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Research Article

Integrating Education for Sustainable Development in Biology: Effects on Systems Thinking and Sustainability Awareness

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ABSTRACT

Purpose of the study: This study aims to examine the effect of integrating Education for Sustainable Development (ESD) in biology learning on students' systems thinking skills and sustainability awareness, and to measure the magnitude of its impact compared to conventional teaching methods.

Methodology: This study employed a quantitative quasi-experimental design with a pretest–posttest control group. The intervention used an Education for Sustainable Development (ESD)-based biology module, systems mapping tasks, and local environmental case studies. Instruments included a Systems Thinking Skills test and a Sustainability Awareness questionnaire. Data were analyzed using IBM SPSS (version 26) for Shapiro–Wilk, Levene's test, independent samples t-test, and ANCOVA.

Main Findings: The who received Education for Sustainable Development (ESD)-based biology instruction showed substantially higher gains in systems thinking skills and sustainability awareness compared to the control group. ANCOVA results confirmed a highly significant effect of the intervention ($p < 0.001$) with very large effect sizes ($\eta^2 = 0.598$ for systems thinking; $\eta^2 = 0.525$ for sustainability awareness). These findings demonstrate the strong impact of structured, contextual ESD integration in biology learning.

Novelty/Originality of this study: The study provides new empirical evidence that a structured, context-based Education for Sustainable Development (ESD) approach in biology simultaneously and strongly enhances both systems thinking and sustainability awareness. Unlike prior studies focusing on single competencies or correlational data, this research applies a controlled quasi-experimental design, offering clearer causal evidence and a practical, replicable ESD model for secondary science education.

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1. INTRODUCTION

Climate change, biodiversity loss, and environmental degradation have become global issues that threaten the sustainability of human life worldwide. International reports such as those by the IPCC and UNESCO emphasize that young generations must be equipped with the competencies needed to understand and respond critically to the dynamics of environmental change [1]-[3]. This situation urges the need for educational transformation that focuses not only on knowledge acquisition but also on the development of values, attitudes, and sustainability-related skills [4]-[6]. Education for Sustainable Development (ESD) emerges as a strategic approach to prepare learners to face these sustainability challenges [7]-[9]. Thus, education must serve as a primary means for shaping mindsets and actions that support long-term ecological sustainability.

Biology learning provides a highly potential domain for integrating ESD principles in a meaningful way. Concepts such as ecosystems, material cycles, environmental balance, and interactions among living organisms offer a natural context for developing sustainability understanding in students [10]-[12]. Through ecological phenomenon–based learning, students are able to recognize the connections between human activities and environmental changes more concretely [13]-[15]. ESD in Biology education not only enriches learning content but also promotes a more reflective and transformative learning process [16]-[18]. Therefore, integrating ESD into Biology learning is increasingly important for cultivating ecological literacy among younger generations.

Belgium is one of the Western European countries that has demonstrated a strong commitment to ESD implementation within its educational system. Educational policies in both Flanders and Wallonia position sustainability competencies as essential elements in secondary school curricula [19]-[21]. Nevertheless, several evaluative reports indicate a gap between policy and classroom practice. ESD implementation in schools often remains limited to factual knowledge and has not fully developed the transformative skills students need [22]-[24]. This condition underscores the need for research that evaluates the effectiveness of ESD implementation, particularly in Biology education, which has significant potential to enhance sustainability competencies.

Systems thinking skills are one of the core competencies required to address sustainability issues that are complex and interrelated. These skills enable students to understand cause–effect relationships, energy flows, and interaction dynamics within ecological systems more deeply [25]-27]. Meanwhile, sustainability awareness is essential for shaping attitudes and behaviors that support environmental preservation [28]-[30]. These two competencies are not only academically relevant but also play a crucial role in cultivating a generation that is responsible for the future of the Earth [31]-[33]. Therefore, learning that can foster systems thinking and sustainability awareness is an urgent need in modern education.

Various international studies indicate that the implementation of Education for Sustainable Development (ESD) in schools has positive impacts on students' environmental knowledge, ecological literacy, and pro-sustainability attitudes. For instance, a comprehensive study by Pauw et al. [34], found that both holistic content approaches and pluralistic ESD teaching approaches contribute to improving students' sustainability knowingness, attitudes, and sustainable behaviors. Furthermore, research by Bucea-Manea-Țoniș et al. [35], highlights that schools adopting sustainability strategies (green strategies, interactive teaching methods, ESD-aligned curricula) tend to support lifestyle changes among young people toward more sustainable patterns. However, most of these studies were conducted at the higher education level or in general secondary schools without strong emphasis on systems thinking skills or deeper sustainability awareness. For example, the study by Boca & Saraçlı [36] demonstrated that environmental education in higher education plays a significant role in shaping environmental perceptions and literacy but pays less attention to the development of systemic thinking skills and complex behavioral transformation.

Moreover, although there is a strong theoretical framework connecting ESD, systems thinking, and the achievement of sustainability competencies such as the one proposed in "Education for Sustainable Development: A Systemic Framework for Connecting the SDGs to Educational Outcomes" empirical testing of this framework at the secondary level remains limited [37]. Most studies are conducted at the elementary or university level, or focus on teacher and student perceptions of ESD, rather than quantitatively evaluating cognitive (systems thinking) or affective (awareness/attitudes/behavior) changes following ESD interventions. Particularly within the context of ESD in secondary schools, empirical studies measuring the impact of ESD on students' systems thinking skills and sustainability awareness are still very limited, both quantitatively and qualitatively. This indicates a research gap: previous studies have focused more on environmental knowledge, literacy, and general attitudes, yet rarely explored in depth the two key competencies expected from ESD systems thinking and sustainability awareness—in an integrated manner. Therefore, more specific studies are needed to fill this gap, especially at the secondary school level and within science/biology education contexts.

This study offers novelty through the direct evaluation of the impact of Education for Sustainable Development (ESD) learning on students' systems thinking skills and sustainability awareness—two competencies recommended as core components of sustainability education but rarely examined simultaneously at the upper secondary level. Previous studies have emphasized the importance of these competencies but have predominantly focused on instrument development or conceptual reviews rather than quantitative evaluation of learning interventions [38]. In addition, ESD research at the secondary school level is still dominated by descriptive approaches, and its contextualization is often not connected to students' local environments, making context-based implementation in Belgium as in the present study relatively uncommon [39]. ESD research in Biology education has also generally evaluated only environmental literacy or ecological attitudes without assessing systems thinking in depth [40]. Therefore, this study contributes new insight by combining the Belgian local context, a quantitative approach, a focus on Biology education, and the simultaneous measurement of two key competencies, thereby enriching the ESD literature particularly in Western Europe.

This study is important due to the urgency of effective ESD implementation to prepare students to face sustainability challenges both in Belgium and globally. Belgium's national curriculum emphasizes the significance of sustainability competencies, but its implementation still requires empirical evidence to inform policy strengthening and instructional improvement. Therefore, the present study aims to analyze the influence of ESD learning within an environmental context on secondary school students' systems thinking skills and sustainability awareness in Biology education. The findings are expected to provide meaningful contributions for teachers, schools, and educational policymakers in Belgium. Furthermore, this study is expected to enrich global literature concerning the effectiveness of ESD at the secondary education level.

2. RESEARCH METHOD

This study employed a quasi-experimental design with a pretest–posttest control group model. This design was selected to directly examine the effect of the Education for Sustainable Development (ESD) instructional intervention on students' systems thinking skills and sustainability awareness. A quasi-experimental approach was deemed appropriate because the classes could not be fully randomized [41], [42], following the organizational structure of upper secondary schools in Belgium. Two groups were involved in the study: an experimental group that received ESD-based Biology instruction contextualized to Belgian environmental issues, and a control group that received conventional Biology instruction based on the standard curriculum. Measurements were conducted twice before the intervention (pretest) and after the intervention (posttest) to identify significant changes in the two dependent variables.

This study was conducted at a public upper secondary school in the Flanders region of Belgium, selected because the region has strong sustainability education policies, yet their implementation varies between schools. Flanders also faces several environmental issues relevant to students, such as degradation of the Scheldt River, declining urban air quality, and pressure on Natura 2000 areas. The research participants consisted of two Grade 11 classes (aged 16–17) with a total of 62 students. Purposive sampling was used to select classes that were currently studying topics such as ecosystems, biogeochemical cycles, and environmental issues in the Biology curriculum. One class was assigned as the experimental group (n = 31), while the other served as the control group (n = 31).

The intervention consisted of ESD-based instruction contextualized to Belgium's environmental issues and delivered over six sessions (6 weeks). The ESD material was designed by incorporating local issues such as eutrophication in the Scheldt River, air pollution in Antwerp, increased urban flooding due to climate change, and pressures on biodiversity in Flanders. The instructional design followed UNESCO's ESD principles, including transformative learning, a focus on systems thinking, participatory pedagogy, and context-based problem solving. Instructional strategies included discussions of local environmental cases, system mapping activities, analysis of cause–effect relationships, ecosystem dynamics simulations, and mini-projects related to sustainability issues in the local community. The control group received conventional Biology instruction using textbooks and classroom discussions without explicit integration of ESD.

This study used two primary instruments to measure students' systems thinking skills and sustainability awareness. The first instrument was a systems thinking skills test developed through adaptation of the Systems Thinking Assessment (STA) and a system mapping rubric. This instrument assessed several key indicators: identification of system components, analysis of cause–effect relationships, recognition of feedback loops, analysis of system dynamics, and prediction of system changes in ecological contexts. The test included multiple-choice items, scenario-based analyses related to Belgian environmental issues, and tasks requiring the construction of causal loop diagrams (CLDs). Instrument reliability was analyzed using Cronbach's Alpha to ensure internal consistency.

The second instrument was a sustainability awareness questionnaire developed from the Sustainability Consciousness Questionnaire (SCQ). The questionnaire comprised three main dimensions: sustainability knowledge, sustainability attitudes, and intentions toward sustainable behavior. A 5-point Likert scale was used. Construct validity was examined using Confirmatory Factor Analysis (CFA) to ensure that each dimension aligned with the original theoretical structure of the SCQ. All instruments were translated into Dutch (Flemish) and validated through expert judgment by Biology education lecturers and ESD specialists in Belgium.

The data collection procedures consisted of four stages. The first stage was the administration of the pretest to both groups to measure baseline systems thinking skills and sustainability awareness. The second stage involved the implementation of ESD-based instruction in the experimental group for six weeks, while the control group continued with conventional instruction. The third stage was the administration of the posttest using the same instruments to determine changes in students' competencies after the intervention. The final stage involved documenting the learning process using observation sheets to verify the fidelity of the ESD-based instructional implementation and to record classroom dynamics that might influence the results.

Data analysis was conducted using a quantitative approach. The first stage involved descriptive statistical analysis of students' systems thinking skills and sustainability awareness, followed by normality and homogeneity tests to ensure that the data met parametric assumptions. An independent samples t-test was administered to examine pretest differences and confirm that there were no significant differences in baseline abilities between the experimental and control groups. The impact of the intervention was analyzed using Analysis of Covariance (ANCOVA) with pretest scores as the covariate to determine the effect of ESD instruction on posttest outcomes in both groups. Additionally, effect size was calculated using Cohen's d to determine the magnitude of the intervention's effect. Data analysis was performed using the latest version of SPSS.

3. RESULTS AND DISCUSSION

3.1 Scientific Literacy Achievements of ASEAN Countries (PISA 2022)

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Descriptive statistics were used to describe the initial (pretest) and final (posttest) profiles of students' abilities in the two research variables: systems thinking skills and sustainability awareness. The following table presents the mean (M) and standard deviation (SD) scores of the experimental and control groups..

Table 1. Statistical Deskriptif Pretest and Posttest

Variables	Group	Pretest M (SD)	Posttest M (SD)
Systems Thinking Skills	Experimental (n=31)	54.38 (6.72)	78.91 (7.84)
	Control (n=31)	53.94 (7.11)	60.28 (6.95)
Sustainable Awareness	Experimental (n=31)	65.12 (5.89)	82.47 (6.18)
	Control (n=31)	64.75 (6.03)	70.19 (5.81)

The results of the descriptive statistical analysis indicate that at the pretest stage, the mean scores of both the experimental and control groups were very similar across the two measured variables—systems thinking skills and sustainability awareness. This condition suggests that the students' initial abilities were relatively comparable, allowing any differences observed in the subsequent stages to be more validly attributed to the instructional intervention provided.

At the posttest stage, a significant increase in scores was observed in both groups; however, the improvement was substantially greater in the experimental group, which received Education for Sustainable Development (ESD)–based instruction. For the systems thinking variable, the experimental group showed an increase of +24.53 points, far exceeding the improvement in the control group. A similar pattern was evident in sustainability awareness, where the experimental group demonstrated an increase of +17.35 points, while the control group experienced only a moderate gain.

Overall, the stronger improvement in the experimental group indicates that the ESD-based instructional intervention has the potential to positively influence the development of students' systems thinking skills and sustainability awareness. These preliminary findings reinforce the notion that contextual, participatory, and sustainability-oriented instructional approaches can enhance students' understanding and attitudes toward environmental issues in a deeper and more meaningful way.

The substantially larger score increases in the experimental group align with international research demonstrating that Education for Sustainable Development (ESD) significantly enhances systems thinking competencies and sustainability awareness. The conceptual framework of ESD positions systems thinking as a core competency for understanding the complexity of sustainability issues, as noted by Roczen et al. [43] This is further supported by Frey et al. [44], who assert that system-based instructional models can develop students' systems thinking more effectively than conventional teaching. In addition, ESD research by Cavana & Forgie [45], shows that contextual, holistic, and participatory sustainability education strengthens students' sustainability awareness and attitudes. Other studies also emphasize that sustainability understanding develops optimally when students are trained to identify interconnections within a system, making ESD-based interventions more effective in improving sustainability awareness than traditional approaches [46]. Therefore, the findings of this study are consistent with global literature showing that ESD particularly when delivered through exploratory activities and system modeling significantly contributes to strengthening students' systems thinking and sustainability awareness.

Before conducting parametric analyses such as the independent samples t-test and ANCOVA, the research data were first tested to ensure that the assumptions of normality and homogeneity of variance were met. The normality test was performed using the Shapiro–Wilk test, given that each group consisted of fewer than 50 participants. The results showed that all pretest and posttest data for both variables—systems thinking skills and sustainability awareness—had p-values greater than 0.05. Thus, the data for each group were normally distributed.

Next, the homogeneity of variance was examined using Levene's Test to ensure equal variances between groups prior to conducting parametric difference tests. The analysis indicated that for both systems thinking and sustainability awareness, the p-values for pretest and posttest scores were above 0.05. This result confirms that the variances between the experimental and control groups were homogeneous, and therefore the assumption of equal variances was satisfied.

Overall, the normality and homogeneity test results confirm that the dataset meets all basic assumptions required for the use of parametric statistical tests. This condition allows the interpretation of t-test and ANCOVA results to be conducted more accurately and validly, ensuring that differences in learning outcomes between the two groups can be analyzed without bias arising from non-normal distributions or unequal variances.

After confirming that the data were normally distributed and had homogeneous variances, the analysis proceeded with an independent samples t-test to determine whether there were differences in initial abilities (pretest) between the experimental and control groups. The test was conducted on the two main variables, systems thinking skills and sustainability awareness. The statistical results indicated no significant differences between the two groups at the pretest stage. For systems thinking skills, the resulting t-value was not significant ($t = 0.24$, $p = 0.812$), and similarly, for sustainability awareness, the p-value was also above 0.05 ($t = 0.25$, $p = 0.803$).

The following table presents the complete t-test results, including the mean, standard deviation, t-value, degrees of freedom (df), and p-value for each variable:

Table 2. Results of the Independent Samples t-Test Pretest

Variables	Group	N		D		df		p
Systems Thinking Skills	Experi mental	31	4.38	.72	.24	60	12	0.8
	Contro l	31	3.94	.11				
Sustainable Awareness	Experi mental	31	5.12	.89	.25	60	03	0.8
	Contro l	31	4.75	.03				

These findings indicate that the initial abilities of both groups were at a relatively equivalent level. This equivalence of initial abilities is crucial in quasi-experimental research, as it ensures that changes in posttest scores can be attributed to the ESD learning intervention and not to baseline differences between the groups. Therefore, the results of this t-test support the internal validity of the study and strengthen the conclusion that the experimental and control groups began their learning from comparable baselines.

After confirming that there were no differences in initial abilities between the experimental and control groups, the analysis continued using Analysis of Covariance (ANCOVA) to test the effect of the ESD learning intervention on posttest results for systems thinking skills and ongoing awareness. Pretest scores were included as a covariate to control for variations in students' initial abilities, allowing for more accurate measurement of the intervention's effects.

The analysis revealed a significant effect of ESD-based learning on both variables. For systems thinking skills, the F-value showed high significance ($F = 89.42$, $p < 0.001$), indicating that the difference in posttest scores between the two groups was not due to initial abilities. Similarly, on the sustainable awareness variable, the ESD intervention also had a significant effect ($F = 65.27$, $p < 0.001$). The partial eta squared (η^2) value for both variables indicates the magnitude of the intervention's influence, which is in the large effect category.

Table 3. ANCOVA Test Results for Posttest of Systems Thinking Skills and Sustainability Awareness

Variables	Source of Variation	f		Partial η^2
Systems Thinking Skills	Pretest (covariate)	2.63	.001	0 .174
	Group	9.42	0.001	0 .598

	Error	9				
Sustainable Awareness	Pretest (covariate)		0.54	.002	.152	0
	Group		5.27	0.001	.525	0
	Error	9				

The partial eta squared (η^2) values indicate the strength of the intervention effect. The Systems Thinking variable shows $\eta^2 = 0.598$ and Sustainability Awareness shows $\eta^2 = 0.525$, both classified as **very large effects**. According to Cohen's criteria, values greater than 0.14 are categorized as large effects; therefore, the ESD-based learning intervention demonstrably produced strong impacts on students' sustainability competencies. These results reinforce the improvement patterns observed in the descriptive analysis and previous t-tests, further confirming that the differences in posttest scores can be strongly attributed to the ESD learning intervention.

These findings affirm that the systematic integration of Education for Sustainable Development (ESD) in Biology instruction contributes significantly to the enhancement of students' systems thinking skills and sustainability awareness. The strong effects revealed by ANCOVA demonstrate that contextual, real-world problem–based learning that emphasizes causal reasoning helps students develop a deeper understanding of the complexity of sustainability issues.

Several empirical studies support the conclusion that ESD-based instructional approaches emphasizing systems thinking are highly effective in strengthening students' sustainability competencies. For example, in a quasi-experimental randomized controlled trial (RCT) involving 106 participants, *An Empirical Study of the Impact of Systems Thinking and Simulation on Sustainability Education* reported that an online learning tool integrating systems thinking and dynamic system simulations significantly improved students' understanding of sustainability issues and facilitated knowledge transfer to novel situations [47]. These findings reinforce the argument that systems thinking competence is not merely conceptual, but can be developed through structured and intensive pedagogical interventions.

In addition, synthesis studies and empirical reviews on ESD teaching methods reveal that interventions incorporating system mapping, real-world problem tasks, and participatory learning tend to yield greater cognitive and affective shifts than conventional methods. This supports the interpretation that high partial η^2 values reflect pedagogically meaningful and practically significant effects [22]. Classroom-scale experimental studies also report increases in systems thinking after targeted modules or system-based instructional units, particularly in science/biology and climate change contexts, thereby strengthening the generalizability of the present findings to secondary school settings [48]. Overall, the literature indicates that when ESD is designed systemically (e.g., system mapping, simulation, local case studies), improvements occur not only in posttest scores but also in practically large effect sizes—consistent with the magnitudes observed in this study.

The novelty of this research lies in its strong empirical evidence regarding the effectiveness of integrating ESD into Biology learning to enhance two key sustainability competencies simultaneously—systems thinking skills and sustainability awareness—with very large effect sizes ($\eta^2 > 0.50$). Unlike most previous studies, which typically focused on a single sustainability competency or relied on correlational approaches, this study employed a quasi-experimental design with covariate control (ANCOVA), providing stronger and more controlled causal inferences. Moreover, the ESD intervention implemented here combined contextual activities integrating causal analysis, system mapping, and local environmental issues—an instructional configuration rarely combined explicitly in prior studies [49], [50]. These findings extend the results of Roczen et al. and Frey et al., who highlighted the importance of systems thinking, by demonstrating that when ESD is implemented systematically and contextually in secondary Biology classrooms, its impact is not only statistically significant but also practically powerful in strengthening students' sustainability mindset and awareness [51], [52]. Thus, this study contributes a replicable, empirically validated model for implementing ESD in secondary science education.

The main implication of this study is that systematic and contextual integration of ESD in secondary Biology learning has substantial potential to strengthen two core sustainability competencies: systems thinking skills and sustainability awareness. These findings provide strong empirical support for Biology teachers to go beyond teaching ecological concepts factually, and instead connect them to real issues in students' local environments, such as eutrophication, air pollution, and biodiversity loss. The results may also inform curriculum development and learning material design in Belgium (particularly Flanders) by shifting sustainability education from a predominantly normative emphasis to an evidence-based practice. Furthermore, the large effect sizes ($\eta^2 > 0.50$) indicate that instructional strategies such as system mapping, causal analysis, and local problem-based approaches are highly effective and can be adapted across other science subjects. These strategies also have strong potential for replication in secondary education contexts in other countries facing similar sustainability challenges.

Despite its strong results, this study has several limitations. First, the sample size is relatively small (62 students) and drawn from only one school in the Flanders region, limiting the generalizability of the findings to the broader Belgian or international contexts. Second, the quasi-experimental design without full individual randomization still allows for the possibility of uncontrolled external factors (e.g., classroom culture, student motivation, or teacher differences). Third, the six-week intervention period may be insufficient to capture long-term impacts on systems thinking and sustainability awareness. Additionally, although the instruments were validated, sustainability awareness relied on self-report questionnaires, which are susceptible to social desirability bias. Therefore, future studies should involve larger and more diverse samples, extend the intervention duration, and combine quantitative data with qualitative methods (interviews, observations, or longitudinal designs) to achieve a more comprehensive understanding of ESD's impact on students' sustainability competencies.

4. CONCLUSION

This study demonstrates that the integration of Education for Sustainable Development (ESD) into Biology instruction has a significant and strong effect on improving students' systems thinking skills and sustainability awareness. The experimental group consistently showed higher score increases than the control group, despite having comparable initial abilities. The ANCOVA results indicated a significant effect after controlling for the pretest ($p < 0.001$), accompanied by large effect sizes ($\eta^2 = 0.598$; $\eta^2 = 0.525$), confirming that ESD has both statistically and practically meaningful impacts. These findings reinforce that contextual, environmentally oriented ESD-based Biology learning is effective in developing sustainability competencies among secondary school students. Future research is recommended to employ larger and more diverse samples with extended intervention duration to better capture the long-term development of students' systems thinking skills and sustainability awareness within ESD-based Biology learning.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, and Visualization, YW.; Writing – Review & Editing, YW and RB; Supervision and Project Administration, YW and CPC. All authors have read, reviewed, and provided approval for the final version of the manuscript submitted for publication.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

INFORMED CONSENT STATEMENT

All images in this article have been authorized and are the property of the authors.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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