Al Ibtida: Jurnal Pendidikan Guru MI

DOI: https://doi.org/10.24235/al.ibtida.snj.v13i1.24037

Journal homepage: http://journal1.uinssc.ac.id/index.php/ibtida

# Examining Self-Regulated Learning as a Dynamic Network in Inquiry-Based Elementary Science Education

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**article info**

Article history:
Received: April 7, 2026
Received in revised form: June 20, 2026
Accepted: June 22, 2026
Available online: June 30, 2026

Keywords:
Self-regulated learning;
Inquiry based learning;
SRL dynamics;
Elementary students;

Published by Department of Madrasah Ibtidaiyah Teacher Education, Universitas Islam Negeri Siber Syekh Nurjati Cirebon, Indonesia in Collaboration with the Indonesian Islamic Elementary Education Lecturers Association

**abstract**

*Background:* Self-regulated learning is a key determinant of successful inquiry-based science learning, yet little is known about how elementary students' regulatory behaviors interact dynamically throughout the inquiry process.
*Aims:* This study examines self-regulated learning as a dynamic network of regulatory behaviors within inquiry-based elementary science education and evaluates changes in students' regulatory ability after instruction.
*Methods:* An embedded mixed-methods design was employed during a six-week intervention involving 207 elementary students from three public schools in Bandung, Indonesia. Qualitative data from inquiry worksheets were transformed into network data to map self-regulated learning behaviors across five inquiry stages, while pretest–posttest self-regulated learning questionnaire data were analyzed using the Wilcoxon signed-rank test.
*Results:* The results indicate that self-regulated learning operates as a dynamic and interconnected network. The self-regulated learning network consisted of 20 nodes and 29 directed edges, with a directed density of 0.076, modularity of 0.662, and directed clustering coefficient of 0.283. Forethought behaviors in the goal-setting stage showed strong weighted connectivity, while monitoring and reflection behaviors in the data-analysis stage acted as regulatory bridges. Wilcoxon signed-rank analysis showed a significant increase in self-regulated learning scores from pretest ($M = 3.13$, $Mdn = 3.08$, $IQR = 0.37$) to posttest ($M = 3.32$, $Mdn = 3.24$, $IQR = 0.59$), $Z = -6.72$, $p < .001$, $r = .47$. However, the N-gain value of 0.23 indicates low normalized improvement.
*Conclusion:* These findings suggest that inquiry-based science learning contributes to measurable improvements in elementary students' self-regulated learning. However, the relatively low learning gain indicates that sustained and explicit scaffolding is necessary to strengthen self-regulatory processes throughout inquiry activities.

**How to cite this article**: Kusumastuti, F. A., Widodo, A., Syaodih, E., & Muslim. (2026). Examining Self-Regulated Learning as a Dynamic Network in Inquiry-Based Elementary Science Education. *Al Ibtida: Jurnal Pendidikan Guru MI*, *13*(1), 82-96. https://doi.org/10.24235/al.ibtida.snj.v13i1.24037

## 1. Introduction

Mindful learning has become a central principle in contemporary elementary education because students are expected not only to acquire knowledge but also to regulate, monitor, evaluate, and redirect their own learning processes. In the Indonesian context, this emphasis is consistent with the Merdeka Curriculum and the Deep Learning Academic Framework, which highlight purposeful, meaningful, and reflective learning as important competencies for students (Kemdikdasmen, 2025). Self-regulated learning (SRL) is therefore relevant for elementary science learning because it explains how students set learning goals, select strategies, monitor understanding, evaluate evidence, and adjust their actions during learning (Dignath & Veenman, 2021; Panadero, 2017; Zimmerman, 2002).

SRL is a multidimensional construct rather than a single learning habit. It includes cognitive strategies, metacognitive monitoring, motivational beliefs, affective regulation, behavioral control, and context management (Boekaerts, 1997, 1999; Panadero, 2017; Schunk & Ertmer, 2000; Winne & Hadwin, 1998). Zimmerman (2002) describes SRL as a cyclical process consisting of forethought, performance, and self-reflection, while Pintrich (2000) expands this view by emphasizing planning, monitoring, control, and reflection across cognition, motivation and affect, behavior, and context. Winne and Hadwin's model also positions SRL as a metacognitive system in which learners compare task conditions, standards, operations, products, and evaluations (de Bruin & van Gog, 2012; Winne & Hadwin, 1998). These models indicate that SRL should be understood as an organized system of regulation that changes as learners interact with tasks and learning environments.

At the elementary level, SRL should not be treated as an ability that students automatically possess. Recent literature emphasizes that young learners require explicit strategy instruction, supportive teacher-student interactions, structured learning guides, and repeated practice to gradually internalize regulatory strategies (de Ruig et al., 2023; Kersna et al., 2025; Olid et al., 2025; P. Sins, de Leeuw, et al., 2024). A systematic review of SRL programs in primary education shows that interventions are more promising when strategies are directly taught, embedded in regular classroom activities, and accompanied by motivational support (Olid et al., 2025). Classroom-based evidence further indicates that children's self-regulation varies depending on executive functions, classroom situations, task demands, and degree of autonomy (Eberhart et al., 2024). Therefore, SRL research in elementary classrooms needs to move beyond general self-report scores and examine how regulatory behaviors actually unfold in authentic learning activities.

Inquiry-based science learning provides a powerful context for observing and developing SRL because students must formulate questions, plan investigations, collect data, evaluate evidence, construct explanations, and communicate findings (Bell et al., 2010; Mario & Mario, 2024; P. H. M. Sins et al., 2025). Inquiry tasks naturally require learners to activate prior knowledge, determine what they need to know, choose sources and strategies, monitor procedures, evaluate whether evidence answers the question, and revise explanations. However, inquiry-based learning may also create cognitive and regulatory demands that are difficult for elementary students when scaffolding is insufficient (Bruckermann et al., 2017; Lazonder & Harmsen, 2016; Mario & Mario, 2024). Thus, the effectiveness of inquiry is strongly linked to the extent to which students are supported in planning, monitoring, controlling, and reflecting on their learning.

Recent studies have begun to connect SRL and inquiry-based science learning more directly. Sins et al. (2025) developed measurement work on primary students' availability and production of SRL strategies during inquiry-based science education, including activation of prior knowledge, planning of time and effort, behavioral monitoring, learning monitoring, and strategy evaluation. Kubsch et al. (2025) show that process data from digital science classrooms can be used to identify students' regulatory patterns and inform early instructional support. Studies on teacher professional development also show that explicit instruction of SRL strategies can be strengthened when teachers receive sustained guidance and reflection opportunities (Arvatz et al., 2025; Olid et al., 2025; P. Sins, de Leeuw, et al., 2024). These findings suggest that SRL in science learning should be analyzed as a process that is situated, supported, and dynamically shaped by classroom tasks.

Nevertheless, three important gaps remain. First, many SRL studies still rely on aggregated questionnaire scores, making it difficult to capture the dynamic interaction among regulatory behaviors during learning (Panadero, 2017; P. H. M. Sins et al., 2025; Winne, 2018). Second, studies on inquiry-based science learning often examine achievement, engagement, or general strategy use without mapping how SRL behaviors are connected across inquiry stages such as goal setting, planning, investigation, analysis, and communication (Bell et al., 2010; Kubsch et al., 2025; Mario & Mario, 2024). Third, elementary science research still needs operational models that link SRL indicators, inquiry stages, and observable learning evidence, so teachers can understand not only whether students regulate learning but also where regulation is strong, weak, or disconnected (de Ruig et al., 2023; Kersna et al., 2025; P. H. M. Sins et al., 2025).

To address these gaps, this study conceptualizes SRL as a dynamic network of regulatory behaviors across inquiry-based elementary science learning. Instead of treating SRL only as a linear cycle or a total score, the study maps how forethought, performance, and reflection behaviors are connected across five inquiry stages. This approach allows the identification of central regulatory behaviors, bridging stages, and weakly connected areas that require further scaffolding. The study also combines process-oriented network analysis with pretest-posttest outcome data to examine both how SRL operates during inquiry and whether students' overall SRL ability changes after instruction.

The study was guided by two research questions: RQ1: How does self-regulated learning function as a dynamic network across inquiry-based learning stages in elementary science classrooms? RQ2: Is there a significant difference in students' self-regulated learning abilities before and after the implementation of SRL-integrated inquiry learning?

## 2. Methods

This section outlines the methodological framework employed in this study, including the research design, procedures, participants, data collection techniques, and data analysis methods. It also describes the steps taken to ensure the validity and rigor of the research process.The presentation of the research method is as follows:

*2.1 Research Design*

This study used an embedded mixed-methods design to examine SRL as both a learning process and a learning outcome. The qualitative strand was process-oriented and focused on students' written responses in inquiry worksheets, which were coded and transformed into relational data for network analysis. The quantitative strand was outcome-oriented and used a one-group pretest-posttest design to examine changes in students' SRL scores before and after the intervention. The embedded design was appropriate because the main phenomenon, namely the dynamic emergence of SRL during inquiry, required detailed process data, while the pretest-posttest data provided complementary evidence about measurable changes in students' regulatory ability

*2.2 Research Procedures*

The intervention was implemented in elementary science learning through structured inquiry activities that integrated SRL prompts into five inquiry stages: (1) finding research question, (2) planning investigation, (3) colecting data, (4) data analysis, and (5) communication. The intervention lasted six weeks and consisted of 12 meetings, with two meetings conducted each week. The classroom teacher served as the main instructor, while the researcher prepared the SRL-integrated inquiry design, worksheets, observation structure, and data collection procedures. Across the 12 meetings, students were repeatedly guided to formulate inquiry goals and questions, design investigations, conduct observations or experiments, record data, interpret evidence, communicate findings, and reflect on the quality of their learning strategies.

The teacher functioned as a facilitator and instructor who provided scaffolding through guiding questions, learning guides, checklists, prompts for monitoring, and reflective questions. The scaffolding was embedded in students' worksheets so that regulatory support was not treated as a separate activity but as part of the inquiry process itself. For example, students were prompted to identify what they already knew, state what they wanted to investigate, choose a strategy for answering the question, monitor whether their data were sufficient, and evaluate whether their conclusion was supported by evidence. This design follows the principle that SRL in elementary classrooms should be explicitly taught, repeatedly practiced, and gradually transferred from teacher-guided regulation to students' own regulation (de Ruig et al., 2023; Kersna et al., 2025; Olid et al., 2025; P. Sins, Leeuw, et al., 2024).

*2.3 Participants*

The participants were fifth-grade students from three public elementary schools (Sekolah Dasar Negeri) in Bandung City, Indonesia. The initial accessible population consisted of 330 students. After screening the submitted research data for completeness and matchability across instruments, 208 students had usable research data. The final quantitative pretest-posttest analysis was conducted using 207 matched records available in the quantitative dataset, because one record did not contain a complete matched set for inferential analysis. The sample was drawn from intact classroom groups because the intervention was implemented as part of regular classroom science instruction; therefore, random assignment at the student level was not feasible.

Permission to conduct the study was obtained from the principals of the participating schools before data collection. The study was conducted in the regular classroom setting with the support of classroom teachers. Students' worksheet and questionnaire data were used only for research purposes, and students' identities were treated confidentially in data processing and reporting.

### *2.4 Data Collection*

Data were collected from two main sources. First, qualitative process data were obtained from students' inquiry worksheets (LKPD). The worksheets documented students' responses across inquiry stages and provided observable evidence of regulatory behaviors, including goal setting, planning, monitoring, data interpretation, communication, and reflection. Second, quantitative data were obtained from an SRL questionnaire administered before and after the six-week intervention.

The operational framework was informed by SRL models and recent measurement literature on SRL in inquiry-based science learning. The SRL questionnaire consisted of 51 indicators aligned with five inquiry stages and three SRL phases: forethought, performance, and self-reflection. The instrument used a four-point response scale. Instrument validation involved two experts specializing in SRL and inquiry-based learning. Before being used in the main study, the instrument was piloted to examine item validity, reliability, and readability for elementary students. The readability check was important because SRL constructs such as monitoring, strategy selection, and self-evaluation must be phrased in language that fifth-grade students can understand. The final instrument was used to calculate students' average SRL scores, with 4.00 representing the maximum possible score.

**Table 1.** Alignment of inquiry stages, SRL phases, and observable evidence

| Inquiry stage | Dominan SRL Phase | Observable evidence in students' worksheets |
|---|---|---|
| Finding research question | Forethought | Activation of prior knowledge, identification of what students want to know, learning goals, and inquiry questions. |
| Planning investigation | Forethought, Performance | Choice of strategy, tools, materials, sources, prediction, division of roles, and planned procedure. |
| Collecting data | Performance | Focused attention, following procedures, data recording, monitoring group work, and adjustment of actions. |
| Data analysis | Performance, self-reflection | Connecting questions, data, evidence, and explanations; evaluating whether evidence supports the answer. |
| Communication | Self reflection | Presentation of findings, response to feedback, revision of explanations, and reflection on presentation quality. |

### 2.5 Data Analysis

Students' worksheet responses were analyzed through a structured coding process. The unit of analysis was a meaningful response segment that indicated a regulatory behavior. Each segment was coded according to its inquiry stage and SRL phase. For example, a statement of what students wanted to know was coded as forethought in goal setting, while a statement evaluating whether data answered the inquiry question was coded as reflection in data analysis.

Coding rigor was strengthened by using a pre-defined codebook derived from established SRL models and inquiry-based science learning indicators. The codebook specified operational definitions for each SRL behavior, examples of student responses, and decision rules for ambiguous responses. Because worksheet coding is interpretive, coding dependability was supported through expert review of the coding framework, repeated checking of coded segments, analytic memoing, and consensus discussion for ambiguous cases. A formal inter-rater reliability coefficient was not calculated in the available dataset; therefore, the study emphasizes transparent coding rules and provides the node and edge structure as supplementary material to support auditability.

The coded qualitative data were transformed into a directed SRL network. Nodes represented SRL behaviors embedded in inquiry stages. The network consisted of 20 nodes: five inquiry-stage nodes and fifteen stage-by-phase SRL behavior nodes. Directed edges represented sequential or functional relations among regulatory behaviors within and across inquiry stages. Three types of edges were used: stage-to-phase edges, phase-to-phase edges within the same inquiry stage, and inter-stage cascade edges linking reflection in one stage to the next inquiry stage. Self-loops were excluded. Edge weights were interpreted as the relative strength of observed regulatory relations, while the reported density, modularity, and clustering values were calculated from the binary directed network for clarity and replicability. The node list and edge list are provided as supplementary material.

Network analysis focused on both structural and centrality metrics. Structural metrics included the number of nodes, number of edges, directed density, undirected density, modularity, number of communities, and average clustering coefficient. Centrality interpretation focused on degree or weighted connectivity, betweenness, and the role of nodes as entry points, bridges, or endpoints in the inquiry-SRL process. The analysis was conducted using Gephi 0.10 and checked against the reconstructed node-edge matrix to ensure consistency between the visualization and reported network indicators.

Quantitative SRL data were analyzed in several steps. Descriptive statistics were calculated for pretest and posttest scores, including mean, standard deviation, median, quartiles, and interquartile range (IQR). The SRL questionnaire contained 51 indicators scored on a four-point scale; therefore, average scores were used to maintain interpretability on the original 1-4 scale. Because the paired-score distribution did not meet normality assumptions, the Wilcoxon signed-rank test was used to compare pretest and posttest scores. Effect size was calculated using $r = |Z| / \text{sqrt}(N)$. Normalized gain was calculated using the average-score formula, N-gain = (posttest - pretest) / (maximum score - pretest), with 4.00 as the maximum possible score.

## 3. Results

*3.1 Dynamic network of students' self-regulated learning across inquiry stages*

The network analysis showed that SRL behaviors were not distributed as isolated actions. Instead, they formed a connected but relatively sparse network across inquiry stages. The final network consisted of 20 nodes and 29 directed edges. The directed density was 0.076, indicating that only a small proportion of all possible directed ties appeared in the observed SRL network. This means that students' regulatory behaviors were organized selectively rather than uniformly connected across all inquiry stages.

Figure 1 presents the dynamic network of SRL behaviors across inquiry stages. The visualization shows five stage-related communities: goal setting, experiment planning, investigation implementation, data analysis, and communication. The modularity value was 0.662, indicating a strong community structure that corresponded to the five inquiry stages. The directed clustering coefficient was 0.283, while the undirected clustering coefficient was 0.567. These values suggest that SRL behaviors were locally clustered within inquiry stages but were not equally integrated across the entire learning sequence.

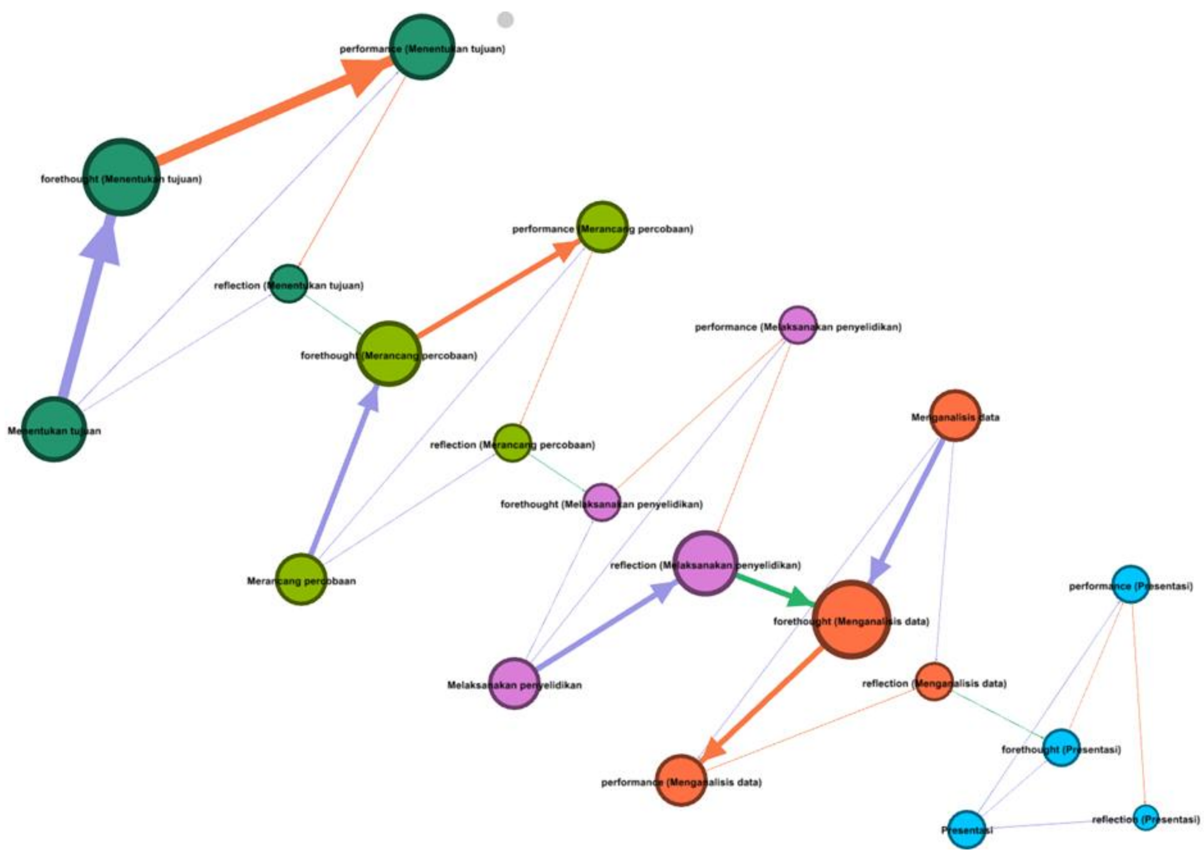


**Figure 1.** Dynamic Network of Self-Regulated Learning Across Inquiry-Based Learning Stages

The centrality pattern showed that forethought behaviors in the goal-setting stage had the strongest degree centrality. This means that these behaviors had the largest number of direct connections to other regulatory behaviors. In practical terms, students' ability to determine goals and formulate inquiry questions appeared to influence how they planned experiments, monitored investigations, and evaluated findings. The analysis stage also emerged as a regulatory hub because monitoring and reflection behaviors in this stage connected earlier planning processes with later communication activities.

The betweenness pattern suggests that data-analysis behaviors functioned as bridges in the network. At this stage, students had to interpret evidence, compare data with predictions, examine whether results answered inquiry questions, and refine explanations. These actions connected performance-oriented behaviors with reflective behaviors. In contrast, the communication stage showed relatively lower connectivity, indicating that students' presentations were less strongly integrated with previous monitoring and reflection processes. This pattern suggests a reflective discontinuity at the final stage of inquiry and points to the need for stronger scaffolding during presentation, peer feedback, and revision.

**Table 2.** Network-level indicators of students' SRL across inquiry stages

| Network indicator | Value | Interpretation |
|---|---|---|
| Number of nodes | 20 | The network included five inquiry-stage nodes and fifteen inquiry-stage-by-SRL-phase behavior nodes. |
| Number of directed edges | 29 | The network contained 29 directed relations among SRL behaviors across inquiry stages. |
| Directed density | 0.076 | The network was relatively sparse; only a small proportion of all possible directed ties appeared. |
| Undirected density | 0.153 | When direction was ignored, the overall level of connectedness remained modest. |
| Average degree | Directed = 1.45; undirected = 2.90 | Each node was connected to a limited number of other SRL behaviors on average. |
| Modularity | 0.662 | The network showed a strong five-community structure corresponding to the inquiry stages. |
| Number of communities | 5 | The communities aligned with goal setting, experiment planning, investigation implementation, data analysis, and communication. |
| Average clustering coefficient | Directed = 0.283; undirected = 0.567 | SRL behaviors showed moderate local clustering, especially when direction was ignored. |

**Table 3.** Main centrality findings from the SRL network

| Centrality focus | Dominant node/stage | Interpretation |
|---|---|---|
| Degree centrality | Forethought behaviors in goal setting | Goal setting acted as the main entry point that connected directly with later regulatory behaviors. |
| Betweenness centrality | Monitoring and reflection behaviors in data analysis | Data analysis acted as a bridge connecting planning and implementation with communication. |
| Lower connectivity | Communication stage | Communication appeared to function more as an endpoint than as an integrated reflective bridge. |

### *3.2 Changes in Students' Self-Regulated Learning Scores*

The quantitative analysis showed an increase in students' SRL score from pretest (M = 3.13, SD = 0.31, Mdn = 3.08, IQR = 0.37) to posttest (M = 3.32, SD = 0.40, Mdn = 3.24, IQR = 0.59), with a mean difference of 0.20 on a four-point scale. The Wilcoxon signed-rank test indicated a statistically significant difference between pretest and posttest scores, W = 4429.00, Z = -6.72, $p < .001$. The rank pattern showed 138 positive ranks, 60 negative ranks, and 9 ties, indicating that more students improved than declined. The effect size was r = .47, which indicates a moderate-to-large practical effect. However, the N-gain score was 0.23, which falls in the low category. Thus, SRL-integrated inquiry learning was associated with statistically reliable improvement, although the normalized magnitude of improvement remained limited.

**Table 4.** Summary of Pretest–Posttest Analysis of Students' Self-Regulated Learning scores

| Data | Pretest | Posttest |
|---|---|---|
| Number of students | 207 | 207 |
| Minimum Score | 2.49 | 2.53 |
| Maximum score | 3.96 | 4.0 |
| Mean | 3.13 | 3.32 |
| Standard deviation | 0.31 | 0.40 |
| Median | 3.08 | 3.24 |
| Interquartile range (IQR) | 0.37 (Q1 = 2.94; Q3 = 3.31) | 0.59 (Q1 = 3.00; Q3 = 3.59) |
| Mean difference | - | 0.20 |
| Normality test | p < .001 | Data were not normally distributed |
| Wilcoxon signed-rank test | W = 4429.00; Z = -6.72; p < .001 | H0 rejected; H1 accepted |
| Rank pattern | Positive ranks = 138; negative ranks = 60; ties = 9 | Most students showed higher posttest SRL scores |

| | | |
|---|---|---|
| Effect size | r = .47 | Moderate-to-large practical effect |
| N-gain | 0.23 | Low normalized improvement |

## 4. Discussion

This study provides two complementary findings. First, SRL functioned as a dynamic network across inquiry stages, consisting of 20 nodes and 29 directed edges. The network was relatively sparse, as shown by directed density = 0.076, but it also had a strong five-community structure, as shown by modularity = 0.662. Second, students' SRL scores were significantly higher following SRL-integrated inquiry learning, with $Z = -6.72$, $p < .001$, and $r = .47$, although the N-gain value of 0.23 indicated low normalized improvement. These findings support the view that SRL is both a process that unfolds during learning and a competence that develops gradually through instructional support (Dignath & Veenman, 2021; Olid et al., 2025; Panadero, 2017; Zimmerman, 2002). The combination of network analysis and pretest-posttest data therefore offers a more nuanced understanding than a single outcome measure.

The centrality of goal setting confirms the importance of the forethought phase in SRL. In Zimmerman's model, forethought provides the foundation for later performance and reflection because learners must first interpret task demands, set goals, anticipate strategies, and activate motivation (Zimmerman, 2002). The present network results extend this idea by showing that goal setting was not only the first stage in a sequence but also a highly connected node in the system. This means that early regulation had a cascading function: once students formulated goals and questions, they were better positioned to plan procedures, monitor actions, interpret data, and reflect on their findings. This finding is consistent with SRL theory, which emphasizes that goal setting and task analysis organize learners' later strategic actions (Dignath & Veenman, 2021; Panadero, 2017; Schunk & Ertmer, 2000).

The emergence of the analysis stage as a regulatory hub is also theoretically important. In inquiry-based science learning, analysis requires students to connect questions, data, evidence, and claims. This means that students must not only perform procedures but also evaluate whether their evidence is adequate and whether their explanation is justified. Such activity reflects the interaction between monitoring, self-evaluation, judgment of learning, and strategic revision (De Bruin et al., 2011; de Bruin & van Gog, 2012; Winne, 2018; Wong et al., 2019). The centrality of analysis therefore suggests that deep SRL in inquiry occurs when students move from doing experiments to judging the quality and relevance of evidence.

This finding aligns with recent work on SRL in inquiry-based science learning. Sins et al. (2025) emphasize that students' SRL during inquiry includes both the availability and production of strategies, including monitoring of behavior, monitoring of learning, and evaluation of strategies. Kubsch et al. (2025) further show that process data in science classrooms can reveal meaningful regulatory patterns and help identify students who need support. The current study contributes to this literature by showing that the analysis stage may be a critical point for detecting whether regulation is coherent or fragmented across inquiry stages.

The weaker connectivity of the communication stage indicates that students' final presentations may not automatically function as reflective learning moments. Students may be able to report findings without fully revisiting the quality of their questions, procedures, data, and explanations. This is consistent with the view that elementary students need explicit scaffolding to engage in deeper metacognitive and reflective processes (de Ruig et al., 2023; Kersna et al., 2025; Olid et al., 2025). Communication should therefore be redesigned not merely as presentation but as reflective argumentation, peer feedback, and evidence-based revision. Teacher prompts such as "Which data best support your answer?", "What evidence is still weak?", and "How did feedback change your explanation?" may help transform communication into a stronger regulatory bridge.

The statistically significant but low normalized improvement in SRL scores requires careful interpretation. The Wilcoxon result indicates that the posttest distribution differed reliably from the pretest distribution, and the effect size suggests that the difference was educationally meaningful. However, the low N-gain shows that students did not approach the maximum possible score after one six-week intervention. Therefore, the finding should not be interpreted as evidence that the intervention fully developed SRL. Rather, SRL-integrated inquiry learning was associated with initial growth in regulatory ability, while stronger and more sustained improvement likely requires longer instructional exposure.

Several explanations may account for the low N-gain. First, the six-week, 12-meeting intervention may not have been long enough for students to internalize regulatory strategies. Second, elementary students may still depend heavily on external scaffolding from teachers and worksheets before they can regulate independently. Third, SRL requires coordination among cognition, motivation, affect, behavior, and context; improvement in one component may not immediately produce large gains across the full SRL system (Boekaerts, 1997, 1999; Panadero, 2017; Schunk & Ertmer, 2000). Recent studies similarly emphasize that SRL interventions in primary education work best when strategy instruction is explicit, repeated, and integrated into regular classroom activity (Dermitzaki, 2025; Olid et al., 2025; P. Sins, Leeuw, et al., 2024).

The findings have practical implications for elementary science instruction in Indonesia. First, SRL prompts should be integrated into every inquiry stage rather than added only at the beginning or end of lessons. Second, communication activities should include explicit reflective prompts so that presentation becomes a moment for evaluating evidence, responding to feedback, and revising understanding. Third, teachers need professional support to design inquiry tasks, learning guides, and feedback routines that move students from teacher-guided regulation toward more independent regulation. This implication is consistent with Indonesian evidence that SRL is closely related to critical thinking in primary schools and that elementary students need learning designs that help them evaluate evidence and justify claims(Nurfaidah P et al., 2026). Digital and AI-supported learning studies also suggest that technology can support SRL only when it is embedded within clear pedagogical scaffolding rather than used as a substitute for teacher guidance (Ardiyanti et al., 2025; Kubsch et al., 2025; Tsz et al., 2024).

Methodologically, this study shows the value of network analysis for examining SRL as a connected process. Traditional pretest-posttest analysis can identify whether scores change, but it cannot show where regulation is activated, where it becomes central, and where it weakens. Network analysis adds this process-level information by showing that the network was sparse but modular, with strong clustering around inquiry stages and weaker integration at the communication stage. For example, the centrality of goal setting suggests the need to strengthen early task interpretation, while the weaker communication stage suggests the need to add reflective prompts and peer-feedback routines. This approach responds to calls for SRL research that is more process-oriented, context-sensitive, and connected to observable learning evidence (Kubsch et al., 2025; Panadero, 2017; Sins et al., 2025; Winne, 2018).

Overall, the study contributes to SRL theory by repositioning SRL not only as a cyclical individual process but also as a networked and context-dependent system embedded in inquiry activity. It contributes to inquiry-based science education by showing that inquiry can activate SRL, but only sustained scaffolding can help students transform inquiry engagement into stronger regulatory competence. It also contributes to elementary education in Indonesia by offering an operational model for connecting SRL indicators, inquiry stages, student worksheet evidence, and outcome measurement.

## 5. Limitations

This study has several limitations. First, the study involved fifth-grade students from three public elementary schools in Bandung City; therefore, the findings should be generalized cautiously to other grades, regions, or school contexts. Second, although the initial accessible population consisted of 330 students and 208 students submitted usable research data, the inferential quantitative analysis was conducted with 207 matched pretest-posttest records available in the final dataset. Third, the qualitative data were derived mainly from written worksheet responses, which may not fully capture internal cognitive, motivational, emotional, or social regulation processes. Fourth, the coding process was supported by a codebook, expert review, and repeated checking, but a formal inter-rater reliability coefficient was not calculated. Fifth, the pretest-posttest component did not include a control group; therefore, the findings should be interpreted as an association between SRL-integrated inquiry learning and improvement in SRL scores rather than as definitive causal evidence. Finally, the low N-gain indicates that longer and more sustained instructional support is needed to produce stronger regulatory development.

## 6. Conclusion

This study examined SRL as a dynamic network within inquiry-based elementary science learning and evaluated changes in students' SRL ability after six weeks of SRL-integrated inquiry instruction. The findings indicate that SRL behaviors formed a structured network consisting of 20 nodes and 29 directed edges, with strong modular organization across the five inquiry stages. Early forethought in goal setting functioned as an important entry point for later regulation, while data analysis acted as a regulatory bridge where students connected questions, evidence, and conclusions. Quantitatively, students' SRL scores increased significantly from pretest to posttest, $W = 4429.00$, $Z = -6.72$, $p < .001$, $r = .47$. However, the N-gain of 0.23 shows that the improvement remained low in normalized terms. These findings suggest that inquiry-based science learning can activate SRL and is associated with measurable improvement, but elementary students require explicit, repeated, and sustained scaffolding to develop more independent regulatory ability. The study contributes theoretically by conceptualizing SRL as a dynamic and networked process, methodologically by combining worksheet-based process data with pretest-posttest outcome data, and practically by highlighting the need for SRL scaffolding across all stages of elementary science inquiry.

## Author Contributions

Fransiska Astri Kusumastuti contributed to the conceptualization of the study, research design, data collection, data analysis, and manuscript writing. Ari Widodo, as the promoter, contributed to the supervision of the research process, refinement of the research design, and critical revision of the manuscript. Ernawulan Syaodih, as co-promoter, contributed to methodological guidance, validation of the research framework, and review of the manuscript. Muslim, as a member of the co-promoter team, contributed to data interpretation, theoretical enrichment, and manuscript review. All authors have read and approved the final version of the manuscript.

## Acknowledgments

The authors gratefully acknowledge the participating elementary school students, teachers, and school leaders who supported the implementation of SRL-integrated inquiry-based science learning. The authors also thank the doctoral supervisory team at Universitas Pendidikan Indonesia for academic guidance during the development of the research framework and manuscript.

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