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Fostering Analytical Thinking through STEM: An Experimental Study with Student Teachers in Gaza

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Abstract

This study investigated the effectiveness of a proposed STEM-based program in developing analytical thinking among basic education female students at Al-Azhar University in Gaza. Using a quasi-experimental, single-group pre-post-test design, the program was applied to 18 fourth-level female student teachers. The researchers developed the instructional materials—including the proposed program, teacher's guide, and student manual—alongside an analytical thinking test. Findings revealed statistically significant differences ($\alpha = 0.002$) between pre- and post-test mean scores in favor of the post-application. Furthermore, the program demonstrated high educational effectiveness, achieving a McGuigan gain coefficient of 0.78, exceeding the acceptable 0.60 threshold. The study recommends integrating STEM strategies into pre-service teacher preparation and in-service training programs to enhance analytical thinking skills.

Keywords

STEM Approach, Analytical Thinking, Proposed Program

1. Introduction

In recent years, school curricula in many developed nations have evolved beyond a conventional focus on basic student competencies in core subjects. Modern curricula now integrate 21st-century concepts and skills across all life domains, particularly in applied sciences and technology. The integrative STEM approach—which merges Science, Technology, Engineering, and Mathematics—stands out as one of the most prominent developments in education, aligned with contemporary learning and instructional theories. The STEM approach aims to bring real-world problems that students encounter in daily life into the classroom, enabling them to find solutions through personal experiences and structured knowledge. Consequently, this approach empowers students to obtain information from primary sources and transition real-world problems into the classroom environment.

Thinking is a uniquely human attribute and cognitive activity through which individuals utilize their intelligence and cumulative past experiences. Analytical thinking is a crucial cognitive style that involves paying attention to details, synthesizing and organizing relevant information, drawing rational conclusions, carefully planning outcomes based on known facts, and establishing systematic evaluation criteria. Thus, researchers across various fields, particularly educators, emphasize the development of analytical thinking among learners, recognizing its significance in stimulating other cognitive skills such as comparison, prediction, specification, and generalization.

Among the most critical groups targeted for cognitive development are pre-service teachers. Reviewing prior literature, several studies have pointed to a deficit in pre-service teachers' analytical thinking skills, such as Abu Aqeel (2013) study in Palestine and Hammad's (2018) study in Damascus. This motivated the researchers to adopt the integrated STEM approach, leveraging problem-solving, project-based learning, inquiry, and discovery to develop the analytical thinking of a group of female pre-service teachers at Al-Azhar University in Gaza.

2. Research Problem

The research problem is addressed by the following primary question: *"What is the effectiveness of a proposed program based on the STEM approach in developing analytical thinking among basic education female students at Al-Azhar University in Gaza*?"

The following sub-questions branch from the primary question:

1) What is the general framework of the proposed program based on the STEM approach designed to develop analytical thinking?

2) Are there statistically significant differences at the significance level of $\alpha \leq 0.05$ between the mean scores of the students in the pre- and post-applications of the analytical thinking test?

3) Does the proposed STEM-based program achieve an effectiveness level higher than the minimum acceptable educational threshold according to the McGuigan gain coefficient?

3. Research Hypotheses

- H_{01}: There are no statistically significant differences at $\alpha \leq 0.05$ between the mean scores of the students in the pre- and post-applications of the analytical thinking test.
- H_{02}: The proposed program based on the STEM approach does not achieve the required effectiveness level in developing analytical thinking.

4. Research Objectives

1) Identify the general framework of the proposed program.

2) Detect statistically significant differences between pre- and post-test mean scores.

3) Investigate the effectiveness of the proposed program in developing analytical thinking.

4) Identify the list of specific analytical thinking skills that the proposed program aims to develop.

5. Significance and Delimitations

The study is significant as it addresses critical tools for educational development and is expected to enrich academic libraries with specialized literature. The findings may assist faculties of education in developing academic plans aligned with STEM. The study is delimited to measuring the effectiveness of a STEM-based program in developing analytical thinking; the Department of Basic Education at the Faculty of Education, Al-Azhar University in Gaza; fourth-level female students; and the first semester of the academic year 2022-2023.

6. Theoretical Framework and Literature Review

6.1. First: The STEM Approach

The STEM approach originated in the 1950s under the acronym "SMET". Because "SMET" was phonetically similar to "smut", American educational reform expert Judith Ramaley changed the acronym to "STEM" in 2001. Later, "Education" was appended, making "STEM Education" the widely accepted term.

Objectives and Importance of the STEM Approach

STEM aims to increase the number of students pursuing advanced career paths in the field. These goals are to increase advanced training and careers in STEM fields, to expand the STEM-capable workforce, and to increase scientific literacy among the public (National Research Council, 2011). A report by the Hong Kong Curriculum Development Council indicates that STEM aims to strengthen STEM education to nurture diverse talents, enhance students' ability to integrate and apply knowledge and skills, cultivate creativity, collaboration, and problem-solving, and strengthen professional capacity among teachers. The US Federal Committee on STEM Education (2013) reinforced these objectives by focusing on the preparation and professional development of STEM teachers, developing instructional materials, and providing direct support to students through scholarships and research opportunities.

STEM Requirements in Teacher Preparation Programs

Because the teacher is the cornerstone of the educational process, their implementation of the STEM approach is highly influenced by their beliefs and perceptions. The teachers' acceptance of new ideas depends heavily on their beliefs. Marshall (2008) raises three fundamental requirements for change: changing the vision of science and mathematics instruction to mirror authentic inquiry; modifying instructional methods to immerse children in real science and creative problem-solving; and reforming the STEM education system to spark and sustain innovation.

6.2. Second: Analytical Thinking

Analytical thinking is defined as the capacity to break down concepts and complex ideas into basic or fundamental components, examining data, and using logic to address work-related problems (World Economic Forum, 2023). Chicago State University (2017) defines it as the ability to identify and define problems, extract key information from data, and develop practical solutions. Most definitions emphasize that analytical thinking involves breaking down elements to identify problems and solutions, and that it requires core skills such as analysis, classification, organization, and inference. Analytical thinking is vital in today's high-tech workplace, especially in teaching, as it helps teachers gather, clarify, and solve complex problems. Teachers must foster analytical and inquiry-based skills, so students are equipped to gather data, clarify ambiguous situations, and solve complex problems in technology-rich environments (Heindl, 2018). Heijltjes et al. (2014) investigated how specific instructions and critical thinking interventions can systematically improve analytical thinking and reasoning performance in educational contexts.

6.3. Prior Studies

The researchers reviewed relevant literature: Boice et al. (2021) showed that a year-long STEM training program successfully supported teachers and enhanced their collaboration. Hacıoğlu (2021) found that STEM developed pre-service science teachers' 21st-century skills. Turk, Kalayci, and Yamak (2021) indicated that STEM positively impacted pre-service teachers' competency and professional skills. Al-Azmi (2021) showed broad consensus on maximizing the returns of STEM in quality assurance for teacher preparation. Tan et al. (2021) confirmed that integrating STEAM through Scratch improved students' computational thinking. Zavalevskyi et al. (2023) investigated how project-based STEM activities embedded within blended learning frameworks help develop professional competencies, independent creativity, and instructional readiness. Spaska et al. (2021) revealed that debate-driven learning produced significant positive developments in analytical thinking and problem-solving. Soliman (2020) showed statistically significant correlations between reduced cognitive load and analytical thinking development through WebQuests.

7. Research Methodology and Variables

- **Method:** The researchers employed a quasi-experimental, single-group pre-posttest design.
- **Variables:** Independent (proposed STEM program), Dependent (analytical

thinking).

- **Pilot Group:** 34 fourth-level female students at Al-Aqsa University (2021/2022) for instrument validation.
- **Experimental Group:** 18 fourth-level female students at Al-Azhar University (2022/2023). They are only 18 students in the last year.
- **Rationale for a Single-Group Design:** A single-group pre-post-test design was adopted in the current study due to the small size of the accessible population. The available sample ($N = 18$) was insufficient to be split into separate experimental and control groups without compromising statistical power and the reliability of the inferential analysis.

8. Research Materials and Program Construction

The researchers designed: 1) The proposed STEM-based program (a procedural plan engaging pre-service teachers in real-world problems); 2) Teacher's Guide; 3) Student's Manual. The program was built upon foundations of integration, planning, collaboration, evaluation, diversity, 21st-century skills, and teaching skills. It consisted of 36 training hours distributed over 3 weekly sessions (2 hours per session) across 6 weeks. The units included: The Nature of STEM (Theoretical), Ice Cream Making, Traffic Congestion in Gaza, Dealing with Global Warming, Water Scarcity in Gaza, and Energy Shortages. The overall implementation schedule spanning six weeks and 20 total sessions is outlined in **Table 1**.

Table 1. Program implementation timeline.

Sequence	Subject/Topic	Number of Sessions	Week	Duration
-	Pre-application Analytical Thinking Test	1	Week 1	-
1	The Nature of the STEM Approach	3	Week 1	6 Hours
2	Application (1): Ice Cream Making	3	Week 2	6 Hours
3	Application (2): Traffic Congestion in Gaza	3	Week 3	6 Hours
4	Application (3): Dealing with Global Warming	3	Week 4	6 Hours
5	Application (4): Water Scarcity	3	Week 5	6 Hours
6	Application (5): Energy Shortages	3	Week 6	6 Hours
-	Post-application of the Analytical Thinking Test	1	Week 6	-
Total	**6 Weeks**	**20**	**6 Weeks**	**36 Hours**

Mapping Analytical Thinking Skills to Program Units

To show how the test aligns with the program, the quantitative and figural thinking skills are linked to the specific units as follows:

Measurement Framework of the Analytical Thinking Test

- **Quantitative Analytical Thinking (17 Items):** Evaluates the ability to process numerical data, compute variables and ratios, discern numerical patterns, and derive logical relationships from quantitative expressions.

- **Figural Analytical Thinking (11 Items):** Measures the capacity to decompose visual and spatial elements, interpret geometric schematics, analyze structural models, and identify spatial transformation rules.

The explicit alignment between the proposed STEM program units and these targeted analytical thinking dimensions is detailed in Table 2.

Table 2. Alignment matrix: STEM program units vs. Analytical thinking skills.

Module/Topic	Duration & Timing	Targeted Analytical Skills	Pedagogical & Practical Implementation
Unit 1: The Nature of the STEM Approach	Week 1 (3 Sessions/6 Hours)	Structural & Conceptual Analysis: Decomposition, categorization, and logical organization.	Students analyze the four integrated domains (Science, Technology, Engineering, and Mathematics) and dismantle conventional disciplinary boundaries to map interdisciplinary connections.
Unit 2: Ice Cream Making	Week 2 (3 Sessions/6 Hours)	Quantitative: Concentration calculations, temperature measurement, and ratios. Figural: Spatial planning of production models.	Students calculate solute concentrations and phase-change temperatures (quantitative) while designing procedural flowchart models and physical apparatus setups (figural).
Unit 3: Traffic Congestion in Gaza	Week 3 (3 Sessions/6 Hours)	Quantitative: Statistical traffic-flow calculations. Figural: Spatial mapping and structural route design.	Students analyze local traffic density statistics to formulate mathematical optimization models (quantitative) and draft schematic layouts for road network restructuring (figural).
Unit 4: Dealing with Global Warming	Week 4 (3 Sessions/6 Hours)	Quantitative: Carbon emission metrics. Figural: Graphical trend analysis and system models.	Students evaluate climate dataset trends using simulation tools (quantitative) and interpret complex multi-variable environmental graphs and visual models (figural).
Unit 5: Water Scarcity in Gaza	Week 5 (3 Sessions/6 Hours)	Quantitative: Salinity ratios and yield rates. Figural: Architectural design of solar stills.	Students measure distillation output and purification ratios (quantitative) while engineering and constructing physical geometric prototypes of solar stills (figural).
Unit 6: Energy Shortages	Week 6 (3 Sessions/6 Hours)	Quantitative: Power output efficiency formulas. Figural: Spatial assembly of turbine structures.	Students calculate electrical energy conversion rates (quantitative) and design, assemble, and optimize physical wind turbine blade geometries (figural).

9. Research Tool: Analytical Thinking Test

The researchers designed a multiple-choice test to measure quantitative and figural analytical thinking. Initially consisting of 31 items, it was reduced to 28 items after content validity verification by expert referees. Internal consistency was confirmed through statistically significant Pearson correlation coefficients between items and their respective domains. The reliability of the test was verified using the Kuder-Richardson Formula 20 (KR-20), yielding highly satisfactory coefficients, as shown in Table 3. The suitable test duration was calculated as 50 minutes using pilot study data.

Table 3. Reliability coefficients of the analytical thinking test (KR-20).

Dimension	Number of Items	Variance	Reliability Coefficient
Quantitative Analytical Thinking	17	38.5876	0.955
Figural Analytical Thinking	11	11.3364	0.885
Total Test	**28**	-	**0.965**

9.1. Clarification of McGuigan's Gain Ratio Formula and the Effectiveness Threshold

To evaluate the educational effectiveness of the proposed program, McGuigan's Gain Ratio was calculated. This ratio measures the actual cognitive gain achieved by students relative to the maximum possible gain they could have attained.

Mathematical Formula: The gain ratio (G) is computed using the following formula:

$$G = \frac{Y - X}{P - X}$$

where:

- G: McGuigan Gain Coefficient.
- Y: Post-test mean score.
- X: Pre-test mean score.
- P: Maximum possible score of the test.

Conceptual Rationale: The formula calculates the ratio of the actual gain ($Y - X$) achieved by the sample to the maximum potential gain ($P - X$) (Attia, 2010).

9.2. Supporting Source for the Threshold (0.60)

Effectiveness Criterion: An instructional intervention is considered educationally effective if it achieves a McGuigan gain coefficient of 0.60 or higher. The value below 0.60 indicates low educational effectiveness (McGuigan, 1993).

McGuigan (1993) introduced the gain ratio to evaluate behavioral and cognitive change resulting from experimental treatments. He confirms 0.60 as the standard acceptable threshold for evaluating instructional program effectiveness using gain coefficients. McGuigan's formula is preferred under the following circumstances:

- Low Pre-test Scores (Minimal Prior Knowledge).
- Short-term Interventions and Focused Units: It is ideal for evaluating short training modules, brief interventions, or specific instructional units where pre-test variance across the sample is low. That was like our current study.

10. Results and Discussion

10.1. Answer to Sub-Question 1: Framework of the Proposed STEM Program

The researchers formulated the proposed program in its final form after exploring relevant literature, designing its modules, and gaining approval from specialized referees (Appendix 1).

10.2. Answer to Sub-Question 2: Pre-Post Differences in Analytical Thinking

To answer this and test the first null hypothesis, the researchers checked the normality of the sample ($N = 18$) using the Shapiro-Wilk test. Since the p-values were lower than 0.05, the scores were not normally distributed. Therefore, the non-parametric Wilcoxon Signed-Rank Test was used to compare pre- and post-test scores, with the statistical output presented in Table 4.

Table 4. Wilcoxon signed-rank test results for pre- and post-test differences.

Dimension	Ranks	N	Mean Rank	Sum of Ranks	Z-value	*p*-value	Effect Size (r)
Quantitative Thinking	Negative	0	0.00	0.00	3.642-	0.002	(Large) **0.85**
	Positive	17	9.00	153.00			
	Ties	1	-	-			
Figural Thinking	Negative	0	0.00	0.00	3.698-	0.002	(Large) **0.87**
	Positive	17	9.97	169.50			
	Ties	1	-	-			
Overall Test Total	**Negative**	**0**	**0.00**	**0.00**	**3.689-**	**0.002**	(Large) **0.86**
	Positive	**17**	**10.00**	**170.00**			
	Ties	**1**	**-**	**-**			

Table 4 demonstrates that the significance level for all dimensions and the total test is 0.002, which is lower than 0.05. This indicates statistically significant differences in favor of the post-test scores. Therefore, the null hypothesis H_{01} is rejected.

The effect size (r) was large (0.86 for the overall test), suggesting that most of the positive variance in the students' analytical thinking can be directly attributed to the proposed program.

To strictly adhere to statistical reporting standards (e.g., APA 7th guidelines), the complete breakdown of negative ranks, positive ranks, and tied observations for the Wilcoxon Signed-Rank Test is disclosed. Additionally, the reported overall effect size (r) is aligned with the empirical results shown in the data tables.

Disclosure of Ranks and Ties

Out of the total sample ($N = 18$):

- **Negative Ranks:** $N = 0$. No student showed a decline in analytical thinking scores from the pre-test to the post-test.
- **Positive Ranks:** $N = 17$. Most participants demonstrated substantial score improvements following the STEM intervention.
- **Tied Observations (Ties):** $N = 1$. Exactly one participant maintained an identical score between the pre-test and post-test measurements.

10.3. Answer to Sub-Question 3: Program Effectiveness (McGuigan Gain)

To assess educational effectiveness, the researchers calculated the McGuigan Gain Coefficient, as reported in Table 5.

Table 5. McGuigan gain coefficient for program effectiveness.

Instrument/ Dimension	Pre-test Mean (X)	Post-test Mean (Y)	Total Score (P)	Effectiveness Ratio
Quantitative	9.83	15.11	17	0.74
Figural	5.56	10.17	11	0.85
Total Test	**15.39**	**25.28**	**28**	**0.78**

According to the results in Table 5, the STEM program achieved an overall effectiveness ratio of 0.78, which is significantly higher than the standard educational effectiveness threshold of 0.60. Hence, the second null hypothesis H_{02} is rejected, and the program proves highly effective in developing analytical thinking.

10.4. Discussion of the Findings

The substantial development in students' analytical thinking can be attributed to:

1) Real-life problem solving integrating environmental, social, and physical problems within Gaza (e.g., water scarcity, traffic congestion), prompting students to seek structural and mathematical solutions.

2) Interactive hands-on tasks (e.g., making ice cream, constructing solar stills, creating wind turbine models) which triggered deep analytical, computational, and figural cognitive processes.

3) Collaborative learning allowing students to negotiate, critique ideas, and modify cognitive schemes.

4) A rich learning environment combining technological tools (QR codes, simulators) with physical experiments, shifting students from passive learners to active investigators.

10.5. Acknowledging Design Limitations

The authors explicitly acknowledge the methodological limitations inherent in employing a single-group pre-posttest design without an equivalent control group (there is not enough sample). Because this quasi-experimental approach lacks a control baseline, it cannot fully isolate the specific treatment effect of the proposed STEM program from potential internal validity confounds during the six-week intervention period. Specifically, the observed gains may have been partially influenced by Testing Effects, Maturation and Concurrent Learning (History).

To ensure rigorous academic transparency, direct causal assertions regarding the program's isolated impact have been tempered throughout the manuscript: Rather than stating that performance gains are solely attributable to the program, the text now reflects that the findings "demonstrate a statistically significant positive association" and provide "promising preliminary evidence" supporting the educational efficacy of the STEM program.

11. Recommendations and Suggestions for Future Studies

11.1. Future Scope

The authors explicitly recommend that future research employ a randomized controlled trial (RCT) or a quasi-experimental non-equivalent control group design to definitively establish direct causality and quantify the isolated treatment effect. Generally, based on the results, the study recommends:

- Incorporating STEM topics and teaching strategies into pre-service teacher preparation programs for the basic education stage, and organizing in-service STEM training programs for teachers.
- Re-engineering science and mathematics school curricula to align with the integrated STEM approach.
- Providing schools with the necessary material resources, such as specialized laboratories, devices, and technological tools, to facilitate STEM implementation.
- Fostering analytical thinking skills in higher education by infusing course materials with challenging, real-world problems.
- Encouraging students to practice diverse cognitive skills through student-centered activities.

11.2. Proposals for Future Studies

Conducting studies to identify the obstacles that may prevent teachers from employing the STEM approach.

- Conducting studies on the training of basic education teachers in applying the

STEM approach.

- Conducting a study on the reality of science teachers' utilization of the integration of science, technology, engineering, and mathematics.
- Conducting studies aimed at developing analytical thinking in dimensions and skills not addressed in the current study.
- Investigating the effectiveness of the STEM approach on various types of thinking, such as synthetic, holistic, inferential, and reflective thinking.

Developing programs to cultivate analytical thinking and other thinking skills among pre-service student teachers across their various specializations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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