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# Research Trends and Intervention Gaps in Students' Science Process Skills and Self-Regulated Learning

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**Abstract**

**Background:** Science education aims to develop both Science Process Skills (SPS) and Self-Regulated Learning (SRL). However, empirical studies indicate that both competencies remain under-developed at the senior secondary level. This study aims to examine research trends, intervention patterns, and research gaps regarding SPS and SRL from 2015 to 2025.
**Methods:** This study utilized bibliometric analysis and a Systematic Literature Review (SLR). Data were retrieved from the Scopus database and analyzed using VOSviewer software and the PRISMA framework. Following rigorous screening and eligibility assessments, 14 SPS articles and 11 SRL articles were selected for comprehensive review.
**Results:** Bibliometric mappings reveal that SPS research is predominantly linked with scientific thinking, inquiry, and local wisdom, whereas SRL research is strongly connected to metacognition, feedback, and assessment practices. Literature analysis indicates that SPS interventions mostly employ inquiry-, project-, problem-, and contextual learning approaches, while SRL interventions consistently rely on assessment-oriented practices. Notably, a significant disconnect and lack of integration between SPS and SRL was found across the reviewed literature.
**Conclusion:** The limited integration of SPS and SRL highlights a critical research gap and an opportunity to develop science learning interventions that bridge scientific inquiry with students' learning regulation. Within this context, Assessment for Learning (AfL) offers a promising framework to simultaneously foster both SPS and SRL at the senior secondary level, specifically through self-assessment, individualized teacher feedback, and structured opportunities for revision.

## INTRODUCTION

Science education is not solely about conveying scientific facts and concepts, but also focuses on developing students' scientific thinking abilities and learning independence (Alberts, 2022). Scientific thinking is one of the primary goals of science education because it involves the ability to pose questions, evaluate evidence, draw conclusions, and reflect on thinking processes based on empirical data (García-carmona, 2025). Research by Parmin et al, (2017) further underscores that learning models integrated with scientific processes also enhance students' scientific work independence, the ability to independently explore knowledge and solve scientific problems without fully relying on teacher guidance. Thus, when students not only 'receive' knowledge but actively engage in scientific inquiry and self-regulate their learning strategies, science learning becomes deeper and more meaningful.

The urgency of strengthening scientific thinking is closely related to the persistent weakness of students' Science Process Skills (SPS). Previous studies have shown that students tend to perform relatively well in basic SPS, such as observation and classification, but continue to struggle with higher-order scientific reasoning, including formulating hypotheses, designing experiments, and applying concepts (Rophi et al., 2024; Widdina et al.2018; Astika et al., 2022).) This condition is problematic because SPS represent the cognitive and procedural abilities needed to construct scientific knowledge through inquiry. Padilla, (1990) defines SPS as a set of abilities used by scientists to develop scientific knowledge, including basic skills such as observing, classifying, measuring, predicting, and inferring, as well as integrated skills such as identifying variables, formulating hypotheses, designing experiments, and interpreting data. Aktamiş and Ergin (2008) add that SPS enables individuals to identify problems in their environment, conduct observations, analyze data, formulate hypotheses, and draw conclusions applicable in new contexts. Harlen (1999) further emphasizes that SPS is not merely a technical procedure, but also a conceptual tool that helps students understand how science works through inquiry, evidence evaluation, and reflection on scientific thinking processes. Thus, weaknesses in SPS indicate not only procedural difficulties, but also limitations in students' ability to engage in scientific inquiry, solve problems, and make evidence-based decisions.

A similar concern is found in students' Self-Regulated Learning (SRL). SRL profiles have been reported to vary from low to moderate categories in both online and offline learning contexts (Palullu & Bahri, 2023; Van Alten et al., 2021). This issue is important because students with low SRL profiles tend to achieve significantly lower learning outcomes than those with moderate to high SRL profiles (Van Alten et al., 2021). Zimmerman (2002) defines SRL as a self-directed process in which learners transform their cognitive abilities into academic skills through goal setting, progress monitoring, and reflection on learning outcomes. Pintrich (2000) explains that SRL is an active and constructive process in which learners set learning goals, then monitor, regulate, and control their cognition, motivation, and behavior based on their goals and the learning context they face. Meanwhile, Panadero (2017) asserts that SRL encompasses cognitive, metacognitive, behavioral, motivational, and affective aspects of the learning process. Therefore, SRL can be understood as learners' ability to consciously plan, monitor, evaluate, and regulate their learning processes, including managing motivation and emotions to achieve established learning goals. Weaknesses in SRL may limit students' ability to manage complex science learning tasks independently.

The empirical problems reported in previous studies were also reflected in a preliminary study conducted with senior secondary students at a school in West Bandung Regency in the context of climate change learning. The analysis showed that 75.55% of students obtained Science Process Skills scores below the minimum reference value, with a class average of 63.55. This finding indicates that students' scientific thinking abilities had not developed optimally despite the implementation of project-based learning. Meanwhile, although the overall SRL scores fell into the high category, more detailed analysis revealed weaknesses in motivational regulation, time planning, learning strategies, and comprehension monitoring. These findings reinforce the urgency of identifying interventions that not only improve students' SPS, but also strengthen their self-regulation abilities, particularly at the senior secondary level.

Science Process Skills and Self-Regulated Learning are closely related because scientific inquiry requires not only procedural scientific abilities, but also students' capacity to regulate their own learning processes. The application of SPS in learning involves planning, monitoring, and reflecting on scientific thinking processes. Empirical evidence shows that metacognitive strategy training emphasizing planning, monitoring, and evaluation steps can improve students' SPS (Gomaa, 2016). This aligns with Zimmerman (2002) Self-Regulated Learning model, which also emphasizes three main phases, forethought, performance, and self-reflection, such that SPS practice can become a context for the formation of SRL in science learning. Although the theoretical relationship between SPS and SRL has been acknowledged, studies that empirically design interventions to improve both simultaneously remain very limited, indicating a gap between the strong conceptual foundation and existing research practice.

Although SPS and SRL have been widely discussed in science education, existing studies tend to examine them as separate constructs. Research on SPS has largely focused on improving scientific inquiry skills, while SRL is conceptually concerned with students' ability to regulate cognition, motivation, and behavior, as explained by Pintrich (2000) and Zimmerman (2002). However, limited attention has been given to how interventions can simultaneously strengthen both SPS and SRL. Moreover, the intervention patterns, thematic trends, and research gaps connecting these two constructs have not been sufficiently mapped through an integrated bibliometric and systematic literature review approach. Therefore, a comprehensive review is needed to map how SPS and SRL have been studied, what intervention patterns have been reported, and which research gaps remain underexplored.

Based on these conditions, bibliometric analysis and a systematic literature review were employed in this study to examine research trends, thematic patterns, intervention characteristics, and gaps in the existing literature. This study seeks to investigate how research trends related to students' Science Process Skills and Self-Regulated Learning have developed during the period 2015–2025, how thematic focuses have evolved in studies concerning SPS and SRL, and how various interventions have been implemented to improve students' Science Process Skills and Self-Regulated Learning. In addition, this study explores research gaps regarding the integration of Science Process Skills and Self-Regulated Learning in science education. By addressing these issues, this study is expected to provide clearer research directions for developing science learning interventions that simultaneously strengthen students' science process skills and self-regulated learning.

## METHODS

This study employed a combined research design integrating bibliometric analysis and Systematic Literature Review (SLR) to map research trends, identify dominant interventions, and uncover research gaps related to Science Process Skills (SPS) and Self-Regulated Learning (SRL). Bibliometric analysis was used to quantitatively examine publication patterns and thematic relationships across the literature, while the SLR was conducted to synthesize findings from previous studies regarding interventions used to improve SPS and SRL. The SLR component followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure a systematic, transparent, and traceable article selection process.

Bibliometric analysis was conducted to examine publication trends and thematic developments in SPS and SRL research. Bibliographic data retrieved from Scopus were exported in CSV format, cleaned using OpenRefine, and analyzed using VOSviewer through keyword co-occurrence analysis. The cleaning process included removing duplicate records, standardizing author information, normalizing keywords, and eliminating irrelevant characters. Minimum occurrence thresholds were set at one occurrence for SPS and five occurrences for SRL. For the SLR component, the selected articles were systematically reviewed. Data extraction focused on the author and year of publication, intervention strategy, educational level, research method, and key findings related to SPS or SRL outcomes. The extracted data were organized into summary tables to facilitate cross-study comparison and pattern identification. The full selection process is illustrated in Figure 1.

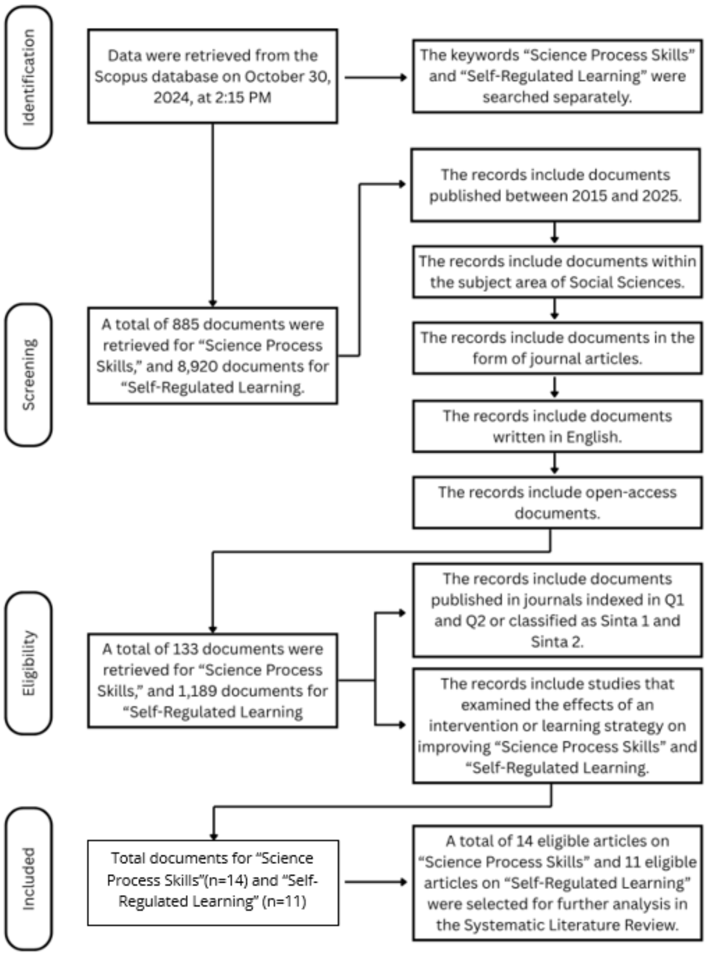


**Figure 1.** PRISMA Flow Diagram of the Systematic Literature Review on Improving Science Process Skills (SPS) and Self-Regulated Learning (SRL)

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Bibliometric data analysis focused on identifying dominant themes, thematic relationships, emerging topics, and research gaps within SPS and SRL literature. Meanwhile, SLR data were analyzed through qualitative content synthesis by categorizing studies based on intervention type, educational level, methodological approach, and research outcomes. Cross-study comparisons were conducted to identify dominant intervention patterns and underexplored areas. In addition, a combined keyword search using "science process skills" AND "self-regulated learning" was conducted in Scopus to examine the extent to which both constructs had been integrated in previous studies.

## RESULT AND DISCUSSION

Publication trends in scientific literature related to Science Process Skills and Self-Regulated Learning over the period 2015–2025 are presented in Figures 2 and 3.

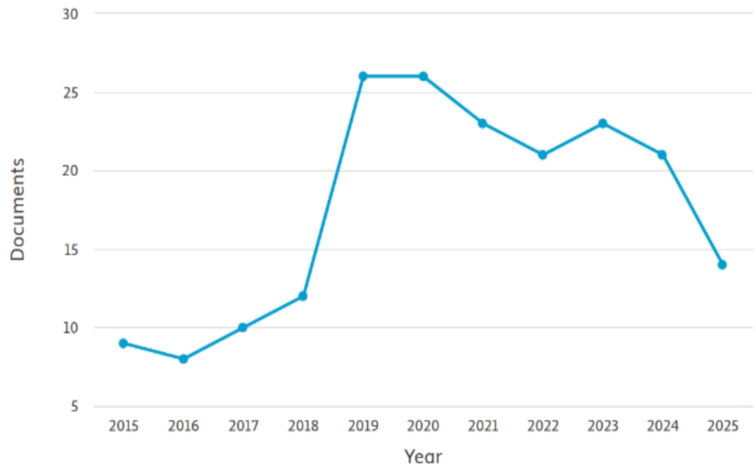


**Figure 2.** Scientific Publication Trends Related to "Science Process Skills" by Year of Publication

Science Process Skills (SPS) related publications between 2015 and 2025 experienced fluctuation. From 2015 to 2018, the number of documents increased gradually from approximately 8 to 12 documents. A sharp increase occurred in 2019 and 2020, reaching approximately 26 documents per year. Publications then declined gradually in 2021–2022, rose slightly in 2023, and declined again through 2025 to approximately 14 documents.

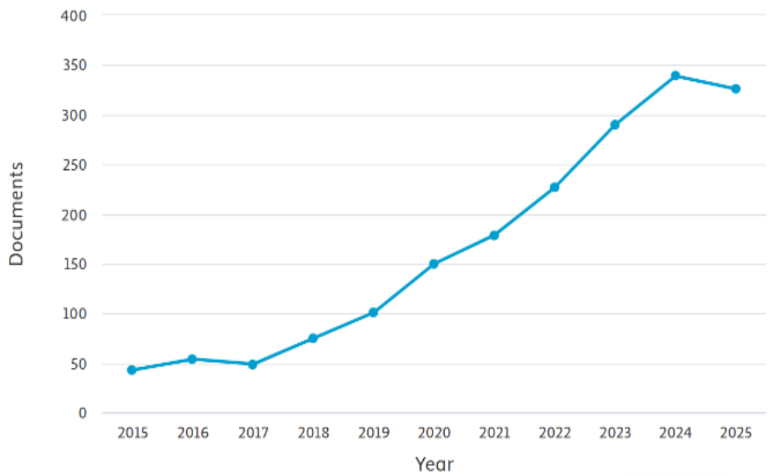


**Figure 3.** Scientific Publication Trends Related to "Self-Regulated Learning" by Year of Publication

Self-Regulated Learning (SRL) related publications showed an overall increasing trend from 2015 to 2025. In 2015, the number of publications was relatively low, at approximately 40–50 documents, followed by a slight increase in 2016 and a small decrease in 2017. The number of publications then increased again in 2018 and continued to rise from 2019 to 2024, reaching approximately 150 documents in 2020 and peaking at around 340 documents in 2024. A slight decline was observed in 2025, which may be attributable to incomplete indexing for the current year.

The fluctuating trend in Science Process Skills (SPS) publications, peaking in 2019–2020, likely reflected heightened global attention to science education reform and competency-based learning during the COVID-19 pandemic period, which prompted educators and researchers to revisit foundational science competencies. The subsequent decline may indicate a natural consolidation phase following a period of intensive publication activity. In contrast, the consistent growth in Self-Regulated Learning (SRL) publications through 2024 reflects the increasing recognition of self-regulation as a critical competency across diverse educational contexts, particularly driven by the rapid expansion of online and blended learning environments that demand greater student autonomy. The substantial difference in publication volume with SRL consistently producing far more publications than SPS, suggests that SRL has become a broader and more cross-disciplinary research area, extending beyond science education into general education, higher education, and technology-enhanced learning.

Keyword co-occurrence analysis using VOSviewer revealed the thematic structure of Science Process Skills (SPS) and Self-Regulated Learning (SRL) research. Minimum co-occurrence thresholds were set at one occurrence for SPS and five occurrences for SRL.

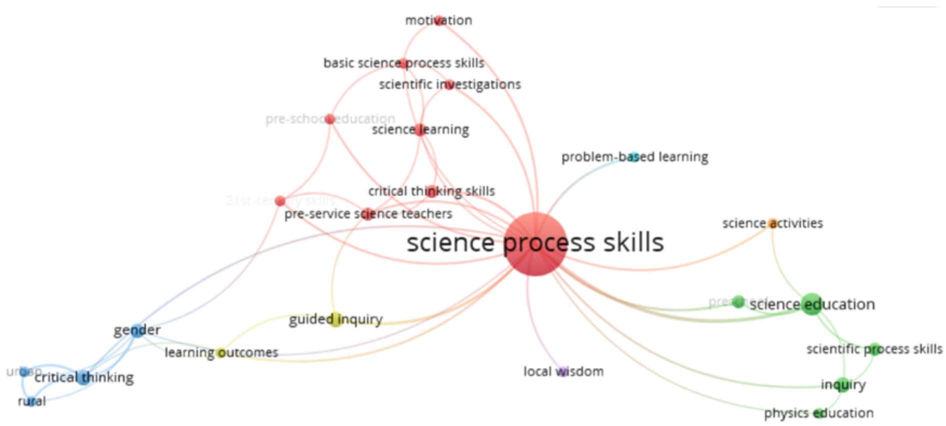


**Figure 4.** Network Visualization "Science Process Skills"

Network visualization revealed seven main clusters in Science Process Skills (SPS) research, with *science process skills* as the central node. The red cluster, the largest, contained three dominant nodes: *critical thinking skills*, *science learning*, and *pre-service science teachers*. The green cluster was dominated by *science education* connected to *inquiry* and *physics education*. The yellow cluster centered on *guided inquiry* linked to *learning outcomes*. The dark blue cluster contained *critical thinking* and *gender* as dominant nodes. The orange cluster was represented solely by *science activities*, the light blue cluster solely by *problem-based learning*, and the purple cluster solely by *local wisdom*. Notably, no cluster in the SPS network explicitly connected SPS to any assessment-related keyword.

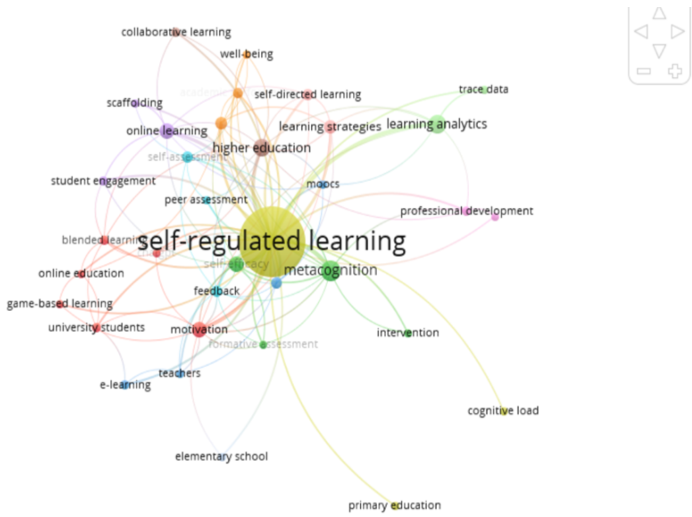


**Figure 5.** Network Visualization "Self-Regulated Learning"

Network visualization revealed nine main clusters in Self-Regulated Learning (SRL) research, with *self-regulated learning* as the central node. The yellow cluster, most directly connected to the central node, contained *primary education* and *cognitive load* as dominant nodes. The red cluster centered on *motivation* connected to *university students*, *online learning*, *blended learning*, and *game-based learning*. The blue cluster contained two dominant nodes, *feedback* and *self-assessment*, connected to *peer assessment*, *e-learning*, and *teachers*. The green cluster was dominated by *metacognition*, *self-efficacy*, and *learning analytics*, with *formative assessment* present but not prominent. The first purple cluster centered on *online learning* connected to *scaffolding* and *student engagement*. The light purple cluster was dominated by *professional development*. The pink cluster focused on *learning strategies* and *self-directed learning*. The orange cluster centered on well-being.

The dominance of the red cluster in Science Process Skills (SPS) research connecting critical thinking skills, science learning, and pre-service science teachers, indicates that SPS has been most extensively studied in the context of preparing science teachers to develop students' critical thinking. The isolation of problem-based learning, science activities, and local wisdom as single-node clusters suggests these are emerging yet underdeveloped research areas that have not yet formed strong thematic networks with other research streams. Most critically, the complete absence of assessment-related keywords from the SPS network visualization indicates that the role of assessment in SPS development has been largely overlooked at the macro level of the literature.

In contrast, the Self-Regulated Learning (SRL) network demonstrated a more mature and interconnected thematic structure. The blue cluster connecting feedback, self-assessment, and peer assessment, represents one of the most well-established research themes in SRL, consistent with theoretical models emphasizing the centrality of feedback in self-regulation cycles (Zimmerman, 2002). The presence of formative assessment within the green cluster, albeit not prominently, suggests that the connection between assessment and metacognition in SRL research is recognized but has not yet been fully elaborated. Together, the contrast between SPS and SRL network structures reveals a fundamental thematic divergence: while assessment is a central theme in SRL research, it is entirely absent from SPS research.

**Table 1.** Analysis of Articles Related to Science Process Skills

| Researcher (Year) | Intervention | Educational Level | Research Method | Findings |
|---|---|---|---|---|
| Wilujeng et al. (2020) | Local Potential Integrated Science Video | Junior Secondary (SMP) | Quasi-experimental nonequivalent control group | Experimental group's SPS improved from low to moderate level |
| Ping et al. (2020) | Scientific Argumentation | Senior Secondary (SMA) | Quasi-experimental Pre-test Post-test Non-equivalent Control Group | SPS significantly improved through Modified Argument-Driven Inquiry approach |
| Sholahuddin et al. (2020) | Cognitive Style-Based Learning (CSBL) | Junior Secondary (SMP) | Pre-experimental (two experimental groups) | Most SPS indicators improved |
| Rosana et al. (2021) | Natural Animal Audio Organic Growth System (NA-AOGS) with STEM approach | Higher Education | Research and Development (R&D) | Effectively improved students' SPS |
| Rusmini et al. (2021) | Self-Project Based Learning | Higher Education | Pre-Experimental One-Shot Case Study | Students' SPS was generally adequate |
| Rahmawati dan Fadhilah (2022) | STEM | Senior Secondary (SMA) | Pre-experimental one group pretest-posttest | STEM approach improved students' SPS |
| Senisum et al. (2022) | GIReSiMCo | Senior Secondary (SMA) | Quasi-experimental non-equivalent pretest–posttest control group | GIReSiMCo significantly influenced SPS improvement |
| Kasuga et al. (2022) | Problem-Based Learning | Junior Secondary (SMP) | Quasi-experimental | Significantly improved students' SPS |
| Beichumila et al. (2022) | Chemistry-Based Computer Simulations and Animations Instructional | Secondary School (O-Level), Form 1–4 | Mixed Methods | Supported the development of students' SPS |
| Leyva-figueroa et al. (2023) | Computer-Based Inquiry | Higher Education | Research and Development (R&D) | Effectively improved students' science process skills |

| Researcher (Year) | Intervention | Educational Level | Research Method | Findings |
|---|---|---|---|---|
| Abas et al. (2024) | Project-Based Learning (PjBL) | Higher Education | Quasi-experimental posttest control group | PjBL significantly improved students' SPS |
| Ramlawati et al. (2025) | Differentiated Science Inquiry | Junior Secondary (SMP) | Quasi-experimental non-equivalent control group | Significantly improved students' SPS |
| Darmayanti et al. (2025) | Environment-Oriented Practicum Guide Integrated with Catur Pramana | Primary School (SD) | Quasi-experimental one-group pre-test and post-test | Effectively improved students' SPS |
| Melesse et al. (2025) | Context-Based Instructional Approach | Secondary School | Quasi-experimental | Quasi-experimental |

Systematic Literature Review (SLR) results in Table 1 revealed that all interventions used to improve students' Science Process Skills (SPS) relied on student-centered learning approaches, grouped into three categories. First, project- and problem-solving-based models including Project-Based Learning (PjBL), Self-Project Based Learning, NA-AOGS with STEM, and Problem-Based Learning (Abas et al., 2024; Kasuga et al, 2022; Rahmawati & Fadhilah, 2022; Rosana et al, 2021; Rusmini et al, 2021). Second, scientific inquiry-based models such as Differentiated Science Inquiry, Scientific Argumentation, CSBL, GIReSiMCo, and Computer-Based Inquiry (Senisum et al., 2022; Ramlawati et al., 2025; Leyva-figueroa et al., 2023; Ping et al., 2020; Sholahuddin et al., 2020). (Ping et al., 2020; Ramlawati et al., 2025; Senisum et al., 2022; Sholahuddin et al., 2020; Leyva-Figueroa et al., 2023). Third, contextual and local wisdom approaches including Context-Based Instructional Approach, Environment-Oriented Practicum Guide, and Local Potential Integrated Science Video (Darmayanti et al., 2025; Melesse et al., 2025 Wilujeng et al., 2020). No study employed an assessment-based approach to improve SPS. In terms of methodology, quasi-experimental designs dominated, with mixed methods and R&D appearing only (Beichumila et al., 2022; Leyva-Figueroa et al., 2023; Rosana et al., 2021).

All interventions identified in Science Process Skills (SPS) research relied exclusively on student-centered learning approaches, particularly inquiry, project-based, and contextual models, reflects a well-established pedagogical tradition in science education that emphasizes learning by doing. These approaches have consistently demonstrated effectiveness in improving SPS. However, the absence of assessment-based interventions in SPS research represents a significant gap. As Harlen (1999) argued, SPS is not merely a procedural skill but also a conceptual tool that involves evaluation of evidence and reflection on scientific thinking dimensions that are precisely what assessment approaches are designed to elicit. The dominance of quasi-experimental designs further suggests that most SPS research has prioritized demonstrating intervention effectiveness over understanding developmental mechanisms, limiting insights into how scientific thinking processes actually unfold during learning.

**Table 2.** Analysis of Articles Related to Self-Regulated Learning

| Researcher (Year) | Intervention | Educational Level | Research Method | Findings |
|---|---|---|---|---|
| Granberg et al. (2021) | Formative Assessment | Junior Secondary, Sweden | Case Study | Significant improvement in students' self-efficacy, strategy use, and perceived autonomy |
| Beekman et al. (2021) | Formative Assessment | Primary School | Quantitative (longitudinal design) | Self- and peer-assessment had a significant positive effect on the development of students' self-regulation |
| Fraile et al. (2023) | Rubrics and Scripts | Higher Education | Quasi-experimental | Rubrics and scripts improved students' self-regulation |
| Ismail et al. (2023) | Authentic Assessment | Higher Education | Quasi-experimental | Authentic assessment improved students' self-regulated learning |
| Mngomezulu and Ramnarain (2024) | Formative Assessment | Grade 10 Physical Sciences / Senior Secondary | Descriptive | Improved students' attentional focus, motivational regulation, learning strategy use, and planning |
| Hartelt & Martens (2024) | Self-Assessment | Upper Secondary (Grades 10–13) | Quasi-experimental 2×2 factorial | Self-assessment group demonstrated higher self-regulation of their own conceptions |
| Öztürk et al. (2025) | Online Peer Feedback vs. Online Teacher Feedback | Higher Education | Mixed Methods (Quan-Qual) | Students in the online peer feedback group demonstrated higher SRL levels; participants showed positive perceptions toward online peer feedback |
| Lee et al. (2025) | Technology-Based Interactive Guidance | Higher Education | Quasi-experimental | Chatbot-assisted SRL significantly improved students' self-regulated learning |
| Liu et al. (2025) | Automated Corrective Feedback-Based Peer Assessment | Higher Education | Quasi-experimental | The ACF-PA group showed significant improvement in self-regulated learning conceptions |
| Aksela et al. (2025) | Computer-Based Writing Task | Grade 7 students (age 13), two Finnish middle schools | Mixed Methods (digital trace analysis and reflective interviews) | High-achieving students demonstrated more SRL cycles, were more actively engaged in monitoring, and exhibited more complex SRL transition patterns |

| Researcher (Year) | Intervention | Educational Level | Research Method | Findings |
|---|---|---|---|---|
| Khoiriyah & Roberts (2025) | Self-Assessment | Higher Education | Pre-test post-test interventional without control group (quantitative) with supporting qualitative approach | A significant positive correlation was found: stronger self-assessment was associated with higher SRL ability; external feedback and revision opportunities further strengthened students' self-regulation |

Systematic Literature Review (SLR) results in Table 2 revealed that assessment-based approaches represented the most prominent intervention pattern and were consistently associated with improvements in students' Self-Regulated Learning (SRL). Formative assessment was the most frequently used intervention across educational levels from primary school to higher education (Beekman et al., 2021; Granberg et al., 2021; Mngomezulu & Ramnarain, 2024). Self-assessment, peer assessment, authentic assessment, and online peer feedback also proved effective particularly at the senior secondary and higher education levels (Hartelt & Martens, 2024; Ismail et al., 2023; Khoiriyah & Roberts, 2025; Öztürk et al., 2025). Some studies employed technology-enhanced approaches such as chatbot-assisted guidance, automated corrective feedback, and computer-based writing tasks (Aksela et al., 2025; Lee et al., 2025; Liu et al., 2025). Quasi-experimental designs dominated, though mixed methods were used in several studies (Aksela et al., 2025; Öztürk et al., 2025).

In contrast to SPS research, Self-Regulated Learning (SRL) research demonstrated a clear convergence around assessment-based interventions, with formative assessment, self-assessment, and peer assessment is theoretically coherent. Formative assessment inherently operationalizes the core phases of SRL, students receiving formative feedback must set or revise goals, monitor their understanding, and strategically adjust their approach, mirroring the forethought, performance, and self-reflection phases described by Zimmerman (2002). The consistent effectiveness of self-assessment and peer assessment across studies further underscores that giving students structured opportunities to evaluate their own and peers' work activates metacognitive processes central to SRL. The methodological maturity of SRL research with some studies employing digital trace data to capture real-time regulation processes (Aksela et al., 2025) also suggests that the field has progressed toward understanding not just whether interventions work, but how self-regulation develops, a level of inquiry not yet reached in SPS research.

An additional combined keyword search using the terms "science process skills" AND "self-regulated learning" was conducted in Scopus, yielding 96 documents. These documents were further examined through titles, abstracts, and, when necessary, full texts to determine whether SPS and SRL were positioned as core constructs within a single intervention framework. The analysis showed that only one article explicitly integrated both SPS and SRL within a single intervention framework, employing a technology-based modified flipped classroom approach. However, this article was indexed in a Q4 journal and did not meet the quality criteria established for the present review. The remaining articles tended to position SRL as an application variable or supporting measure rather than integrating it substantively with SPS. This finding highlights that explicit integration of SPS and SRL remains an important area for further development in science education research.

The finding that Science Process Skills (SPS) and Self-Regulated Learning (SRL) have developed along relatively distinct intervention trajectories indicates a promising direction for future science education research. While SPS intervention studies have been predominantly characterized by inquiry-based, project-based, problem-based, and contextual learning approaches, SRL intervention studies have shown a strong orientation toward assessment-related practices, including self-assessment, feedback, peer assessment, and authentic assessment. This contrast suggests that assessment-oriented approaches may offer a meaningful pathway for integrating SPS and SRL development in science learning.

In this regard, Assessment for Learning (AfL) offers a relevant framework for integrating SPS and SRL because it positions assessment as part of the learning process, in which teachers and students use evidence of learning to identify current learning positions, clarify learning goals, and determine subsequent steps for improvement (Assessment Reform Group, 2002; Wiliam & Thompson, 2008). This orientation is aligned with SRL, which involves cyclical processes of forethought, performance, and self-reflection (Zimmerman, 2002), and with SPS, which requires students to plan investigations, evaluate evidence, interpret data, and reflect on scientific conclusions (Harlen, 1999). Through self-assessment, students can evaluate the quality of their scientific work and monitor their learning progress, a process that has been shown to support SRL and self-efficacy (Panadero et al., 2017). Meanwhile, individualized teacher feedback can help students understand the gap between their current performance and expected scientific standards and identify specific next steps for improvement (Hattie & Timperley, 2007; Sadler, 1989).

The integration of AfL into science learning is particularly important at the senior secondary level, where students are expected to engage in more complex scientific inquiry and demonstrate greater independence in managing their learning. Higher-order SPS indicators, such as hypothesis formulation, variable identification, experimental design, data interpretation, and evidence-based conclusion making, require not only procedural engagement but also continuous monitoring, evaluation, and revision. These processes correspond closely with SRL mechanisms and can be supported through AfL cycles involving clear success criteria, student self-assessment, individualized teacher feedback, and opportunities for revision. Thus, future research may focus on designing and empirically testing AfL-based science learning interventions that explicitly support both students' SPS and SRL. Such research would extend existing SPS intervention studies beyond student-centered instructional models and contribute to a more integrated understanding of how assessment practices can support scientific thinking and self-regulated learning simultaneously.

## CONCLUSION

This study shows that intervention research for improving students' Science Process Skills (SPS) during 2015–2025 has been dominated by student-centered learning approaches, including inquiry-, project-based, problem-based, and contextual learning models. In parallel, research on students' Self-Regulated Learning (SRL) indicates that assessment-oriented practices, such as self-assessment, feedback, peer assessment, authentic assessment, and formative assessment, have been consistently reported to support students' self-regulated learning across educational contexts. The contrast between these two research trajectories highlights an important opportunity to further explore assessment-oriented approaches in science education, particularly for integrating SPS and SRL development. The findings suggest that Assessment for Learning (AfL) may serve as a promising framework for future science learning interventions because it positions assessment as part of the learning process and involves teachers and students in using evidence of learning to guide improvement. AfL practices such as clear success criteria, student self-assessment, individualized teacher feedback, and opportunities for revision may support higher-order SPS, including hypothesis formulation, variable identification, experimental design, data interpretation, and evidence-based conclusion making, while simultaneously strengthening students' self-regulated learning. Therefore, future research may focus on designing and empirically testing AfL-based science learning interventions, particularly at the senior secondary level.

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