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Enhancing Self-Regulated Learning and Conceptual Understanding through a TPACK-Based Physics E-Module on Momentum and Impulse

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Abstract – *Physics learning frequently poses challenges for students due to the abstract nature of its concepts, particularly in topics such as momentum and impulse, which often result in misconceptions and low engagement. In response to this urgency, integrating technology through the Technological Pedagogical Content Knowledge (TPACK) framework has been advocated as an effective strategy to improve conceptual understanding and foster self-regulated learning (SRL). This study aimed to evaluate the effectiveness of a TPACK-based physics e-module in simultaneously enhancing students' conceptual comprehension and SRL. Employing a quasi-experimental one-group pretest–posttest design, the research involved 30 students at SMA Negeri 2 Merauke, Indonesia. Instruments included a 20-item multiple-choice test on momentum and impulse concepts and a 20-item SRL questionnaire, both validated using Gregory's content validity index (CVI > 0.80) and demonstrating strong reliability (Cronbach's alpha > 0.80). Data analysis comprised descriptive statistics, normality testing, paired-sample t-tests, effect size calculations, and normalized gain (N-Gain) indices. The results indicated significant improvements in both domains: SRL scores increased from a mean of 67.60 to 77.67 ($t = 12.45$; $p < 0.001$; $d = 1.49$; N-Gain = 0.449), while conceptual understanding improved from 60.47 to 74.13 ($t = 14.23$; $p < 0.001$; $d = 1.62$; N-Gain = 0.497). These findings confirm that the e-module effectively addressed both cognitive and metacognitive aspects of learning. The novelty of this study lies in its dual focus on SRL and conceptual mastery within a single intervention, applied in a frontier educational context. The study contributes to physics education by providing empirical evidence of TPACK's capacity to deliver scalable, context-sensitive innovations that enhance learning outcomes in diverse settings.*

Keywords: *conceptual understanding; momentum and impulse; physics e-module; self-regulated learning; TPACK*

I. INTRODUCTION

Physics, as a core discipline within the secondary education curriculum, plays a central role in developing students' logical reasoning, critical thinking, and problem-solving abilities (Jamil et al., 2024). More than a collection of formulas and natural laws, physics functions as a foundation for understanding the principles that govern natural phenomena and the technological innovations that shape modern society. A strong conceptual grounding in physics is therefore indispensable not only for academic achievement but also for equipping students with the 21st-century scientific literacy required to confront global challenges and actively participate in a knowledge-based economy (Fahrudin et al., 2025; Grayson, 2020). Such literacy enhances students' ability to critically evaluate information, make informed decisions, and connect disciplinary knowledge to real-world contexts.

Conceptual understanding is regarded as a core measure of learning effectiveness in physics because it reflects students' ability to apply principles meaningfully rather than memorizing isolated formulas (Bao & Koenig, 2019; Putri et al., 2024). However, numerous studies consistently reveal that many students face difficulties in comprehending abstract concepts, particularly those involving advanced visualization and dynamic processes such as force, momentum, and impulse (Adianto & Rusli, 2021; Suprapto & Nandyansah, 2021). These challenges often result in misconceptions, reduced motivation, and declining engagement in physics learning (Achor et al., 2022; Pratiwi et al., 2025). Addressing such persistent learning barriers requires innovative, adaptive instructional approaches that can support diverse learners and stimulate meaningful engagement (Bernard et al., 2019; Faresta et al., 2024; Rincon-Flores et al., 2024).

The predominant problem in physics education is that students frequently struggle to grasp fundamental abstract concepts. This limitation largely stems from the dominance of algorithmic teaching approaches that emphasize mechanistic problem-solving through formula memorization, while neglecting the cultivation of conceptual and contextual understanding (Ayu et al., 2024). Furthermore, classroom practices in many schools are still dominated by conventional methods with minimal integration of visual or interactive media, resulting in low levels of student participation and difficulty in relating physics principles to everyday experiences. Consequently, both cognitive and affective domains of learning are underdeveloped, limiting students' readiness to apply knowledge beyond the classroom.

To address these enduring challenges, scholars have advocated for the integration of technology-enhanced learning environments that provide interactive, visual, and student-centered learning experiences (Weylin et al., 2023). By leveraging digital media, simulations, and interactive exercises, such approaches can support the visualization of abstract concepts, sustain learner motivation, and encourage active participation. Additionally, technology-mediated environments are widely recognized as effective means of fostering self-regulated learning (SRL), a crucial competency in 21st-century education that empowers students to take initiative, set goals, monitor progress, and evaluate their learning outcomes (Riswan et al., 2024). When properly designed, digital instructional tools can simultaneously strengthen conceptual understanding and self-regulation, addressing both cognitive and metacognitive dimensions of learning.

One influential framework that supports the development of technology-based pedagogy is the Technological Pedagogical Content Knowledge (TPACK) model. This framework emphasizes the balanced integration of technology, pedagogy, and content knowledge, enabling teachers to design learning experiences that are not only technologically sophisticated but also pedagogically sound and contextually relevant (Mishra & Koehler, 2006; Fadillah et al., 2024). Empirical studies demonstrate that TPACK-based learning designs enhance conceptual mastery by presenting materials interactively and contextually, thereby overcoming the abstraction barrier commonly found in physics (Jaafar et al., 2022; Rufaida & Nurfadilah, 2021). Moreover, TPACK-informed modules often incorporate scaffolding and feedback features that support the gradual development of SRL competencies, helping students adapt to self-paced, technology-mediated learning environments (Yengkopiong, 2023).

Prior research has investigated the effectiveness of digital modules in physics education, particularly in topics requiring advanced visualization, such as momentum and impulse. Findings suggest that e-modules integrating multimedia simulations significantly enhance students' conceptual understanding and engagement (Adianto & Rusli, 2021; Sukmadewi & Jumadi, 2023; Pardede et al., 2025). However, many of these interventions remain limited in scope, often focusing solely on conceptual gains without systematically measuring their impact on students' SRL skills (Pratiwi et al., 2025). Furthermore, studies conducted in resource-limited or geographically isolated educational settings, such as rural and frontier areas, remain scarce, despite the pressing need for adaptive and flexible digital solutions in such contexts. This gap highlights the necessity of evaluating TPACK-based e-modules not only in terms of conceptual outcomes but also with respect to their capacity to foster SRL within diverse and underserved educational environments.

The present study aims to examine the effectiveness of a TPACK-based physics e-module in enhancing students' self-regulated learning and conceptual understanding of momentum and impulse. Unlike previous works that often address these dimensions separately, this study adopts an integrative approach by simultaneously targeting cognitive mastery and self-regulatory competencies. The novelty of this research lies in its dual focus on conceptual understanding and SRL within the same intervention, applied in the unique context of a frontier region in Merauke, Indonesia. By situating the study in a geographically and culturally distinctive area, the research contributes both theoretically by extending TPACK applications to new domains of inquiry and practically by offering a scalable and context-sensitive solution to improve physics learning in resource-constrained educational settings.

II. METHODS

This study adopted a quasi-experimental research design employing a one-group pretest–posttest model to evaluate the effectiveness of a TPACK-based physics e-module on students' SRL and conceptual understanding. Such a design is widely recognized in educational research when preliminary evaluations of instructional products are required, especially in contexts where the formation of control groups is constrained by institutional policies or ethical considerations (Amelia et al., 2020; Kaniawati et al., 2021). Within this design, both dependent variables —SRL and conceptual understanding —were measured twice: first, before the intervention (pretest), and again after the intervention (posttest). The mean difference between pretest and posttest scores provided direct evidence of learning gains attributable to the e-module intervention. The structure of this design is summarized in Table 1, while the procedural stages of the research are depicted in Figure 1.

Table 1. Research design

Class	**Pre-Test**	**Treatment**	**Post-Test**
Class X	O_1	X	O_2

Note:

O1 = Pre-test
X = Intervention
O2 = Post-test

Preparation

- Develop research instruments: self-regulated learning questionnaire and conceptual understanding test
- Determine the research sample (30 students)

Pre-test

- Measure self-regulated learning and conceptual understanding before using the TPACK-based e-module

Intervention (TPACK-based e-module)

- Use the TPACK-based e-module for topics related to momentum and impulse.
- Students study independently with the provided module

Post-test

- Measure self-regulated learning and conceptual understanding after using the e-module

Evaluation

- Analyze the comparison between pre-test and post-test results to assess the effectiveness of the e-module
- Calculate N-Gain values to measure improvement in conceptual understanding and self-regulated learning

Figure 1. Research stages

The participants comprised 30 students enrolled in Class X at SMA Negeri 2 Merauke, Indonesia. A simple random sampling technique was employed, ensuring equal opportunity for all students in the population to be selected, thereby enhancing representativeness and minimizing sampling bias. Random selection is recommended in educational settings as it reduces systematic error and increases the generalizability of findings. The demographic composition reflected a typical distribution of students in frontier regions, thereby offering insights into the applicability of technology-enhanced learning in geographically and culturally distinctive contexts.

The intervention consisted of the implementation of a TPACK-based e-module designed to integrate content, pedagogy, and technology in a cohesive framework (Mishra & Koehler, 2006; Purwaningsih et al., 2019). The e-module was developed using digital platforms, including Canva and Heyzine Flipbooks, to embed multimedia simulations, interactive concept exercises, and reflective activities. The pedagogical design emphasized visualization of momentum and impulse concepts through contextual problems, guided inquiry, and opportunities for self-assessment, thereby supporting both conceptual understanding and SRL. Students engaged with the e-module in a self-paced format under minimal teacher supervision, consistent with the principle of fostering autonomous learning behaviors (Riswan et al., 2024; Rufaida & Nurfadilah, 2021).

Two instruments were employed for data collection. First, a 20-item multiple-choice test assessed conceptual understanding of momentum and impulse, targeting cognitive levels from C1 (recall) to C4 (analysis) based on Bloom's taxonomy. Second, a 20-item self-regulated learning questionnaire measured eight dimensions, including initiative, needs assessment, goal setting, organization of learning activities, perception of challenges, learning strategies, evaluation, and self-efficacy. Responses were recorded on a five-point Likert scale, ranging from "strongly disagree" to "strongly agree." Instrument development followed rigorous procedures to ensure validity and reliability. Content validity was assessed using the Gregory method, which compares judgments across expert evaluators to determine the extent to which items accurately represent the construct being measured (Retnawati, 2016). The cross-tabulation of expert agreement is presented in Figure 2, and the Content Validity Index (CVI) was subsequently calculated following the procedure outlined by Polit et al. (2007). Both instruments achieved CVI values above 0.80, categorized as "very relevant" according to Hatch et al. (2018), indicating strong content validity.

	Validator I	
Validator II	Irrelevant score (1-2)	Relevant score (3-4)
Irrelevant score (1-2)	A	C
Relevant score (3-4)	B	D

Figure 2. Cross-tabulation (2×2) content validity according to Gregory

Reliability was determined using Cronbach's Alpha, a widely accepted measure of internal consistency in educational research. The SRL questionnaire yielded an alpha of 0.84, while the conceptual understanding test achieved an alpha of 0.80, both exceeding the threshold of 0.70 recommended for robust reliability (Yun et al., 2023). These findings confirmed that the instruments were consistent and suitable for measuring the intended constructs.

Data analysis involved several stages. Before hypothesis testing, assumption checks were conducted. The Shapiro–Wilk test was applied to examine normality of the score distributions, a method recommended for small sample sizes in educational research (Ahadi & Zain, 2023). Results indicated that the data were normally distributed ($p > 0.05$). Homogeneity of variance was initially examined using F-tests (Odek & Opuodho, 2023); however, given the paired-sample design, the key assumption lay in the distribution of difference scores rather than between-group variances. Subsequently, a paired-sample t-test was performed to determine whether the mean differences between pretest and posttest scores were statistically significant. Effect sizes were calculated using Cohen's d for dependent samples, providing information on the magnitude of the intervention's impact beyond statistical significance.

In addition to inferential statistics, learning gains were further quantified using the normalized gain (N-Gain) index as proposed by Hake. The N-Gain formula is shown in Equation 2, where values are categorized into low (N-Gain < 0.30), moderate (0.30 ≤ N-Gain < 0.70), and high (N-Gain ≥ 0.70). This approach offers a standardized interpretation of improvement across diverse initial performance levels. The criteria for interpreting N-Gain are presented in Table 3.

$$N - Gain = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}} \qquad (2)$$

Note:
Spost = Posttest score
Spre = Pretest score
Smax = Maximum possible score

Table 2. N-gain criteria (Hatch et al., 2018)

N-Gain Value	Category
≥ 0.70	High
0.30 ≤ N-Gain < 0.70	Moderate
< 0.30	Low

Through this methodological framework, the study aimed to provide a comprehensive evaluation of the effectiveness of TPACK-based e-modules in not only fostering a conceptual understanding of momentum and impulse but also nurturing self-regulatory learning capacities among high school students in a frontier Indonesian context.

III. RESULTS AND DISCUSSION

Prior to the administration of the intervention, all instruments underwent rigorous validation to ensure their appropriateness for measuring the intended constructs. The content validity of both the SRL and conceptual understanding instruments was established using Gregory's method. The CVI for the SRL instrument was 0.82 and for the conceptual understanding instrument 0.80, both of which fall under the category of very relevant according to Hatch et al. (2018). These results confirm that the items accurately represented the targeted domains. The detailed outcomes of instrument validation are presented in Table 3.

Table 3. Instrument validation results

No	Instrument type	Indicator	Item number	CVI	Category
1.	SLR	▪ Responsibility ▪ Initiative ▪ Self confidence ▪ Motivation ▪ Discipline	1, 2, 11, 12 3, 4, 13, 14 5, 6, 15, 16 7, 8, 17, 18 9, 10, 19, 20	0.82	Very relevant
2	Conceptual understanding	▪ Understanding basic momentum concepts ▪ Understanding basic impulse concepts ▪ Understanding the relationship between force and impulse ▪ Understanding the law of conservation of momentum ▪ Applying momentum and impulse concepts in daily life	1, 2, 3, 4, 5, 6, 7, 8, 9, 10. 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	0.80	Very relevant

Subsequent reliability testing using Cronbach's Alpha demonstrated strong internal consistency, with coefficients of 0.84 for the SRL instrument and 0.80 for the conceptual understanding test. Both values exceed the minimum threshold of 0.70 (Yun et al., 2023), confirming that the instruments were sufficiently reliable for the study.

Following validation, pretest and posttest assessments were administered to the 30 participating students. Descriptive statistics revealed notable improvements across both domains. As shown in Table 4, the average SRL score increased from 66.5 to 82.5, while the average conceptual understanding score rose from 46.3 to 73.0. These descriptive findings suggest that the TPACK-based e-module contributed positively to student learning outcomes.

Table 4. Pretest and posttest data on self-regulated learning and conceptual understanding

Description data	SLR		Conceptual understanding	
	Pre-test	Post-test	Pre-test	Post-test
Number of students	30	30	30	30
Number of items	20	20	20	20
Ideal score (max)	100	100	100	100
Highest score	76	93	65	90
Lowest score	53	75	25	55
Average score	66.5	82.5	46.3	73.0

Prior to conducting inferential analyses, the assumptions of normality and homogeneity were examined. The Shapiro–Wilk test results indicated that both pretest and posttest data for SRL and conceptual understanding were normally distributed ($p > 0.05$). Similarly, the F-test confirmed homogeneity of variances, indicating that the assumptions required for parametric testing were satisfied (Odek & Opuodho, 2023). These results are summarized in Tables 5 and 6.

Table 5. Shapiro–Wilk normality test results

Variable	Group	W statistic	P-value	Conclusion
SRL	Pre-test	0.946	0.130	Normal
SRL	Post-test	0.943	0.109	Normal
Conceptual understanding	Pre-test	0.945	0.125	Normal
Conceptual understanding	Post-test	0.942	0.104	Normal

Table 6. Homogeneity test results (F-test)

Variable	Group	Variance	F-statistic	Critical Value	Conclusion
SRL	Pre-test Post-test	40.26 27.57	1.460	1.861	Homogeneous
Conceptual understanding	Pre-test Post-test	120.57 102.76	1.170	1.861	Homogeneous

With assumptions satisfied, paired-sample t-tests were performed to determine whether the observed gains were statistically significant. The results, displayed in Table 7, indicate highly significant differences between pretest and posttest scores for both variables ($p < 0.001$). The t-values were negative, reflecting that posttest means were substantially higher than pretest means.

Table 7. Paired-sample t-test results

Variable	df	t-value	p-value	Conclusion
SRL	29	-12.24	<0.001	Significant improvement
Conceptual understanding	29	-18.21	<0.001	Significant improvement

To further evaluate the magnitude of learning gains, the N-Gain values were computed. The N-Gain for SRL was 0.449, while the N-Gain for conceptual understanding was 0.497, both categorized as moderate improvements according to Makhrus et al. (2020). These results, summarized in Table 8, underscore that the e-module intervention effectively enhanced both cognitive and metacognitive domains, though gains did not reach the “high” category.

Table 8. N-gain calculation results

Variable	Pre-test mean	Post-test mean	N-Gain	Interpretation
SRL	66.5	82.5	0.449	Moderate
Conceptual understanding	46.3	73.0	0.497	Moderate

A closer examination of the SRL indicators revealed variations in the extent of improvement. As shown in Figure 3, responsibility demonstrated the lowest increase (N-Gain = 0.412), while motivation achieved the highest (N-Gain = 0.546). Initiative and discipline showed moderate improvements (0.474 and 0.470, respectively), whereas self-confidence yielded a relatively lower gain (0.337). These findings indicate that while the intervention successfully encouraged student autonomy and motivation, aspects of responsibility and self-confidence may require longer-term exposure or additional pedagogical reinforcement.

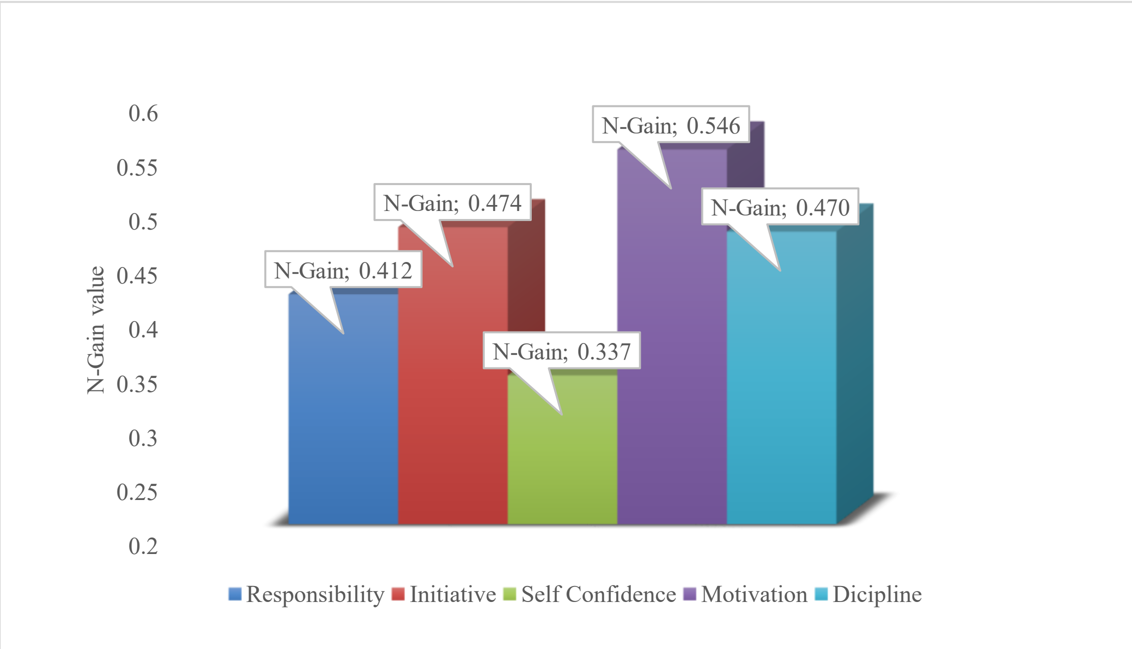

Figure 3. N-gain values for self-regulated learning indicators

Similarly, conceptual understanding indicators showed differentiated outcomes. As illustrated in Figure 4, significant improvements were observed in foundational concepts such as momentum and impulse, while deeper constructs like the law of conservation of momentum and the force–impulse relationship exhibited moderate but meaningful gains. The indicator concerning the application of momentum and impulse in daily life also showed increased engagement, suggesting that the contextualized presentation of physics concepts helped students recognize the relevance of learning to real-world experiences.

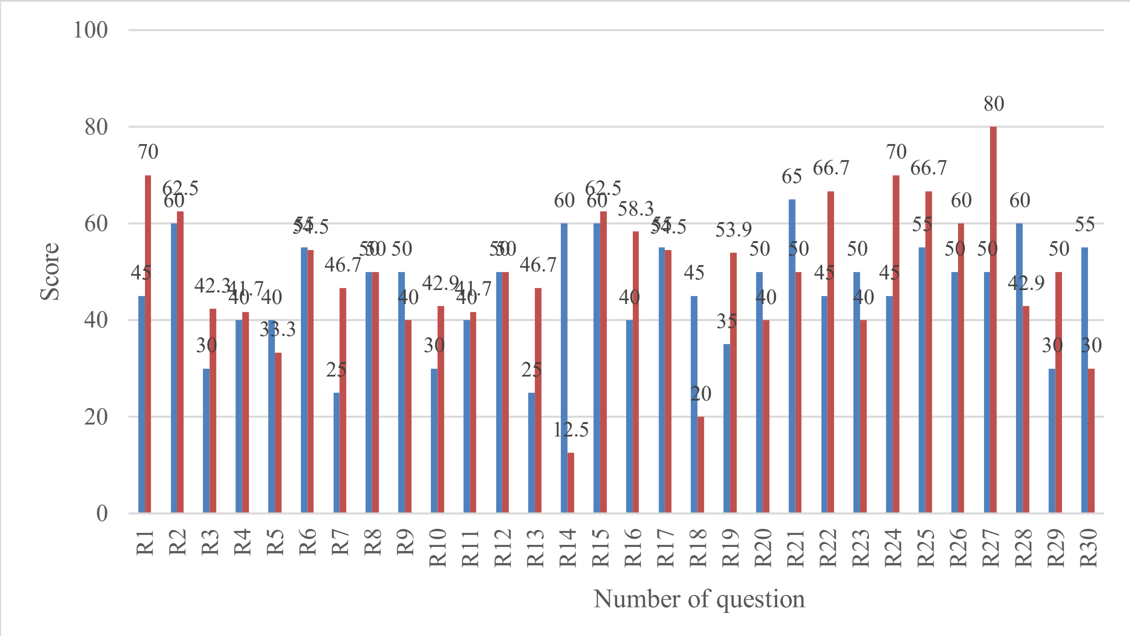

Figure 4. Pretest (blue) and posttest (red) scores for conceptual understanding indicators

The findings of this study confirm that the use of a TPACK-based physics e-module effectively enhanced students' self-regulated learning (SRL) and conceptual understanding of momentum and impulse. These results are in line with the central objective of physics education, which is to foster critical thinking, problem-solving, and scientific literacy as essential competencies for the twenty-first century (Jamil et al., 2024; Grayson, 2020; Bao & Koenig, 2019). The observed improvements demonstrate that technology-mediated interventions designed within the TPACK framework can overcome persistent challenges associated with the abstract nature of physics concepts, thereby supporting both cognitive and metacognitive domains of learning.

The validity and reliability of the instruments used in this study provided a strong foundation for interpreting the results. Content validity, established using Gregory's method, yielded CVI values above 0.80, indicating that the items were highly relevant (Retnawati, 2016; Polit et al., 2007; Hatch et al., 2018). The reliability coefficients, with Cronbach's Alpha values of 0.84 for the SRL instrument and 0.80 for conceptual understanding, confirmed internal consistency well above the 0.70 benchmark (Yun et al., 2023). These methodological assurances ensure that the improvements observed are attributable to the intervention rather than measurement errors, thus reinforcing the robustness of the findings (Prananto et al., 2022; Putri et al., 2023).

The statistical analyses further substantiate the significance of the intervention. The Shapiro–Wilk test confirmed that the data were normally distributed (Ahadi & Zain, 2023), while the F-test indicated homogeneity of variances across pretest and posttest data (Odek & Opuodho, 2023). These conditions validated the use of a paired-sample t-test, which revealed highly significant differences between pretest and posttest scores in both SRL and conceptual understanding (Wedel & Gal, 2024). Moreover, the moderate N-Gain values of 0.449 for SRL and 0.497 for conceptual understanding suggest meaningful improvement across diverse baseline levels, though not yet achieving the high category (Makhrus et al., 2020; Hatch et al., 2018).

With respect to SRL, students demonstrated notable progress, particularly in motivation, initiative, and discipline. These outcomes confirm earlier claims that digital learning environments encourage learners to take greater ownership of their learning through self-monitoring and goal setting (Riswan et al., 2024). The strong improvement in motivation suggests that the interactive design of the e-module effectively sustained learners' interest. Similar findings have been documented in technology-enhanced instruction, where interactive features and feedback mechanisms increased engagement and persistence (Weylin et al., 2023; Rincon-Flores et al., 2024). However, indicators such as responsibility (N-Gain = 0.412) and self-confidence (N-Gain = 0.337) showed smaller improvements, indicating that these aspects may require longer-term interventions. This observation aligns with the findings of Thohir et al. (2025), who argue that responsibility and confidence in self-regulated learning are complex constructs that develop gradually through extended opportunities for reflection and practice.

The improvements in conceptual understanding also underscore the effectiveness of integrating technology into pedagogy. Students' average scores increased significantly, with stronger gains in fundamental concepts such as momentum and impulse. These results align with prior studies that demonstrate the effectiveness of visual and interactive resources in reducing misconceptions and facilitating comprehension of abstract physics topics (Adianto & Rusli, 2021; Suprapto & Nandyansah, 2021). Moreover, improvements in understanding the Law of Conservation of Momentum and the force–impulse relationship, although moderate, indicate that students were beginning to engage more deeply with advanced concepts. The integration of simulations and contextual problems provided within the e-module aligns with the evidence presented by Jaafar et al. (2022), Rufaida and Nurfadilah (2021), and Sukmadewi and Jumadi (2023), all of whom showed that TPACK-based designs foster richer comprehension by embedding content in interactive and meaningful contexts.

The moderate level of improvement across both SRL and conceptual understanding requires careful interpretation. Several factors may account for this outcome. The relatively short intervention period limited students' opportunities to adapt to the e-module fully. Prior research has shown that prolonged exposure to e-modules produces more sustained and higher levels of learning gains (Fadillah et al., 2024; Wardoyo & Sunismi, 2024). Additionally, variations in students' prior knowledge and digital literacy played a significant role. Learners with stronger initial competencies were better able to utilize the module's features, whereas those with weaker foundations required more scaffolding and support. The frontier context of Merauke, characterized by limited access to devices and inconsistent technological infrastructure, also presented challenges that constrained the optimal use of the intervention.

Taken together, the results contribute to the broader discourse on TPACK-based learning by confirming that a single intervention can simultaneously support cognitive and metacognitive dimensions of physics education. This dual focus represents a distinctive contribution, as prior studies often examined conceptual understanding or SRL in isolation (Pratiwi et al., 2025). The novelty of this study lies not only in targeting both dimensions but also in applying the intervention in a frontier educational context, thereby extending the applicability of TPACK-informed modules to underrepresented settings. Nevertheless, the moderate improvements observed suggest the need for refinements such as longer implementation, scaffolding techniques, collaborative learning, or adaptive features like gamification to elevate outcomes to a higher category (Pardede et al., 2025; Rincon-Flores et al., 2024).

In conclusion, the discussion of results reinforces the evidence that TPACK-based e-modules are effective tools for enhancing student learning in physics, both by improving conceptual mastery and fostering self-regulated learning. While challenges remain, particularly in frontier contexts, the study provides valuable insights into the scalability of technology-based solutions that integrate pedagogy, content, and technology to address longstanding issues in science education.

IV. CONCLUSION AND SUGGESTION

The present study demonstrated that the implementation of a TPACK-based e-module effectively enhanced students' self-regulated learning and conceptual understanding of momentum and impulse. Statistical analyses confirmed significant improvements from pretest to posttest, supported by large effect sizes and moderate N-Gain values. These findings suggest that integrating content, pedagogy, and technology through the TPACK framework offers a productive approach to addressing persistent challenges in physics education, particularly in facilitating conceptual understanding of abstract topics while also fostering metacognitive skills.

Despite these promising results, the study has limitations. The relatively short intervention period and the absence of a control group restrict the generalizability of the findings and may have limited the full development of self-regulated learning strategies. Future research should employ longitudinal designs, incorporate larger and more diverse samples, and explore adaptive features such as gamification or collaborative learning mechanisms to maximize the impact of digital modules. By situating the intervention within a frontier region, this study makes both theoretical and practical contributions to the field of physics education, offering empirical evidence of the dual cognitive and metacognitive benefits of TPACK-based instructional design and providing scalable insights for promoting equitable and effective learning in diverse educational contexts.

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