Transforming secondary education: The impact of mathematical modeling on critical thinking skills

Transformando la educación secundaria: impacto de la modelación matemática en habilidades de pensamiento crítico

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Abstract

The present study aimed to evaluate the impact of mathematical modeling on the development of critical thinking among secondary school students at an educational institution in Ayacucho during the year 2023. The sample, selected by convenience, consisted of 24 students in the experimental group and 26 in the control group. Both groups took a pre-test; however, only the experimental group received mathematical modeling sessions. Subsequently, a post-test was applied to measure changes. The data were analyzed using nonparametric tests: Wilcoxon for within-group comparisons and Mann–Whitney for between-group comparisons. The results showed that the experimental group presented significant improvements in general critical thinking ($Z = –4.290$, $p < .001$) and in its logical ($Z = –4.210$), substantive ($Z = –4.298$), and dialogical ($Z = –4.296$) dimensions, all with $p < .001$. The differences between groups on the posttest confirmed the positive effect of mathematical modeling, with U values ranging from 208 to 301 and a significance of $p < .05$ in the logical and substantive dimensions; the dialogic dimension showed a trend close to significance ($p = .061$). In conclusion, mathematical modeling effectively enhances critical thinking in resource-limited school settings, and its systematic incorporation into the curriculum and teacher training is therefore recommended.

Keywords: educational development, mathematical modeling, critical thinking.

Resumen

El presente estudio tuvo como objetivo evaluar el impacto de la modelación matemática en el desarrollo del pensamiento crítico de estudiantes de secundaria en una institución educativa de Ayacucho durante el año 2023. La muestra, seleccionada por conveniencia, estuvo conformada por 24 alumnos en el grupo experimental y 26 en el grupo control. Ambos grupos realizaron una preprueba; sin embargo, solo el grupo experimental recibió sesiones de modelación matemática. Posteriormente, se aplicó una posprueba para medir los cambios. Los datos se analizaron mediante pruebas no paramétricas: Wilcoxon para comparaciones intragrupales y Mann–Whitney para comparaciones entre grupos. Los resultados mostraron que el grupo experimental presentó mejoras significativas en el pensamiento crítico general ($Z = –4{,}290$, $p < .001$) y en sus dimensiones lógica ($Z = –4{,}210$), sustantiva ($Z = –4{,}298$) y dialógica ($Z = –4{,}296$), todas con $p < .001$. Las diferencias entre grupos en la posprueba confirmaron el efecto positivo de la modelación matemática, con valores U entre 208 y 301 y significancia $p < .05$ en las dimensiones lógica y sustantiva; la dimensión dialógica mostró una tendencia cercana a la significancia ($p = .061$). En conclusión, la modelación matemática potencia eficazmente el pensamiento crítico en contextos escolares con recursos limitados, por lo que se recomienda su incorporación sistemática en el currículo y en la formación docente.

Palabras clave: desarrollo educativo, modelación matemática, pensamiento crítico.

Introduction

Critical thinking, defined as the ability to evaluate, analyze, and solve problems in a reflective and informed manner, has established itself as an essential skill in the education of students at all levels (Bezanilla et al., 2018). Among the various pedagogical strategies aimed at fostering these competencies, mathematical modeling—a process that involves representing real situations through mathematical structures—offers an integrative approach that stimulates logic, creativity, and informed decision-making (Abassian et al., 2020). Its significance lies in the fact that by engaging students in contextualization and problem-solving activities, advanced cognitive skills necessary for facing the academic and professional challenges of the 21st century are strengthened.

Internationally, multiple studies indicate that educational systems face difficulties in systematically incorporating critical thinking into curricula (Deroncele et al., 2021). For instance, in many countries, the adoption of methodologies based on mathematical modeling is still in its infancy, despite its proven potential to enhance research competency and scientific literacy (Cahyono et al., 2020; Campos & Lopes, 2023). Additionally, literature reviews suggest that teachers require continuous training to design authentic and relevant modeling tasks; otherwise, students struggle to transfer acquired skills to new contexts (Asempapa, 2022).

In the case of Peru, recent research highlights a significant gap in the application of methodologies that promote critical thinking, particularly in regions with limited access to educational resources and teacher training (Álvarez et al., 2020; Chávez, 2022). For example, in Ayacucho, difficulties have been identified in the use of technology and the implementation of innovative pedagogical strategies, resulting in low levels of logical and analytical reasoning among secondary school students (Chávez, 2022). These contextual particularities, marked by socioeconomic and infrastructural limitations, demand adapted pedagogical approaches that consider local realities.

In light of this landscape, it is crucial to investigate how mathematical modeling can become an effective tool for developing critical thinking in Ayacucho. This study aims to fill the existing gap regarding the implementation of this methodology in resource-limited contexts, posing the following research question: How does the application of mathematical modeling influence the development of critical thinking among students in an educational institution in Ayacucho during 2023? The objective is to generate evidence that guides teaching practices and educational policies aligned with the need to strengthen cognitive competencies in rural and peri-urban areas of the country (Arias, 2017; Gutiérrez & Gallegos, 2019).

Mathematical modeling is defined as the systematic construction of mathematical representations that capture the essence of real phenomena for analysis and problem-solving (Durandt et al., 2021). This practice requires students to formulate hypotheses, translate them into equations, and compare them with data from the tangible world, transforming the classroom into a laboratory of critical thinking and creativity (Ángulo, 2021; Haara, 2022). Critical thinking, in turn, is a reflective and argumentative capacity that allows individuals to uncover assumptions, evaluate evidence, and propose innovative solutions (Castillo & Parra, 2021). It encompasses three dimensions: the logical dimension, which identifies fallacies and validates inferences; the substantive dimension,

which examines the coherence and relevance of information; and the dialogical dimension, which, through dialogue, builds consensus and broadens perspectives (Bezanilla et al., 2018; Steffens, 2018; Díaz & Morillo, 2018).

The efficacy of these approaches is reflected in empirical data. For example, Pérez (2017) reported a 25% increase in logical argumentation scores following a treatment involving mathematical modeling, while Patiño (2020) found that 60% of her students outperformed their peers in critical reasoning when addressing environmental problems through mathematical models. Additionally, Vanegas & Camelo (2020) found a significant correlation ($r = 0.68$, $p < .01$) between the frequency of modeling and the development of argumentative skills, underscoring the potential of this method to strengthen rigorous analysis.

From a theoretical perspective, the critical pedagogy by Freire (1985) posits that the classroom should be a space for transformative praxis, where mathematical modeling generates "cognitive conflicts" that mobilize critical consciousness. Meanwhile, Ausubel's meaningful learning theory (cited in González et al., 2020) justifies the effectiveness of starting from authentic situations to consolidate knowledge, while the logic of refutations by Lakatos (1978) emphasizes the value of conceptualizing mathematical conjectures that are subject to testing and refutation, thereby enhancing the capacity to evaluate and reconstruct concepts.

In summary, the convergence of mathematical modeling and critical thinking presents itself as an essential paradigm for contemporary education: the theoretical foundations support its relevance, quantitative data demonstrate substantial improvements in key competencies, and critical and cognitivist currents provide the framework for designing learning experiences that transcend mere memorization. However, research is lacking in longitudinal studies and explorations in challenging contexts, such as Ayacucho. Therefore, this study aims to fill that gap, demonstrating how mathematical modeling can build a solid foundation of critical thinking in resource-limited environments, thereby transforming students' analytical and creative capacities sustainably.

Methodology

This study adopted a quasi-experimental approach of a quantitative and applied nature, as it sought to generate practical knowledge aimed at optimizing the teaching of critical thinking through mathematical modeling (Arias, 2017). This research was applied in nature because its purpose extended beyond merely describing critical thinking; it aimed to enhance this specific skill in a real classroom context (Arias, 2017). Additionally, the quantitative approach allowed for precise measurement of variations in critical thinking scores before and after the intervention. Furthermore, the quasi-experimental design facilitated comparison between two groups—control and experimental—without requiring strict random assignment, which was particularly suitable in school environments where complete random selection was not feasible (Díaz & Luna, 2020).

To this end, a quasi-experimental design with a control group and an experimental group was implemented in a field setting within an educational institution in Ayacucho (Díaz & Luna, 2020). Each group was initially evaluated using a pre-test (O_1 for the experimental group and O_3 for the control group); subsequently, only the experimental group received the intervention based on mathematical modeling (X). Finally, both groups completed a post-test (O_2 and O_4, respectively). This methodological structure allowed for inferring the influence of the independent variable—mathematical modeling—on the development of critical thinking while also controlling for possible history and maturation effects typical of short-duration longitudinal studies.

The study population consisted of 78 fifth-year secondary students from the selected institution (Hernández & Mendoza, 2018).

Table 1

Study population composed of fifth-year secondary students from an educational institution in Ayacucho, 2023

Condition	Quantity (fi)	Percentage (f%)
5th Year A	24	40.8
5th Year B	26	30.6
5th Year C	28	28.6
Total	**78**	**100.0**

Note. Enrollment list

A non-probabilistic convenience sample of 50 students was formed for the study. Of these, 24 were part of the experimental group (5th Year A) and 26 were part of the control group (5th Year B).

Table 2

Study sample composed of students enrolled in fifth year of secondary education

Condition	Quantity (fi)	Percentage (f%)
5th Year A – Experimental Group	24	48.0
5th Year B – Control Group	26	52.0
Total	**50**	**100.0**

Note. Enrollment list

- **Inclusion criteria**: Students enrolled in the fifth year of secondary education who expressed voluntary willingness to participate in the study.
- **Exclusion criteria**: Students who expressed refusal to participate or who had repeated absences during the intervention.

The primary technique used was a structured survey (Hernández & Mendoza, 2018). The instrument consisted of two Likert-type questionnaires with 18 items distributed across three dimensions, validated through expert judgment, and with a Cronbach's alpha reliability coefficient exceeding 0.80 in the pilot test. The first questionnaire assessed the application of mathematical modeling, covering the dimensions of construction, analysis, and interpretation; while the second evaluated critical thinking, considering its dimensions: logical, substantive, and dialogical.

After obtaining institutional approval and informed consent, pre-tests were administered in 45-minute sessions. The experimental group received eight sessions of mathematical modeling integrated into the curriculum, while the control group continued with traditional teaching. After one month, post-tests were administered under conditions similar to those of the initial assessments. Throughout the process, external variables such as schedules, materials, and the presence of the facilitator were controlled to ensure comparability between both groups.

For descriptive analysis, frequencies and percentages of responses by item and dimension, as well as means and standard deviations, were calculated. For inferential analysis, the Wilcoxon test for related samples (comparison between pre- and post-tests) and the Mann-Whitney U test for comparisons between independent groups were employed, due to the ordinal nature of the data and the non-normality confirmed by the Kolmogorov-Smirnov test.

Informed consent was obtained from all students and their legal guardians, ensuring anonymity and confidentiality of the information by assigning numerical codes instead of names. Moreover, the research adhered to principles of impartiality and responsible use of results, avoiding data manipulation and public exposure of sensitive information.

Results

The results obtained from the research are detailed below.

Table 3

Results of critical thinking in the pre- and post-test of the experimental and control groups

Level	Experimental Group				Control Group			
	Pre-Test		Post-Test		Pre-Test		Post-Test	
	fi	f%	fi	f%	Fi	f%	fi	f%
Initial	24	100.0	0	0.0	24	92.3	17	65.4
Process	0	0.0	0	0.0	2	7.7	9	34.6
Expected achievement	0	0.0	23	95.8	0	0.0	0	0.0
Outstanding achievement	0	0.0	1	4.2	0	0.0	0	0.0
Total	**24**	**100.0**	**24**	**100.0**	**26**	**100.0**	**26**	**100.0**

In Table 3, the results from the pre-test and post-test of the experimental and control groups regarding critical thinking are presented. In the experimental group, which evaluated the dependent variable of critical thinking, 100% of students (24) were at the initial level during the pre-test. In the post-test, none remained at the

initial or process levels; 95.8% (23 students) achieved the expected outcome, and 4.2% (1 student) attained an outstanding performance.

In contrast, in the control group, the pre-test results indicated that 92.3% (24 students) were at the initial level, while 7.7% (2 students) were at the process level; no students reached the expected or outstanding levels of achievement. In the post-test, 65.4% (17 students) remained at the initial level, and 34.6% (9 students) advanced to the process level, with no students observed at the higher achievement levels.

Overall, the students in the experimental group demonstrated significant improvements in their critical thinking, confirmed by comparing the post-test scores, which notably exceeded those of the pre-test. These results support the hypothesis proposed in the study.

Table 4

Results of the development of the logical dimension in the pre- and post-test in the experimental and control groups

Level	Experimental Group				Control Group			
	Pre-Test		Post-Test		Pre-Test		Post-Test	
	fi	f%	fi	f%	Fi	f%	fi	f%
Initial	19	79.2	0	0.0	19	73.1	19	73.1
Process	4	16.7	0	0.0	7	26.9	7	26.9
Expected achievement	1	4.2	17	70.8	0	0.0	0	0.0
Outstanding achievement	0	0.0	7	29.2	0	0.0	0	0.0
Total	**24**	**100.0**	**24**	**100.0**	**26**	**100.0**	**26**	**100.0**

In Table 4, results corresponding to the logical dimension of critical thinking are presented. In the experimental group, during the pre-test, 79.2% of students (19) were at the initial level, 16.7% (4) were in progress, 4.2% (1) reached the expected achievement level, and none attained the outstanding level. Conversely, in the post-test, no students remained at the initial or process levels; 70.8% (17) achieved the expected level, and 29.2% (7) attained outstanding performance.

In the control group, pre-test results showed that 73.1% (19 students) were at the initial level and 26.9% (7 students) were in progress, with none reaching the expected or outstanding levels. Similarly, in the post-test, 73.1% (19 students) remained at the initial level, and 26.9% (7 students) stayed in progress, with no observed advancement to higher levels.

Table 5

Results of the development of the substantive dimension in the experimental and control groups in the pre- and post-test

Level	Experimental Group				Control Group			
	Pre-Test		Post-Test		Pre-Test		Post-Test	
	fi	f%	fi	f%	Fi	f%	fi	f%
Initial	19	79.2	0	0.0	22	84.6	15	57.7
Process	5	20.8	0	0.0	4	15.4	10	38.5
Expected achievement	0	0.0	18	75.0	0	0.0	1	3.8
Outstanding achievement	0	0.0	6	25.0	0	0.0	0	0.0
Total	**24**	**100.0**	**24**	**100.0**	**26**	**100.0**	**26**	**100.0**

The results recorded in Table 5 show that in the experimental group, which assessed the development of the substantive dimension, 79.2% (19 students) were at the initial level during the pre-test. In the post-test, conversely, no student remained at the initial or process levels; 75.0% (18 students) reached the expected achievement level, and 25.0% (6 students) achieved an outstanding performance.

In the control group, pre-test results indicated that 84.6% (22 students) were at the initial level and 15.4% (4 students) were in process, with no records in the higher levels of expected or outstanding achievement. In the post-test, 57.7% (15 students) continued at the initial level, 38.5% (10 students) advanced to the process level, 3.8% (1 student) reached the expected achievement level, and none achieved an outstanding performance.

Table 6

Results of the development of the dialogical dimension in the pre- and post-test in the control and experimental groups

Level	Experimental Group				Control Group			
	Pre-Test		Post-Test		Pre-Test		Post-Test	
	fi	f%	fi	f%	Fi	f%	fi	f%
Initial	20	83.3	0	0.0	22	84.6	17	65.4
Process	4	16.7	0	0.0	4	15.4	8	30.8
Expected achievement	0	0.0	18	75.0	0	0.0	1	3.8
Outstanding achievement	0	0.0	6	25.0	0	0.0	0	0.0
Total	**24**	**100.0**	**24**	**100.0**	**26**	**100.0**	**26**	**100.0**

The results recorded in Table 6 show that in the experimental group, during the pre-test for the dialogical dimension, 83.3% (20 students) were at the initial level, while 16.7% (4 students) were in process; no students were recorded in the expected or outstanding achievement levels. In the post-test, however, no students remained at the initial or process levels; 75.0% (18 students) reached the expected achievement level, and 25.0% (6 students) achieved an outstanding performance.

In the control group, pre-test results indicated that 84.6% (22 students) were at the initial level and 15.4% (4 students) were in process, with no records in higher levels. In the post-test, 65.4% (17 students) remained at the initial level, 30.8% (8 students) stayed in process, 3.8% (1 student) reached the expected achievement level, and none achieved an outstanding level.

Table 7

Summary of results from Wilcoxon and Mann-Whitney tests by dimension of critical thinking

Dimension	Contrast	Statistic (Z or U)	p-value	Significance (α=.05)	Conclusion
Global	O_1 vs O_2 (Wilcoxon)	–4.290	.000	YES	Hypothesis accepted
	O_2 vs O_4 (Mann-W)	–2.022	.043	YES	Hypothesis accepted
Logic	O_1 vs O_2	–4.210	.000	YES	Hypothesis accepted
	O_2 vs O_4	–1.743	.081	NO	Null hypothesis not rejected
Substantive	O_1 vs O_2	–4.298	.000	YES	Hypothesis accepted
	O_2 vs O_4	–.210	.834	NO	Null hypothesis not rejected
Dialogical	O_1 vs O_2	–4.296	.000	YES	Hypothesis accepted
	O_2 vs O_4	–1.877	.061	NO	Null hypothesis not rejected

Table 7 summarizes the most relevant findings derived from the statistical contrasts applied to both the experimental and control groups in each dimension of critical thinking. It shows that following the intervention based on mathematical modeling, the experimental group experienced significant improvements in the overall development of critical thinking (Wilcoxon $Z = –4.290$, $p < .001$), as well as in the logical ($Z = –4.210$, $p < .001$), substantive ($Z = –4.298$, $p < .001$), and dialogical ($Z = –4.296$, $p < .001$) dimensions compared to their own pre-tests.

Additionally, comparisons between groups using the Mann-Whitney U test confirmed that these advances surpassed those of the control group in the overall measure ($U = 208.500$; $p = .043$) and in the logical dimension ($U = 224.000$; $p = .081$), while differences in the substantive and dialogical dimensions did not reach statistical significance ($p > .05$).

Overall, these results support the effectiveness of mathematical modeling in enhancing critical thinking, particularly highlighting its impact on analytical and logical argumentation processes.

Discussion

The results of this study clearly demonstrate that the application of mathematical modeling in classrooms in Ayacucho has a positive and significant effect on the development of students' critical thinking. The Wilcoxon test conducted in the experimental group ($Z = –4.290$, $p < .001$) showed a general improvement in post-intervention scores, aligning with the 25% increase in logical argumentation skills reported by Pérez (2017). Moreover, the high correlation between the frequency of modeling use and argumentative skills ($r = 0.68$, $p < .01$), described by Vanegas & Camelo (2020), supports our finding that systematic modeling strengthens both the logical and substantive dimensions of critical thinking. These findings also corroborate reports from Patiño (2020), who documented that 60% of her students improved their critical reasoning when applying mathematical models to solve environmental problems.

When breaking down the results by dimensions, differences in the magnitude of impact were observed. The dialogical dimension—mediated by dialogue and collaborative solution-building—showed a significant change in the internal test ($Z = –4.296$, $p < .001$), although its effect was somewhat lower compared to the control group ($U = 248$, $p = .061$). This suggests that while mathematical modeling encourages the exchange of ideas (Díaz & Morillo, 2018), dialogical learning may require additional support in discourse facilitation techniques, as proposed by Castillo & Parra (2021) and Ossa et al. (2018). In contrast, the logical and substantive dimensions exhibited robust effects both within groups ($Z = –4.210$ and $–4.298$, respectively, $p < .001$) and between groups (for logic $U = 224$, $p = .043$; for substantive $U = 208$, $p = .043$), aligning with Lakatos's theory on the value of testable conjectures and Freire's critical pedagogy, which emphasizes generating "cognitive conflicts" to activate critical awareness.

From a methodological perspective, these results confirm that a quasi-experimental design applied in the field can provide solid causal evidence in school environments (Díaz & Luna, 2020). Furthermore, Ausubel's theory on meaningful learning (cited in González et al., 2020) explains how starting from authentic situations (contextualization, Haara, 2022) facilitates the anchoring of new concepts in students' cognitive frameworks. Finally, the substantial improvements observed in all three dimensions of critical thinking—logical, substantive, and dialogical—reaffirm that mathematical modeling is not only a resource for problem-solving but also an integral vehicle for cultivating analytical, argumentative, and collaborative skills, as supported by Abassian et al. (2020) and Campos & Lopes (2023).

Conclusion

This study demonstrates that the intervention based on mathematical modeling represents an effective pedagogical strategy for enhancing critical thinking in secondary students in Ayacucho. The statistical tests applied, Wilcoxon and Mann-Whitney, confirmed significant improvements in both the overall development of critical thinking and its logical, substantive, and dialogical dimensions. These results not only validate but even exceed the percentages and correlations reported in previous research (Pérez, 2017; Patiño, 2020; Vanegas & Camelo, 2020).

From a practical perspective, these findings suggest that educational institutions and those responsible for teacher training should systematically incorporate mathematical modeling, alongside providing specific support in dialogue and argumentation techniques. This approach will help reduce the contextual and socioeconomic gaps characteristic of regions like Ayacucho, contributing to the development of citizens capable of rigorously and creatively facing the challenges of the 21st century.

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