RESEARCH ARTICLE

Empirical evidence of students' systems thinking skills in ESD-oriented: A Rasch analysis approach

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Abstract: Education for Sustainable Development (ESD) serves as a key accelerator for achieving the Sustainable Development Goals (SDGs), emphasizing systems thinking as an essential competency that must be cultivated in the learning process. This study investigates students' systems thinking skills within the ESD framework through assessments on environmental change—one of the core topics in biology education. Systems thinking enables students to analyze complex real-world phenomena by examining the interactions among system components and their role in forming an integrated whole. This descriptive quantitative study involved sixty 10th-grade students who were assessed using twelve essay questions, each designed to evaluate specific indicators of systems thinking within the ESD context. Data were analyzed using Rasch modeling in Winsteps, focusing on student ability levels, item validity, reliability, and Differential Item Functioning (DIF). Results indicated high item reliability, yet most students demonstrated pre-aware or emerging levels of systems thinking, particularly in identifying system components, recognizing interconnections, and applying systems thinking to sustainability issues. The low Person Measure Average suggests a pressing need for instructional improvements to strengthen students' systems thinking competencies. These findings underscore the necessity of integrating systems thinking into curricula to better prepare students for addressing sustainability challenges effectively.

Keywords: biology education; education for sustainable development; environmental change; systems thinking skills

Introduction

Climate change, a well-documented environmental issue, has garnered global attention due to its profound impacts on ecosystems, biodiversity, water resources, weather patterns, and human settlements. These environmental disruptions significantly affect socioeconomic conditions and human well-being (OECD, 2024). Consequently, environmental concerns have become central to the Sustainable Development Goals (SDGs) and are recognized as one of the three core dimensions of sustainable development—social, economic, and environmental (UNESCO, 2014).

The SDGs emphasize the need for all systems of life to advance toward sustainability. Addressing the root causes of current environmental challenges requires a coordinated and in-depth approach (Ullah et al., 2022). As one of the 17 SDG agenda items, Education for Sustainable Development (ESD) plays a crucial role in fostering high-quality education systems worldwide. ESD aims to promote changes in knowledge, skills, and attitudes, equipping societies with the capacity to transition toward sustainable practices. Beyond merely transferring 21st-century skills, education should enable students to internalize the principles and values necessary to achieve a sustainable future (Zguir et al., 2021). The integration of ESD into learning processes is expected to address various sustainability challenges while fostering students' awareness of environmental issues (Grund & Brock, 2019; Abdurrahman et al., 2023).

Sustainability is closely linked to specific ways of thinking and actions that adhere to ethical principles and active participation in promoting social and environmental well-being, both in the present and the future. It encompasses multiple cognitive dimensions, including collaborative thinking, future-oriented thinking, and systems thinking (Lander, 2015). Among these, systems thinking has been identified as a fundamental competency for achieving sustainability (UNESCO, 2017). This cognitive approach enables individuals to comprehend and address complex societal, economic, and environmental issues (Costa et al., 2019; Lacovidou et al., 2021; Lezak & Thibodeau, 2016).

Developing systems thinking skills is crucial for fostering sustainable behavior (Holfelder, 2019). According to Lezak and Thibodeau (2016), systems thinking shapes attitudes that influence perceptions of climate change risks and support for sustainability policies. Additionally, it promotes decision-making that integrates economic, social, and ecological perspectives. Systems thinking enhances individuals' abilities to analyze challenges, develop solutions, and contribute effectively as global citizens (Lee et al., 2017). It represents a cognitive framework in which learners perceive phenomena as interconnected components forming an integrated whole (Ballew et al., 2019).

Three major theoretical frameworks underpin systems thinking: (1) General Systems Theory (GST) – Focuses on hierarchical structures and interrelations within systems; (2) Cybernetics (C) – Emphasizes self-regulation and feedback mechanisms within systems; (3) Dynamic Systems Theories (DST) – Address the constantly evolving nature of systems (Boersma et al., 2011; Gilissen et al., 2020; Verhoeff et al., 2018). Gilissen et al. (2020) further identified key characteristics of systems thinking, including emergence, wherein new properties arise from interactions between system components rather than from individual elements.

Despite the importance of systems thinking, many students perceive systems as static, isolated components, failing to recognize the spatial and temporal relationships essential for understanding dynamic systems (York et al., 2019). To overcome this limitation, systems thinking serves as a student-centered approach that enhances motivation and develops competencies needed to analyze and solve real-world problems. Arnold and Wade (2017) describe two core systems thinking skills: (1) gaining insights, which refers to deepening one's understanding of a system, and (2) applying insights, which involves using this understanding to analyze and influence the system. A failure to distinguish between these aspects may lead to an incomplete grasp of systems thinking.

Developing systems thinking skills through education has numerous benefits. Zhang and Ahmed (2020) highlighted that implementing systems thinking in K-12 education: (1) Enables science teachers to create student-centered learning environments; (2) Encourages active student participation in problem-solving; (3) Provides more relevant learning experiences that enhance comprehension; (4) Improves students' critical thinking and problem-solving abilities; (5) Changes both teachers' and students' perspectives on interconnected systems; (6) Facilitates learning that adheres to scientific principles (7) Promotes collaboration and teamwork in tackling complex challenges; and (8) Supports the design of solutions. The application of the Conceptual Modeling Process (CMP) has also been shown to develop students' systems thinking skills, resulting in more coherent systems thinking (Hmelo-Silver et al., 2016).

Several methods have been developed to assess systems thinking skills (Seher Budak & Defne Ceyhan, 2024). Miller et al. (2023) used picture-based questionnaires to evaluate undergraduate students' abilities in recognizing patterns, understanding interconnections, and interpreting complex structures. Similarly, Systemic Assessment Questions (SAQs) developed by Vachliotis et al. (2014) effectively capture students' comprehension of systems thinking principles. Additionally, scenario-based assessments by Norris et al. (2022) revealed that students often lack opportunities to develop complex problem-solving skills necessary for systems thinking.

Another widely used method is essay-based assessment, which requires students to construct written responses that demonstrate higher-order thinking skills (Brookhart & Nitko, 2019). Essays can be categorized into restricted-response (which limits the scope and structure of answers) and extended-response (which allows students to organize and articulate their thoughts independently). These assessments are typically evaluated using rubrics or scoring scales (Brookhart & Nitko, 2019). A study by Saragih et al. (2021) utilized an essay-based instrument to measure systems thinking skills among 10th-grade students, incorporating ESD-related indicators. However, the study's scope was limited, as it failed to comprehensively assess essential aspects such as empathy, responsibility, contextual awareness, and the application of systems thinking in everyday life (Semiz & Teksöz, 2019). These aspects are crucial for fostering a holistic understanding of human-environment interconnections (UNESCO, 2017).

Given the limitations of previous studies, there is a pressing need for an instrument specifically designed to assess students' systems thinking skills within the ESD framework. A more comprehensive evaluation tool would provide valuable insights into students' proficiency in this area. This study aims to examine and assess students' systems thinking skills in the context of ESD, utilizing an essay-based assessment on environmental change topics in biology education. The research also seeks to contribute to the limited body of literature on systems thinking skills in biology education.

Method

This study employed a descriptive research design with a quantitative approach, conducted over a six-month period from February to August 2024. The participants consisted of sixty 10th-grade students from a senior high school in West Sumatera, selected using a non-random sampling technique. The use of non-random sampling was due to practical constraints and limited resources, which made the application of a random sampling technique infeasible.

The instrument used to assess students' systems thinking skills was developed by the researcher based on systems thinking indicators within the context of Education for Sustainable Development (ESD), as proposed by Semiz & Teksöz (2019). The test consisted of 12 essay questions, each focusing on environmental change topics, aligned with the learning outcomes outlined in Kurikulum Merdeka. Each systems thinking indicator was represented by a corresponding essay question. The scoring rubric for students' responses was adapted from Semiz & Teksöz (2019), with modifications made to accommodate specific indicators and skill levels relevant to the study. The revised rubric provided a structured framework for evaluating students' conceptual understanding, reasoning, and application of systems thinking skills in the context of ESD (see Table 1).

Table 1. Modified rubric for assessing systems thinking skills

Systems Thinking Skills (STS)	Pre-aware (0)	Emerging (1)	Developing (2)	Mastery (3)
STS-1. Identifying the meaning and aspects of sustainability	Students are less able to explain the meaning of sustainability and do not refer to aspects of sustainability.	Students are able to explain the meaning of sustainability or refer to one aspect of sustainability.	Students are able to explain the meaning of sustainability and refer to two aspects of sustainability.	Students are able to explain the meaning of sustainability and clearly refer to more than two aspects of sustainability (social, economic, environmental)
STS-2. Seeing nature as a system	Students do not explain the events and impacts caused by human activities that damage the environment and do not view nature as a system without considering integral ecological aspects (culture, behavior, systems and individuals) and does not describe human-nature relationships	Students explain events that will occur and the impacts caused by human activities that damage the environment, but are not yet precise, and only consider one aspect of integral ecology (culture or behavior or system or individual) and describe human-nature relationship	Students explain events that will occur and the impacts caused by human activities that damage the environment, and are able to see nature as a system by considering two aspects of integral ecology (culture, behavior, systems and individuals) and describe human-nature relationships holistically	Students explain events that will occur and the impacts caused by human activities that damage the environment, and are able to see nature as a system by considering two or more aspects of integral ecology (culture, behavior, systems and individuals) and describe the human-nature relationship holistically
STS-3. Identifying system components	Students cannot identify the components of a system	Students can identify examples or members of components but do not classify them into components (biotic or abiotic) of a system.	Students can identify examples or members of components and classify them into one of the components (biotic or abiotic) of a system.	Students can identify examples or members of components and classify them into both components (biotic and abiotic) of a system clearly.
STS-4. Analyze the relationships between aspects of sustainability.	Students do not explain efforts that can be made based on sustainability principles and do not analyze the interconnections between aspects of sustainability.	Students are able to explain efforts that can be made based on the principles of sustainability but do not analyze the interconnections between aspects of sustainability.	Students are able to explain efforts that can be made based on the principles of sustainability and are able to analyze interconnections by considering one or two aspects of sustainability.	Students are able to explain efforts that can be made based on the principles of sustainability and are able to critically analyze the interconnections between system components by considering all aspects of sustainability.
STS-5. Recognizing hidden dimensions in a system	Students cannot identify hidden dimensions in a system	Students identify one hidden dimension in a system but are not precise.	Students are able to identify one hidden dimension in a system and relate it to the problem in a simple way.	Students are able to identify two hidden dimensions in a system by clearly relating them to the problem.
STS-6.	Students are unable to	Students make	Students make	Students are able to make

Systems Thinking Skills (STS)	Pre-aware (0)	Emerging (1)	Developing (2)	Mastery (3)
Acknowledge own responsibility in the system	make connections between problems/issues and personal life.	connections between problems/issues and their personal lives but they are not yet accurate.	connections between problems/issues and personal life in a simple way.	connections between problems/issues and personal life clearly.
STS-7. Consider the relationship between past, present, and future actions	Students are unable to interpret data and are unable to make connections between past, present, and future human actions.	Students do not interpret data correctly, and only consider one time (past or present or future)	Students interpret data correctly, and make connections between past, present and future human actions. Students mostly consider two-time spans (e.g., past and present)	Students interpret data correctly, and can make clear connections between human actions in the past, present and future.
STS-8. Recognize the cyclical nature of systems.	There is no explanation of the cyclical nature of the system.	Students explain the relationship between green areas and the water cycle and provide an explanation of the nature of the cycle, but it is not yet correct.	Students explain the relationship between green areas and the water cycle and recognize the cyclical nature of the system in a simple way.	Students explain the relationship between green areas and the water cycle and can recognize the cyclical nature of the system by providing examples (e.g. natural cycles).
STS-9. Developing empathy with others	Students cannot develop empathy with others by not making statements that show empathy.	Students develop empathy with others but are unable to provide explanations for their needs or reasons.	Students develop empathy with others, but only provide simple explanations of their needs or reasons.	Students are able to develop empathy with others by explaining the reasons or needs behind their actions without blaming others.
STS-10. Developing empathy with non-human beings	Students are unable to make connections with non-human beings.	Students make connections with non-human creatures but are not appropriate.	Students express their relationships with non-human beings in a simple way.	Students can clearly state their relationships with non-human creatures and with the rest of nature.
STS-11. Developing a sense of place	Students cannot build any sense of place without defining a place with certain dimensions.	Students define a place with only one dimension	Students build a multidimensional understanding of place. Students can define the place based on two dimensions.	Students can build a multidimensional and holistic understanding of place. Students can associate more than two meanings (dimensions) to a place (biophysical, social, cultural, political, etc.)
STS-12. Adapting systems thinking perspectives to personal life	Students are unable to adapt the systems thinking perspective into their personal lives.	Students describe actions that adapt a systems thinking perspective to personal life but are not yet appropriate.	Students adapt a systems thinking perspective to their personal lives by taking small, observable steps from the behavioral examples provided.	Students are able to adapt the systems thinking perspective into their personal lives by taking transformative actions through the habits they practice that can be observed from the explanations given.

Students' responses were scored, compiled, and organized using Microsoft Excel before being imported into the Winsteps application for Rasch model analysis. The Rasch model was employed to provide an in-depth examination of students' systems thinking abilities through the person logit value (PLV). To ensure the validity and reliability of the instrument, several statistical analyses were conducted:

1. Content validity was assessed through fit validity, determined using two indices:
   a. Infit MNSQ (Mean-Square)
   b. Outfit MNSQ (Mean-Square)
2. Construct validity was evaluated through a unidimensionality test, ensuring that all test items measured a single underlying construct.
3. Reliability and separation measures were calculated, including:
   a. Person reliability and item reliability (to assess consistency in responses).
   b. Person separation and item separation indices (to determine the degree of differentiation between students' abilities and item difficulty levels).

The Rasch model analysis also facilitated the identification of potential gender-based differences in students' systems thinking abilities. Differential Item Functioning (DIF) analysis was conducted using Winsteps, allowing for the detection of test items that functioned differently based on gender. To ensure clarity in the analysis, the following coding system was applied:

M = Male students
F = Female students
ST = Systems Thinking item codes (e.g., ST-1 represents the first systems thinking skill indicator—STS-1).

Results and Discussion

Validity Analysis

Content validity was assessed through fit validity, specifically examining two fit indices: Infit MNSQ (Mean-Square) and Outfit MNSQ (Mean-Square) (Bond et al., 2021). The initial evaluation, based on the Outfit MNSQ data column, revealed a value of 0.98, indicating that all items conform to the model (Boone et al., 2014; Boone & Staver, 2020). Table 2 reveals an Outfit MNSQ value of 0.98, indicating that all items conform to the model. Boone et al. (2014) explain that a range between 0.5 and 1.5 generally signifies a good fit between the data and the model. This falls within the acceptable range of 0.5 to 1.5, confirming a good fit between the data and the model.

Table 2. Summary of Rasch parameters for the systems thinking skills test in the ESD context

Psychometrics attribute	Results
Number of items	12
Mean	
Item outfit MNSQ	0.98
Item Infit MNSQ	1.02
Person outfit MNSQ	0.98
Person Infit MNSQ	1.01

Construct validity was assessed using a unidimensionality test, considering two aspects: raw variance and unexplained variance in the 1st contrast. The raw variance by measure reflects the scale's capacity to predict item performance (Bond et al., 2021). As presented in Table 3, the obtained raw variance by measure is 45.9%, which exceeds the 40% threshold and can be categorized as satisfactory (Sumintono & Widhiarso, 2015). A high proportion of raw variance by measure indicates that the scale effectively predicts item performance (Bond et al., 2021).

Table 3. Rasch parameters for construct validity

Psychometrics attribute	Results
Unidimensionality	
Raw variance by measure	45.9%
Unexplained variance 1st contrast	9.9%

Another aspect of unidimensionality to consider is unexplained variance. Measurement inaccuracies due to shortcomings in the instrument, rather than other types of errors, are referred to as unexplained variance (Bond et al., 2021). Thus, unexplained variance is naturally occurring variance that reflects error variance, without any specific interventions (Andrich & Marais, 2019). An ideal unexplained variance for an instrument should not exceed 15% (Sumintono & Widhiarso, 2014). Bond et al. (2021) further highlight that the unexplained variance of the 1st contrast is critical. Additionally, an eigenvalue below 3.0 for the first contrast satisfies the unidimensionality criterion (Eakman, 2012). Table 3 shows the unexplained variance in the 1st contrast in this study is 9.9%, with an eigenvalue of 2.1938. Therefore, all items are deemed productive for measurement and provide reasonable predictions.

Reliability Analysis

In this study, Table 4 demonstrates the item reliability score of >0.94, specifically 0.97, which indicates that the quality of the test items in the instrument falls into the "excellent" category (Sumintono & Widhiarso, 2015). Additionally, the items exhibit more than five levels of item difficulty, with a separation value of 5.38. However, the person reliability score is low at 0.41, with a separation value of 0.84, indicating an inability to differentiate the tested students' abilities (Sumintono & Widhiarso, 2015). This low score can be attributed to the relatively small sample size. Nevertheless, the person Outfit MNSQ value of 0.98 (as shown in Table 2) demonstrates that the overall student data fits the model (Boone et al., 2014).

Table 4. Rasch parameters for reliability and separation

Psychometrics attribute	Results
Reliability	
Item reliability	0.97
Person reliability	0.41
Separation	
Item separation	5.38
Person separation	0.84

Students' System Thinking Skills

The interaction between test items and students, as well as the distribution of item difficulty and student ability, is illustrated through the Wright map (Bond et al., 2021; Soeharto & Csapó, 2022). Items positioned above the average item logit line are classified as more difficult, while those below the line are relatively easier. Similarly, in the context of Education for Sustainable Development (ESD), students' systems thinking skills are reflected in their ability measures. Students with logit scores above zero demonstrate higher competency, whereas those with lower logit scores exhibit weaker abilities (Baghaei, 2008; Soeharto & Csapó, 2022).

Based on the Wright map (Figure 1), item ST1 emerged as the most challenging, while item ST4 was the easiest. The Rasch analysis further confirmed that the first systems thinking indicator (STS-1) in the ESD context, assessed through item ST1, posed the greatest difficulty for students. Moreover, the overall difficulty level of the test items exceeded the Person Measure Average, indicating that students had less than a 50% probability of responding correctly to all items (Chan et al., 2021). Despite this, the instrument remains robust for assessing systems thinking skills in ESD, as reflected in the strong item reliability score of 0.97—categorizing it as "excellent" (Boone & Noltemeyer, 2017; Sumintono & Widhiarso, 2015). This high reliability suggests that the distribution of item difficulty is well-structured, allowing for an accurate assessment of students' systems thinking abilities.

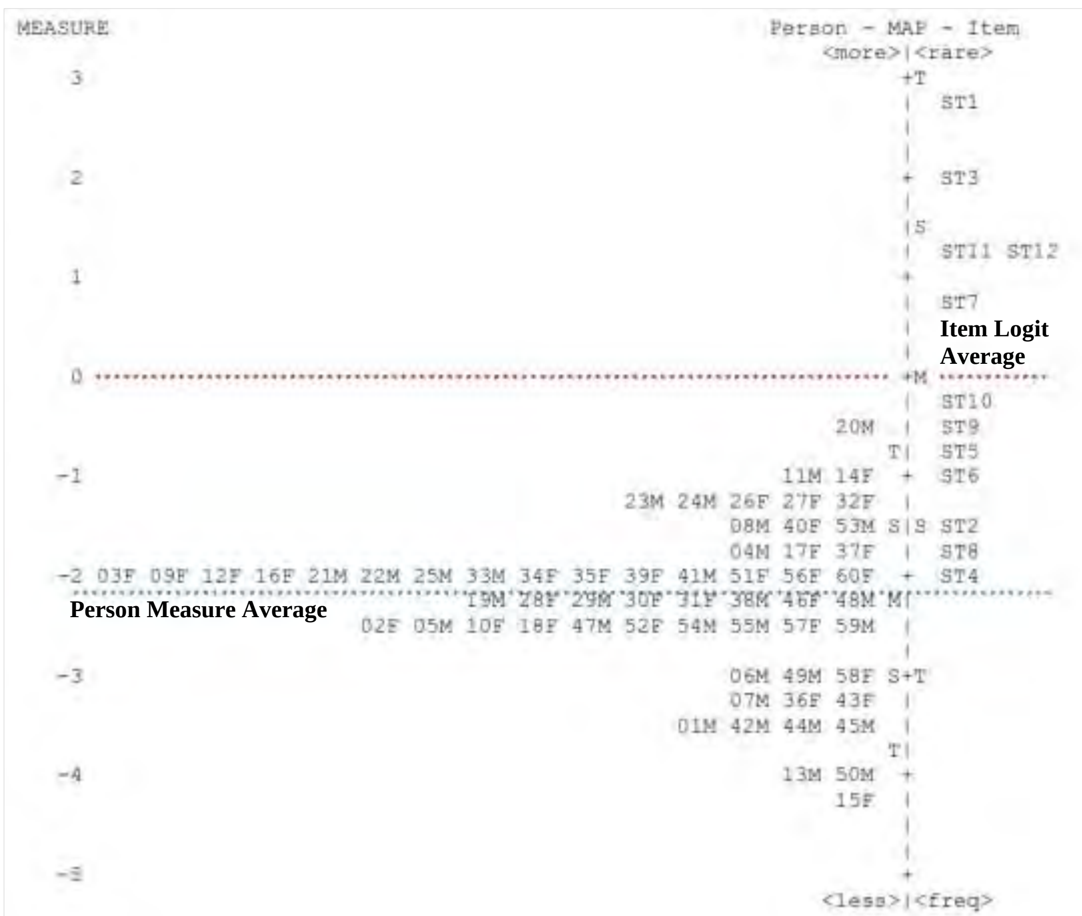

Figure 1. Wright maps of students' systems thinking skills in the context of ESD

The overall difficulty of the test items can be attributed to students' low systems thinking skills, as reflected in the Person Measure Average of -2.33. Approximately 50% of students (29 individuals) scored above this average. The highest logit score, -0.48, was achieved by student 20M. Overall, students' systems thinking skills can be categorized as low, with the majority struggling to demonstrate proficiency in the assessed indicators (Table 5). The most challenging indicator, STS-1, which pertains to the three dimensions of sustainability—environmental, social, and economic—had a logit value of 2.64. A striking 87% of students remained at the pre-aware stage, indicating a widespread struggle to grasp the complexity of sustainability. However, one student (2%) demonstrated a higher level of understanding, achieving an average logit value of -1.02, which corresponds to the developed stage for STS-1. This suggests that while the majority of students found this concept difficult, a small fraction exhibited stronger comprehension.

Table 5. Students' systems thinking skills in the context of ESD

Item	Score Value	Data (%)	Mean ability
	0	87	-2.42
ST1	1	12	-1.81
	2	2	-1.02
	0	77	-2.49
ST3	1	20	-1.82
	2	3	-1.68
ST11	0	58	-2.55
	1	42	-2.02
ST12	0	57	-2.64
	1	43	-1.92
	0	65	-2.59
ST7	1	13	-2.22
	2	22	-1.61
	0	28	-2.81
ST10	1	55	-2.31
	2	17	-1.57
	0	30	-2.68
ST9	1	43	-2.20
	2	27	-2.13
	0	2	-3.88
ST5	1	93	-2.34
	3	5	-1.55
ST6	1	87	-2.37
	2	13	-2.08
	0	7	-2.23
ST2	1	55	-2.40
	2	38	-2.25
	0	7	-3.71
ST8	1	43	-2.54
	2	50	-1.96
	0	15	-3.23
ST4	1	18	-2.44
	2	67	-2.09

Several other indicators, including STS-3, STS-7, STS-11, and STS-12, also revealed students' limited systems thinking skills. A total of 77% of students were at the pre-aware stage for STS-3, indicating difficulties in recognizing system components—a fundamental skill in systems thinking (Housh et al., 2022). Similarly, 65% of students struggled with STS-7, which assesses their ability to consider connections between past, present, and future actions. For STS-11 and STS-12, 58% and 57% of students, respectively, were still at the pre-aware level, highlighting difficulties in developing a sense of place and applying a system thinking perspective to their personal lives. Students struggled to perceive the environment through multiple dimensions, such as biophysical, social, cultural, and political aspects. Recognizing the connections between people, places, and nature is essential for fostering sustainability awareness (Masterson et al., 2017, 2019). These findings underscore the need to enhance student's understanding of environmental systems from a multidimensional perspective.

Despite these challenges, students demonstrated emerging systems thinking skills in certain indicators, including STS-2, STS-5, STS-6, STS-9, and STS-10. For STS-2 and STS-10, 55% of students were at the emerging level, indicating that they had started to perceive nature as a system by considering one ecological aspect and developing empathy for non-human beings, though not yet accurately. These results suggest that further exploration of instructional strategies is necessary to help students build a more holistic understanding of the interconnectedness between human actions and broader ecological systems.

For STS-5, 93% of students scored at the emerging level, meaning they had begun to recognize hidden dimensions within a system, though not accurately. Enhancing students' ability to identify these hidden factors requires additional scaffolding, such as using real-world data to help them identify relationships between various geographical or social contexts and the impact of daily actions on current and future socio-environmental systems (Lorenzo-Rial et al., 2024). In STS-6, students' abilities were found at only two levels: 87% of students were at the emerging level, meaning they had started to recognize connections between sustainability issues and their personal lives, though their understanding remained fragmented. Meanwhile, 13% of students reached the developed level, demonstrating that they had started to make connections between issues and personal choices in a simple manner, recognizing their roles in sustainability, albeit in a limited way. For STS-9, 43% of students began to develop empathy for others but were unable to articulate the reasons behind it, placing them at the emerging stage. This highlights the need for further development of empathy skills, as empathy is a key predictor of systems thinking (Davis et al., 2018).

The majority of students who demonstrated developed systems thinking skills were found in STS-4 and STS-8, with 67% and 50% of students, respectively, at this level. These findings suggest that students were able to explain sustainability efforts and analyze interconnections by considering one or two aspects of sustainability. Additionally, students could explain the relationship between green areas and the water cycle and recognize the cyclical nature of systems. This indicates that students were beginning to see systems integratively, understanding that system components are interconnected and form recurring patterns over time (Hrin et al., 2017). Overall, the results indicate that while many students still struggle with systems thinking in the context of ESD, there are areas where they are beginning to develop these skills. Thus, more targeted instructional strategies are needed to address these gaps and embed systemic reasoning into students' daily thought processes (Traeber-Burdin & Varga, 2022).

Gender Differences in Systems Thinking Skills

Differences in student responses based on gender were analyzed using Differential Item Functioning (DIF). An item is considered to exhibit DIF if it meets the following criteria: a t-value below -2.0 or above 2.0, a DIF contrast value below -0.5 or above 0.5, and a p-value less than 0.05 (Bond et al., 2021; Boone et al., 2014). Based on these criteria, two items—ST2 and ST7—were identified as having DIF, as shown in Table 6.

Table 6. Differential Item Functioning of students' systems thinking skills in the context of ESD

Item	DIF		DIF Contrast	t	Prob
	Male (M)	Female (F)			
ST2	-2.12	-0.83	1.29	2.90	0.0055
ST7	1.39	0.20	-1.18	-2.42	0.0188

Item ST2 corresponds to the second systems thinking indicator in the ESD context, which assesses students' ability to perceive nature as a system. Similarly, item ST7 represents the seventh systems thinking indicator, which requires students to consider the relationships between past, present, and future actions. Apart from these two items, no DIF was detected for other indicators, as illustrated in Figure 2.

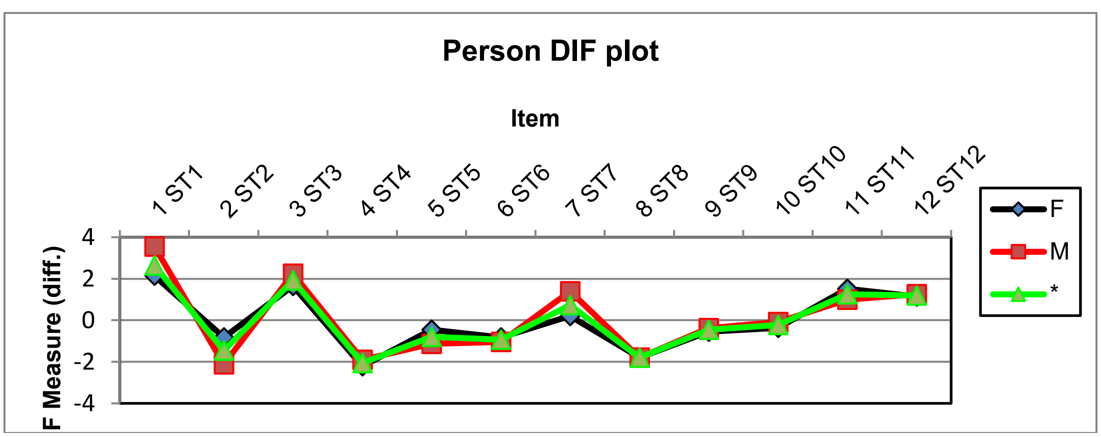

Figure 2. Visualization of Differential Item Functioning of students' systems thinking skills

Item ST2 was found to be more challenging for female students, as indicated by a DIF measure of -0.83 for females and -2.12 for males. This significant difference suggests that female students faced greater difficulty in explaining the consequences of deforestation on a hillside and the associated losses compared to their male counterparts. Item ST2 corresponds to the second systems thinking indicator (STS-2), which involves perceiving nature as a system. The results indicate that male students found it easier to understand the relationship between humans and nature, particularly in terms of ecological aspects. This suggests that, in this context, male students may have a greater tendency to recognize nature as an interconnected system.

Conversely, item ST7 was more challenging for male students, with a DIF measure of 1.39 for males and 0.20 for females. This item presents a graph titled *Global Temperature Anomalies and Selected Regions*, requiring students to analyze temperature changes over time and relate human actions in the past, present, and future to global warming. As a representation of the seventh systems thinking indicator in the ESD context (STS-7), item ST7 assesses students' ability to consider the relationship between past, present, and future. The findings suggest that female students demonstrated a stronger ability to grasp temporal dimensions and identify connections across different time frames. This indicates that female students may have a more nuanced understanding of the long-term implications of human actions on environmental changes.

According to Ling et al. (2020), societal roles and gender positions influence individuals' perspectives on environmental issues. Additionally, social and personal identities shape attitudes toward environmental behaviors (Wild & Heuling, 2024). The gender differences observed in this study may, therefore, be linked to varying personal experiences and external influences shaped by societal expectations. These outside factors significantly impact how people understand and react to environmental challenges, which in turn affects their growth in systems thinking.

Conclusion

The findings of this study indicate that students' systems thinking skills in the context of ESD remain at a low level, as reflected in the Person Measure Average obtained from the Rasch analysis. Most students were at the pre-aware stage, particularly in understanding the interconnectedness of environmental, social, and economic sustainability. Difficulties were evident in recognizing system components, linking actions across time, and integrating sustainability perspectives into personal decision-making. Despite these challenges, some students demonstrated emerging systems thinking skills, beginning to recognize sustainability-related aspects, albeit in a fragmented manner. A small proportion reached the developed stage, particularly in understanding sustainability principles and identifying simple interconnections within systems. These findings highlight the need for more effective instructional approaches to strengthen students' ability to analyze complex sustainability issues holistically. While this study has certain limitations, particularly in the sampling method, which may influence the generalizability of the results, it contributes valuable insights into the development of systems thinking skills in biology education. The results underscore the importance of enhancing educational strategies to better equip students with the ability to approach sustainability challenges through a systemic and interconnected perspective.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contributions

I. Khairati: Methodology; Analysis; Writing ─ original draft; Writing ─ review and editing. **L. Lufri:** Writing ─ review and editing. **M. Fadilah:** Writing ─ review and editing.

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