This study contributes to the growing body of research on digital literacy and science education by demonstrating that students' self-efficacy in ICT plays a crucial role in enhancing their science literacy, but its effects are largely mediated by their engagement with digital tools for inquiry-based learning and subject-specific instruction. The moderating role of ICT use frequency and regulation further underscores the importance of structured and pedagogically meaningful ICT integration in educational settings.

The findings suggest that simply having access to digital tools is not enough to improve science literacy. Instead, how students engage with these tools—particularly through inquiry-driven and subject-focused learning activities—determines their impact on academic performance. Furthermore, excessive or unstructured ICT use outside the classroom may dilute the benefits of digital self-efficacy, reinforcing the need for balanced digital learning strategies.

In light of these insights, educational institutions should focus on fostering digital literacy that is purposefully integrated into science instruction, rather than allowing unrestricted or unstructured technology use. Schools should also consider implementing ICT policies that optimize students' engagement with digital tools in structured learning environments, ensuring that technology serves as a facilitator of scientific reasoning rather than a passive medium for content consumption.

Recommendations

Based on the study's findings, the following recommendations are proposed for educators, policymakers, and curriculum developers to enhance the effective use of ICT in science education.

Integration of Inquiry-Based ICT Learning in Science Curricula

Schools should emphasize the use of digital tools for scientific inquiry and experimentation, ensuring that ICT is not just a supplementary resource but a central component of science education. Teachers should receive professional development on integrating inquiry-based digital learning activities, leveraging simulations, virtual labs, and interactive experiments to promote scientific problem-solving skills.

Regulation and Optimization of ICT Use for Learning

Schools should adopt structured ICT policies that encourage quality over quantity in digital learning, ensuring that students engage with technology in purposeful ways rather than passive consumption. Overuse of digital devices outside structured learning contexts should be discouraged, as the findings suggest that moderate ICT use is more beneficial for science literacy than excessive screen time.

Enhancement of Subject-Specific Digital Engagement

The study highlights that ICT use in subject-based learning (ICTSUBJ) significantly enhances science literacy, suggesting that science teachers should incorporate digital resources, data visualization tools, and AI-driven educational platforms into their lesson plans. Schools should invest in subject-specific educational technologies that align with science curricula, such as interactive simulations, real-time data analysis software, and digital science textbooks.

Promotion of Digital Literacy Programs in Schools

Students should receive structured training on digital self-efficacy, focusing on how to critically evaluate online scientific resources, conduct digital experiments, and use technology for evidence-based reasoning. Schools should embed digital literacy modules in their curricula to equip students with the skills needed to effectively navigate and utilize ICT in academic contexts.

Balancing ICT Use Inside and Outside the Classroom

The findings suggest that students benefit most from ICT use when it is embedded within structured learning environments rather than excessive exposure outside school. Schools should encourage blended learning models, where ICT use in the classroom is complemented by hands-on, experiential science activities, ensuring that students develop both digital and practical scientific skills.

Encouraging a Research-Based Approach to ICT Policies

Educational policymakers should use empirical evidence, such as the findings from this study, to design ICT policies that balance access, regulation, and effective digital engagement. Further longitudinal research should be conducted to examine how the long-term effects of digital self-efficacy and ICT engagement evolve as educational technology continues to advance.

As the move is toward increasing digitalization in education, it is crucial to develop strategic ICT integration frameworks that enhance—not hinder—students' academic performance. This study provides strong evidence that digital self-efficacy positively influences science literacy, but only when students engage with ICT in structured, inquiry-driven, and subject-specific ways. Future research should further explore how emerging digital technologies, such as artificial intelligence (AI) and virtual reality (VR), can be leveraged to optimize science education. Ultimately, the goal should be to create digital learning environments that empower students to think critically, solve complex scientific problems, and apply their knowledge in real-world contexts (Adıgüzel et al., 2026; Bulut, 2026; Yurdunkulu et al., 2025).

Statements and Declarations

Conflict of Interest: Authors claim no conflict of interest.

Funding: The study is not funded by any persons/institutions.

References

Adıgüzel, T., Aşık, G., Bulut, M. A., Kaya, M. H., & Özel, S. (2023). Teaching self-regulation through role modeling in K-12. In *Frontiers in education*. *Frontiers Media SA*, *8*, 1105466. https://doi.org/10.3389/feduc.2023.1105466

Adiguzel, T., Kaya, M. H., Bulut, M. A., Mete, S. E., & Nalkesen-Akin, Y. (2023). Integrating cognitive presence strategies: A professional development training for K-12 teachers. *Contemporary Educational Technology*, *15*(2), ep417. https://doi.org/10.30935/cedtech/12987

Adıgüzel, T., Kaya, M.H., Bulut, M.A. (2026). Artificial Intelligence and Educational Leadership: A Bibliometric

Analysis (2004-2024) and Global Policy Review. *Revísta Espanola de Pedagogía*. 1-43

Araujo, A. de, Papadopoulos, P. M., McKenney, S., & Jong, T. de. (2024). A learning analytics-based collaborative conversational agent to foster productive dialogue in inquiry learning. *Journal of Computer Assisted Learning.* https://doi.org/10.1111/jcal.13007

Ba, S., Hu, X., & Stein, D. (2024). Anatomizing online collaborative inquiry using directional epistemic network analysis and trajectory tracking. *British Journal of Educational Technology.* https://doi.org/10.1111/bjet.13441

Bandura, A. (1997). *Self-efficacy: The exercise of control.* W.H. Freeman.

Bell, R. L., Gess-Newsome, J., & Luft, J. A. (2010). Technology in science teacher education: An international perspective. *Studies in Science Education, 46*(1), 105–107. https://doi.org/10.1002/sce.20340

Bers, M. U. (2010). The role of digital technologies in supporting inquiry-based learning in the science classroom. *Computers in Education, 54*(3), 555–562.

Binkley, M., Erstad, O., Herman, J., Raizen, S., Ripley, M., Miller-Ricci, M., & Rumble, M. (2012). Defining twenty-first century skills. In P. Griffin, B. McGaw, & E. Care (Eds.), *Assessment and teaching of 21st century skills* (pp. 17–66). Springer. https://doi.org/10.1016/B978-0-12-381451-1.00002-6

Birgili, B., Bulut, M. A., Gülünay, O., Koçoğlu, M., & Baş, F. R. (2025). Technology-enhanced GipSci approach in developing contexts performs well at interest and curiosity, yet, needs reinforcing at inquiry level. *Research in Science & Technological Education*, 1–38. https://doi.org/10.1080/02635143.2025.2578303

Bulut, M. A. (2026). Aidemics" Examined Analytically through the Connectivist Theory: Institutional AI-Mediation in Higher Education via an Artificial Intelligence Center (CILT-AI). *Interactive Learning Environments*, 1-37. https://doi.org/10.1080/10494820.2026.2647982

Bulut, M. A., Adıgüzel, T., & Kaya, M. H. (2025). Exploring views and experiences of faculty members' participation in an asynchronous online program: Using a micro-learning format and cop framework. *Innovations in Education and Teaching International*, 1–17. https://doi.org/10.1080/14703297.2025.2532056

Bulut, M. A., Koçoğlu, M., Baş, F. R., Gülünay, O., & Birgili, B. (2026). Techno-philosophical and techno-pedagogical implications of a nonformal technology and design education model to empower youth: T3 foundation's DENEYAP technology workshops program. *International Journal of Technology and Design Education*, 1-36. https://doi.org/10.1007/s10798-025-10055-6

Bybee, R. W. (2010). The teaching of science: 21st-century perspectives. *Science Education International, 21*(4), 177–183. https://doi.org/10.1002/sce.20414

Carretero, S., Vuorikari, R., & Punie, Y. (2017). *DigComp 2.1: The digital competence framework for citizens with eight proficiency levels and examples of use.* Publications Office of the European Union. https://doi.org/10.2760/38842

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*(6130), 305–308. https://doi.org/10.1007/s10648-013-9225-2

Dede, C., Salzman, M. C., & Loftin, R. B. (1996). ScienceSpace: Virtual realities for learning complex and abstract scientific concepts. *IEEE Virtual Reality Conference.* https://doi.org/10.1109/VRAIS.1996.490534

Eastin, M. S., & LaRose, R. (2006). Internet self-efficacy and the psychology of the digital divide. *Journal of Computer-Mediated Communication.* https://doi.org/10.1111/j.1083-6101.2000.tb00110.x

Effectiveness of a Digital Health Game Intervention on Early Adolescent Smoking Refusal Self-Efficacy. (2024). *Health Education & Behavior.* https://doi.org/10.1177/10901981241237788

Ertmer, P. A., & Ottenbreit-Leftwich, A. T. (2013). Removing obstacles to the pedagogical changes required by Jonassen's vision of authentic technology-enabled learning. *Educational Technology Research and Development, 61*(3), 469–484. https://doi.org/10.1080/10494820.2013.764261

Ferrari, A. (2013). *DIGCOMP: A framework for developing and understanding digital competence in Europe.* Publications Office of the European Union. https://doi.org/10.2788/52966

Fraillon, J., Ainley, J., Schulz, W., Friedman, T., & Gebhardt, E. (2014). *Preparing for life in a digital age: The IEA international computer and information literacy study international report.* Springer. https://doi.org/10.1787/9789264190658-en

Göçemen, B. (2023). *Matematik öğretmen adaylarının matematiksel okuryazarlık özyeterlikleri, evrensel fen okuryazarlılıkları ve dijital okuryazarlık öz-yeterlilikleri arasındaki ilişki.* Balıkesir Üniversitesi Açık Erişim Arşivi.

Göçen, A., & Bulut, M. A. (2024). Teaching ethics in teacher education: ICT-enhanced, case-based and active learning approach with continuous formative assessment. *Journal of Academic Ethics*, *22*(3), 447-465. https://doi.org/10.1007/s10805-024-09503-0

Hämäläinen, R., De Wever, B., Nissinen, K., & Cincinnato, S. (2018). What makes the difference: PIAAC as a resource for understanding the problem-solving skills of Europe's higher-education adults. *British Journal of Educational Technology, 49*(6), 1043–1058. https://doi.org/10.1080/01411926.2018.1463805

Hayes, A. F. (2018). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach* (2nd ed.). Guilford Press.

Hiğde, E., & Aktamış, H. (2023). The impact of inquiry-based learning on students' scientific process skills and attitudes towards science.

Hinostroza, J. E., Mellar, H., & Espinosa, M. (2016). ICT in education: Policies and practices in Latin America and Asia. *Computers in Human Behavior, 62,* 416–420. https://doi.org/10.1016/j.chb.2016.02.013

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*(2), 99–107.

Janssen, J., Erkens, G., Kanselaar, G., & Jaspers, J. (2013). Visualization of participation: Does it contribute to awareness and learning? *Computers & Education, 65,* 58–71. https://doi.org/10.1016/j.compedu.2013.01.001

Karanfiloğlu, M., & Bulut, M. A. (2025). Techno-pedagogical communication, ed-tech and media professionals: Crossroads for enhancing instructional quality. *Interactive Learning Environments, 33*(7), 4193–4217. https://doi.org/10.1080/10494820.2025.2459180

Kozma, R. B. (2011). The use of multiple representations and the social construction of understanding in chemistry. *Educational Technology Research and Development, 59*(5), 671–695. https://doi.org/10.1080/10494820.2011.528104

Liao, Y. W., & She, H.-C. (2009). Enhancing eighth grade students’ scientific conceptual change and scientific reasoning through a web-based learning program. *Educational Technology & Society.*

Linn, M. C., Gerard, L., Matuk, C., & McElhaney, K. (2014). Science learning and inquiry with technology: A framework for learning with technology. *Educational Psychologist, 49*(4), 267–289. https://doi.org/10.1007/s11251-013-9301-2

Looi, C. K., Seow, P., Zhang, B. H., So, H. J., Chen, W., & Wong, L. H. (2011). Leveraging mobile technology for sustainable seamless learning: A research agenda. *British Journal of Educational Technology, 42*(5), 680–699. https://doi.org/10.1016/j.compedu.2011.04.011

MacKinnon, D. P., Lockwood, C. M., & Williams, J. (2004). Confidence limits for the indirect effect: Distribution of the product and resampling methods. *Multivariate Behavioral Research, 39*(1), 99–128. https://doi.org/10.1207/s15327906mbr3901_4

Mamun, Md. A. A. (2022). Fostering self-regulation and engaged exploration during the learner-content interaction process: The role of scaffolding in the online inquiry-based learning environment. *Interactive Technology and Smart Education.* https://doi.org/10.1108/itse-11-2021-0195

Maxim, S. (2023). Operationalizing collaborative problem-solving skills: A framework for assessment and development in the digital age. *Studia Universitatis Babes-Bolyai-Psychologia.*

Miller, J. D. (2014). The measurement of science literacy. *Public Understanding of Science, 23*(7), 767–784.

Milner-Bolotin, M. (2023). Investigating student collaborative problem-solving competency and science achievement with multilevel modeling: Findings from PISA 2015. *PLOS ONE.*

Nasırcı, H., & Kerkez, B. (2023). PISA'da başarılı ülkeler ile Türkiye'nin K12 beceriler çerçevesine göre karşılaştırmalı analizi. *Milli Eğitim Dergisi.*

Passey, D. (2014). Inclusive technology enhanced learning: Overcoming cognitive, physical, emotional, and geographic challenges. *Computers & Education, 72,* 100–112. https://doi.org/10.1016/j.compedu.2014.01.001

Rahman, F., Suyidno, S., Miriam, S., & Husain, S. (2023). Developing learners' digital literacy through guided discovery learning on the matter of work and energy. *JPPS (Jurnal Penelitian Pendidikan Sains).*

Rocard, M., Csermely, P., Jorde, D., Lenzen, D., Walberg-Henriksson, H., & Hemmo, V. (2007). *Science education now: A renewed pedagogy for the future of Europe.* European Commission.

Rohde, J., Marciniak, M. A., Henninger, M., Homan, S., Ries, A., Paersch, C., Friedman, O., Brown, A. D., & Kleim, B. (2024). Effects of a digital self-efficacy training in stressed university students: A randomized controlled trial. *PLOS ONE.* https://doi.org/10.1371/journal.pone.0305103

Sam, R. (2024). Systematic review of inquiry-based learning: Assessing impact and best practices in education. *F1000Research.* https://doi.org/10.12688/f1000research.155367.1

Sánchez, I., & Cortés Orduna, M. (2024). Possibilities and challenges of STEAM pedagogies. *ArXiv.*

Scherer, R., & Siddiq, F. (2015). Revisiting the concept of digital competence: The role of technology-mediated assessments. *Computers in Human Behavior, 53,* 511–522. https://doi.org/10.1080/10494820.2014.912627

She, H.-C., & Liao, Y. W. (2010). Bridging scientific reasoning and conceptual change through adaptive web-based learning. *Journal of Research in Science Teaching.* https://doi.org/10.1002/TEA.20309

Sotiriou, S., Lazoudis, A., & Bogner, F. X. (2020). Inquiry-based learning and e-learning: How to serve high and low achievers. *Smart Learning Environments.* https://doi.org/10.1186/s40561-020-00130-x

Szigethy, E., Wolfson, D., Sinclair-McBride, K., Williams, K., Jhe, G., Lee, E. H., Bialostozky, M., Wallace, M. L., Bhatnagar, S., DeMaso, D. R., Yealy, D. M., & Hollenbach, K. A. (2023). Efficacy of a digital mental health intervention embedded in routine care compared with treatment as usual in adolescents and young adults with moderate depressive symptoms: Protocol for randomised controlled trial. *BMJ Open.* https://doi.org/10.1136/bmjopen-2022-067141

Taba, M., Allen, T. B., Caldwell, P. H. Y., Skinner, S. R., Kang, M., McCaffery, K., & Scott, K. M. (2022). Adolescents' self-efficacy and digital health literacy: A cross-sectional mixed methods study. *BMC Public Health.* https://doi.org/10.1186/s12889-022-13599-7

Temel Aslan, S. (2024). Fen bilgisi eğitimi alanında okuryazarlık ile ilgili yapılan lisansüstü tezlerin incelenmesi (2014–2023). *International Journal of Eurasia Social Studies.*

Tondeur, J., van Braak, J., Ertmer, P. A., & Ottenbreit-Leftwich, A. T. (2016). Understanding the relationship between teachers' pedagogical beliefs and technology use in education: A systematic review of qualitative evidence. *Computers & Education, 95,* 66–84. https://doi.org/10.1016/j.compedu.2016.05.001

Turmo, M. P. (2023). Digital cognitive maps for scientific knowledge construction in initial teacher education. *RIED: Revista Iberoamericana de Educación a Distancia.* https://doi.org/10.5944/ried.26.2.36067

Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st-century competences: Implications for national curriculum policies. *Journal of Curriculum Studies, 44*(3), 299–321. https://doi.org/10.1016/j.edurev.2011.11.002

Vuorikari, R., Punie, Y., Carretero, S., & Van den Brande, G. (2016). *DigComp 2.0: The digital competence framework for citizens. Update phase 1: The conceptual reference model.* Publications Office of the European Union. https://doi.org/10.2791/11517

Yurdunkulu, A., Bulut, M. A., & Göçen, A. (2025). From academics to Aidemics: Unpacking the human–AI symbiosis in higher education. *Acta Psychologica, 261, 105796*. https://doi.org/10.1016/j.actpsy.2025.105796

Zhang, F., Brynildsrud, H., Papavlasopoulou, S., Sharma, K., & Giannakos, M. N. (2024). Where inquiry-based science learning meets gamification: A design case of Experiverse. *Behaviour & Information Technology.* https://doi.org/10.1080/0144929x.2024.2433058

Zhang, X., & Liu, S. (2016). A study on ICT integration in teaching: An investigation of levels of use and reasons behind the gap in Hong Kong primary schools. *Computers & Education, 95,* 115–129. https://doi.org/10.1016/j.compedu.2016.06.003