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Effectiveness of a Model-Based Mathematics Laboratory Intervention on Undergraduate Science Students' Academic Achievement: A Pretest-Posttest Study

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Abstract: ***Mathematics laboratories that let learners build, manipulate and reason from physical and computational models are increasingly advocated as a remedy for the passive, procedure-driven instruction that dominates undergraduate mathematics classrooms. This study examined the effectiveness of a model-based mathematics laboratory intervention on the academic achievement of undergraduate science students using a single-group pretest–posttest design. We have collected nearly three hundred sixty seven samples from the mentioned institutions here for this study we have taken Fifty-nine (B.Sc. with Mathematics, and B.Sc.–B.Ed.) samples drawn from three affiliated colleges in Gujarat participated in nine hands-on laboratory activities spanning applied and pure mathematics topics (simple pendulum, planimeter, RLC circuit, linear independence/dependence of vectors, complex numbers, linear operators, Lagrange's interpolation, derivatives, and Rolle's/Lagrange's/Cauchy's mean value theorems). An Achievement Test comprising nine unit-wise sub-tests (15 marks each; 135 marks total) was administered before and after the intervention. Results showed a statistically significant gain in overall achievement, from a pretest mean of 54.88 (SD = 21.44, 40.7%) to a posttest mean of 83.44 (SD = 22.13, 61.8%), $t(58) = 18.02$, $p < .001$, with a very large effect size (Cohen's $d = 2.35$) and a normalized (Hake's) gain of 0.37, indicating medium overall gain. All nine laboratory units showed statistically significant, large-magnitude improvement (d ranging from 1.00 to 1.62). Gains were significant and comparable in direction across the three academic programmes, although a marginal between-group difference emerged ($F = 3.10$, $p = .053$). The findings support model-based mathematics laboratory work as an effective pedagogical strategy for strengthening undergraduate science students' conceptual and procedural achievement in mathematics, and the study offers implications for curriculum designers and teacher educators seeking to embed laboratory-based, hands-on learning in undergraduate STEM programmes.***

Keywords: mathematics laboratory; model-based learning; academic achievement; undergraduate science education; pretest–posttest design; hands-on pedagogy

1. Introduction

Mathematics continues to be perceived by a substantial proportion of undergraduate science students as an abstract, symbol-laden subject that is learned by rote rather than understood through experience (Freudenthal, 1991; Skemp, 1976). Conventional lecture-based instruction, in which theorems, formulae and proofs are transmitted verbally and reproduced by students in examinations, offers few opportunities for learners to construct meaning through direct manipulation of mathematical objects. This gap between abstract formalism and concrete understanding has long been recognised as a major contributor to mathematics anxiety, weak conceptual retention, and declining interest in mathematics-intensive science programmes (Hembree, 1990; NCTM, 2000).

A mathematics laboratory approach attempts to close this gap by engaging learners in model-based, activity-centred tasks constructing physical apparatus, plotting geometric loci, verifying theorems experimentally, and using measurement-based reasoning to arrive at mathematical generalisations. Rooted in the constructivist and constructionist traditions (Piaget, 1970; Bruner, 1966; Papert, 1980), the underlying premise is that mathematical understanding is strengthened when abstract ideas are first encountered, manipulated and verified through tangible, visual or computational models before being generalised symbolically. For undergraduate science students in particular who must apply mathematics as a working tool in physics, chemistry and applied science courses rather than study it in isolation a laboratory-based, model-driven approach is argued to be especially suited to building the kind of applied, transferable understanding their disciplines demand.

Despite this theoretical appeal, empirical evidence on the effectiveness of mathematics laboratory interventions at the undergraduate level in the Indian context remains limited, with most existing studies concentrated at the school level. The present study addresses this gap by evaluating a nine-unit, model-based mathematics laboratory intervention delivered to undergraduate science students drawn from three affiliated colleges, using a systematic pretest–posttest design and a common Achievement Test.

2. Review of Related Literature

The theoretical foundation for laboratory-based mathematics instruction draws on Piaget's (1970) constructivist account of learning, in which knowledge is actively built through interaction with concrete materials rather than passively received, and on Bruner's (1966) enactive–iconic–symbolic model of representation, which holds that abstract symbolic understanding is most durable when it is preceded by hands-on and visual engagement with the underlying concept. Papert's (1980) constructionist perspective extends this argument by proposing that learning is strengthened when students build external, shareable artefacts- models, apparatus, or constructions that make their thinking visible and testable.

A growing body of research on active and experiential learning supports these theoretical claims. Hake's (1998) large-scale analysis of over six thousand physics students demonstrated that interactive-engagement methods produced normalized learning gains roughly two to three times greater than traditional lecture instruction, establishing the normalized gain (g) as a standard metric for comparing pretest–posttest interventions across contexts a metric adopted in the present study. Similarly, meta-analytic work by Freeman et al. (2014) found that active-learning approaches across STEM disciplines were associated with significantly higher examination performance and markedly lower failure rates compared with traditional lecturing. Hattie's (2009) synthesis of classroom-level influences on achievement likewise identifies feedback-rich, activity-based instructional strategies among the more powerful moderators of student learning.

Within mathematics education specifically, Freudenthal's (1991) theory of Realistic Mathematics Education argues that mathematical concepts are best learned when they are ‘re-invented’ by learners through guided, experience-based activity rather than presented as finished formal knowledge. The National Council of Teachers of Mathematics (2000) similarly identifies representation, connection and hands-on reasoning as central process standards for meaningful mathematics learning. Bonwell and Eison (1991) further argue that active-learning formats, including laboratory and activity-based work, promote deeper processing of content than passive listening, a claim consistent with the durable, transferable gains reported in several Indian school-level mathematics laboratory studies.

Taken together, this body of work provides a clear theoretical and empirical rationale for expecting a model-based mathematics laboratory intervention to produce measurable gains in student achievement, while also indicating that such gains should be assessed using both statistical significance testing and standardised effect-size and normalized-gain measures- an approach adopted in the present study.

3. Need and Significance of the Study

Undergraduate science students frequently carry mathematics content from school into higher education as a set of memorised procedures rather than internalised concepts, a gap that becomes especially consequential when mathematics must be applied as a tool within physics, engineering and applied science coursework. Most published evaluations of mathematics laboratory pedagogy in India have been conducted at the secondary or senior-secondary level; systematic, quantitatively evaluated evidence at the undergraduate science level remains comparatively scarce. Further, laboratory interventions that combine applied, physically-grounded activities (e.g., the simple pendulum, the planimeter, an RLC circuit experiment) with purely mathematical topics (vectors, complex numbers, linear operators, interpolation, differentiation, and the mean value theorems) are rarely evaluated together within a single, unified achievement framework. The present study was undertaken to generate such evidence, using a multi-institutional sample and a common nine-unit achievement instrument, so that the effectiveness of model-based mathematics laboratory work can be examined both overall and unit-by-unit. The study was carried out as a Seed Money Research Project and is intended to inform curriculum planning for mathematics laboratory courses in undergraduate science and teacher-education programmes.

4. Statement of the Problem

The study is stated as: “Effectiveness of a Model-Based Mathematics Laboratory Intervention on Undergraduate Science Students' Academic Achievement: A Pretest–Posttest Study.”

5. Objectives of the Study

- To develop and implement a model-based mathematics laboratory intervention comprising nine hands-on activities for undergraduate science students.
- To assess the pretest and posttest academic achievement of undergraduate science students following the mathematics laboratory intervention, overall and for each of the nine laboratory units.
- To determine the statistical significance and magnitude (effect size) of the difference between pretest and posttest achievement scores.
- To compare the achievement gain obtained by students enrolled in different undergraduate programmes (B.Sc., B.Sc. with Mathematics, and B.Sc.–B.Ed.).

6. Hypotheses

The following null hypotheses (H_0) were formulated and tested at the 0.05 level of significance:

- H_{01}: There is no statistically significant difference between the mean pretest and mean posttest overall achievement scores of undergraduate science students following the mathematics laboratory intervention.
- H_{02}: There is no statistically significant difference between the mean pretest and mean posttest scores of students on each of the nine individual mathematics laboratory units.
- H_{03}: There is no statistically significant difference in the mean achievement gain among students of the three undergraduate programmes (B.Sc., B.Sc. with Mathematics, and B.Sc.–B.Ed.).

7. Methodology

7.1 Research Design

The study employed a single-group pretest–posttest pre-experimental design, in which the same group of participants was assessed on a common Achievement Test before and after exposure to the model-based mathematics laboratory intervention. This design permits a direct, within-subject evaluation of change in achievement attributable to the intervention, while the absence of an untreated control or comparison group is acknowledged as a limitation of causal inference (see Section 11).

7.2 Population and Sample

The population comprised undergraduate science students enrolled in mathematics-related programmes in colleges affiliated with the study region in Gujarat, India. Using purposive sampling, 59 third-semester undergraduate students were drawn from three institutions: Indian Institute of Teacher Education, Gandhinagar (n = 20, B.Sc.–B.Ed. programme); Swaminarayan University, Kalol (n = 20, B.Sc. with Mathematics programme); and Samarpan College of Science and Commerce, Gandhinagar (n = 19, B.Sc. programme). All participants were enrolled in Semester III at the time of data collection.

7.3 Tool / Instrument

A researcher-developed Achievement Test (AT) was used to measure student achievement. The test comprised nine unit-wise sub-tests, one corresponding to each mathematics laboratory activity, each carrying a maximum of 15 marks, for a total possible score of 135 marks. The nine units were: (i) Simple Pendulum, (ii) Planimeter, (iii) RLC Circuit Experiment, (iv) Linear Independence and Dependence of Vectors, (v) Complex Numbers (Z-plane, W-plane, and polar form), (vi) Linear Operators, (vii) Lagrange's Interpolation Method, (viii) Derivative of a Function, and (ix) Rolle's, Lagrange's, and Cauchy's Mean Value Theorems. The same test was administered as both pretest and posttest to permit direct pre–post comparison.

7.4 The Intervention: Model-Based Mathematics Laboratory

The intervention consisted of nine structured mathematics laboratory sessions, each built around a physical, geometric, or computational model that made the underlying mathematical or applied concept directly manipulable. Activities combined applied/experimental tasks (e.g., determining the value of g using a simple pendulum; measuring plane areas using a planimeter; verifying circuit relationships in an RLC circuit) with model-based explorations of core mathematical content (visualising linear dependence and independence of vectors; representing complex numbers on the Z- and W-planes and in polar form; illustrating the action of linear operators; constructing Lagrange interpolating polynomials; graphically and numerically exploring derivatives; and verifying Rolle's, Lagrange's, and Cauchy's mean value theorems using function plots and physical/graphical demonstrations). Each laboratory session followed a common structure of orientation, guided hands-on activity, peer discussion, and instructor-facilitated generalisation of the underlying mathematical principle.

7.5 Procedure

The Achievement Test was administered to all 59 participants as a pretest prior to the start of the laboratory intervention. Students then completed the nine laboratory sessions under the guidance of trained instructors over the course of the intervention period. Immediately following completion of all nine laboratory units, the same Achievement Test was re-administered as a posttest under comparable conditions. Scripts were scored by the researchers using a common scoring key, and both pretest and posttest scores were compiled unit-wise and as an overall composite (out of 135) for analysis.

7.6 Statistical Techniques

Descriptive statistics (mean, standard deviation, percentage) were computed for pretest and posttest scores, overall and for each laboratory unit. The paired-samples t-test was used to test the significance of the difference between pretest and posttest means (H_{01} and H_{02}). Effect size was estimated using Cohen's d for paired samples, and the normalized learning gain (Hake's g) was computed as g = (Post − Pre) / (Maximum possible score − Pre) to express the gain relative to the room for improvement available to each student. A one-way ANOVA was used to compare mean achievement gain across the three undergraduate programmes (H_{03}). All analyses were conducted at $\alpha = 0.05$.

8. Results

8.1 Overall Achievement: Pretest vs. Posttest (Testing H_{01})

The overall achievement of the 59 participants improved substantially following the mathematics laboratory intervention. The mean pretest score was 54.88 (SD = 21.44), corresponding to 40.65% of the maximum possible score of 135, while the mean posttest score rose to 83.44 (SD = 22.13), corresponding to 61.81% — a mean gain of 28.56 marks (SD = 12.17). A paired-samples t-test showed this difference to be statistically highly significant, $t(58) = 18.02$, $p < .001$, with the 95% confidence interval of the mean gain (25.39 to 31.73) excluding zero. The effect size was very large (Cohen's d = 2.35), and the normalized gain (Hake's g = 0.37) falls in the medium-gain band, indicating that students recovered slightly over a third of the achievement they had room to gain between pretest and the maximum possible score. Accordingly, the null hypothesis H_{01} is rejected: the mathematics laboratory intervention was associated with a statistically significant and practically meaningful improvement in students' overall achievement.

Table 1: Descriptive Statistics for Overall Achievement Scores (N = 59, Max = 135)

Measure	Pretest	Posttest	Gain (Post- Pre)
Mean	54.88	83.44	28.56
SD	21.44	22.13	12.17
% of maximum (135)	40.65%	61.81%	—
95% CI of mean gain	—	—	25.39 – 31.73

Table 2: Paired-Samples t-Test and Effect Size for Overall Achievement Gain

Statistic	Value
N (paired)	59
t (df = 58)	18.02
p-value	< .001
Cohen's d (paired)	2.35 (very large)
Normalized gain, Hake's g	0.37 (medium gain)
Wilcoxon signed-rank test (non-parametric confirmation)	p < .001

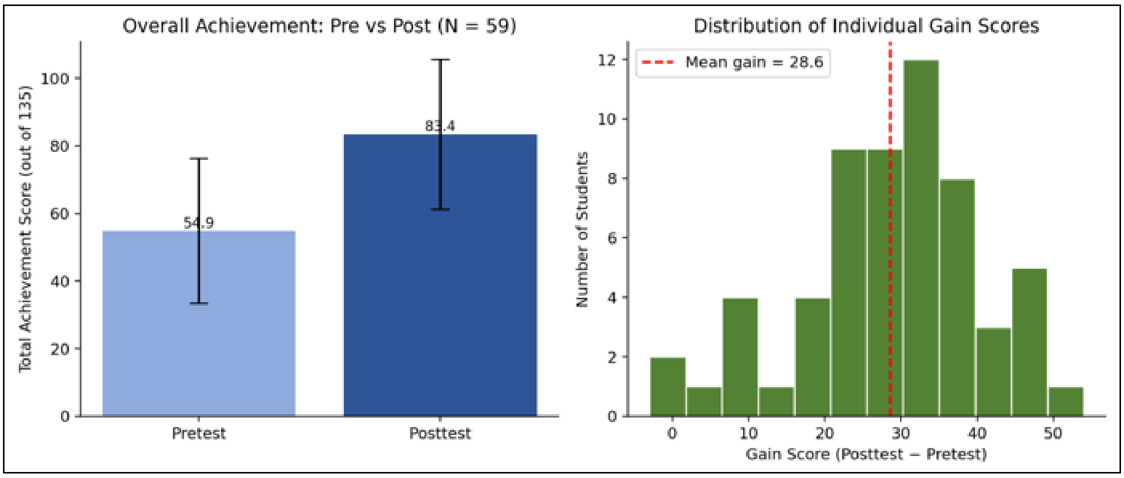

Figure 1: Overall pretest and posttest achievement (left) and distribution of individual gain scores (right), N = 59

8.2 Unit-wise Achievement (Testing H_{02})

Table 3 presents the pretest and posttest means, gain scores, and paired t-test results separately for each of the nine mathematics laboratory units. Every unit showed a statistically significant improvement from pretest to posttest ($p < .001$ in all cases), with effect sizes ranging from $d = 1.00$ (Linear Operators) to $d = 1.62$ (Complex Numbers), all of which fall in the large-to-very-large range by conventional benchmarks. The largest absolute gain was recorded for Complex Numbers (Z-plane, W-plane and polar form) (gain = 4.25 marks), followed by Simple Pendulum (gain = 3.44 marks) and Rolle's/Lagrange's/Cauchy's Mean Value Theorems (gain = 3.39 marks). The smallest, though still statistically significant and large in magnitude, gain was recorded for Linear Operators (gain = 2.58 marks). These results indicate that the intervention was effective across the full range of laboratory units- spanning applied/experimental activities and purely mathematical topics alike- rather than being driven by improvement in a small subset of units. Accordingly, the null hypothesis H_{02} is rejected for all nine units.

Table 3: Unit-wise Pretest–Posttest Comparison for the Nine Mathematics Laboratory Activities (N = 59, each unit scored out of 15)

Laboratory Unit (/15)	Pretest M (SD)	Posttest M (SD)	Gain	t(58)	p	d
Simple Pendulum	5.46 (2.88)	8.90 (2.77)	3.44	9.79	<.001	1.27
Planimeter	6.34 (2.49)	9.71 (2.55)	3.36	9.58	<.001	1.26
RLC Circuit Experiment	6.10 (2.60)	8.86 (3.00)	2.76	8.18	<.001	1.06
Linear Indep./Dep. of Vectors	7.37 (2.82)	10.25 (2.40)	2.88	10.92	<.001	1.42
Complex Numbers	5.86 (3.29)	10.12 (2.58)	4.25	12.42	<.001	1.62
Linear Operators	6.03 (2.95)	8.61 (2.92)	2.58	7.67	<.001	1.00
Lagrange's Interpolation	6.39 (2.85)	9.37 (3.42)	2.98	9.68	<.001	1.26
Derivative of a Function	6.24 (2.88)	9.24 (2.81)	3.00	7.83	<.001	1.02
Rolle's/Lagrange's/Cauchy's MVT	5.15 (2.78)	8.54 (2.85)	3.39	10.42	<.001	1.36

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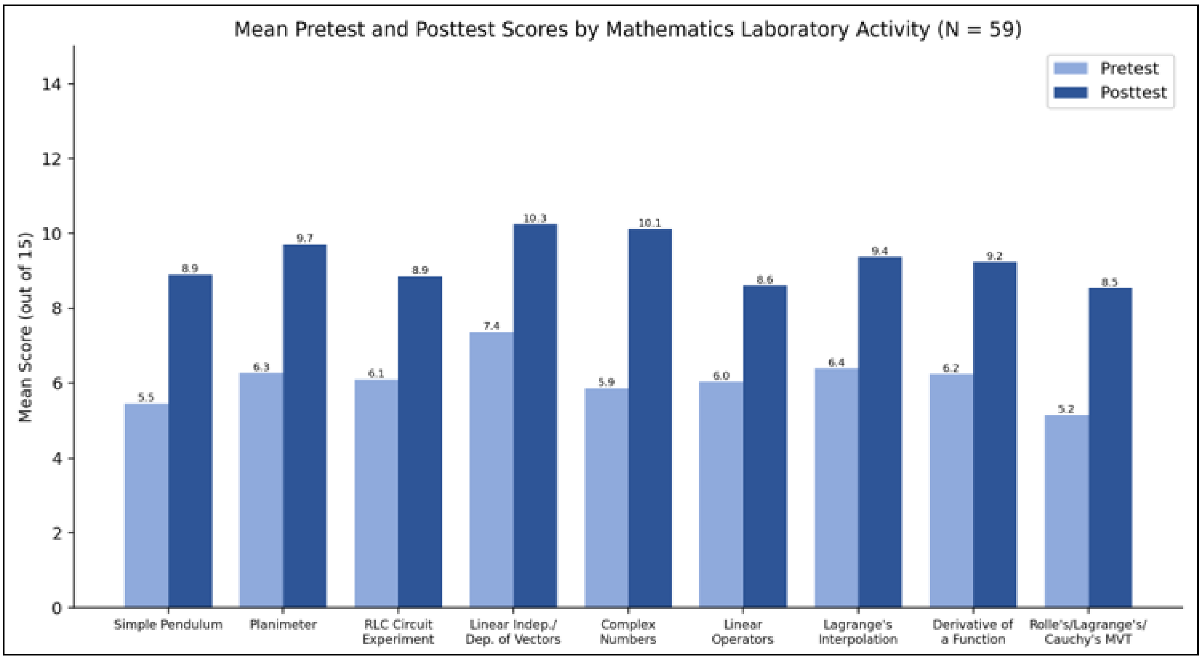

Figure 2: Mean pretest and posttest scores for each of the nine mathematics laboratory activities

8.3 Comparison Across Undergraduate Programmes (Testing H_{03})

Table 4 disaggregates overall pretest, posttest and gain scores by the three undergraduate programmes represented in the sample. Students in all three programmes showed statistically significant pre-to-post gains with very large effect sizes (d ranging from 2.01 to 2.95), confirming that the intervention was effective regardless of programme of enrolment. The largest mean gain was observed among B.Sc. students (M = 34.05), followed by B.Sc.–B.Ed. students (M = 26.50) and B.Sc. with Mathematics students (M = 25.40). A one-way ANOVA comparing gain scores across the three programmes approached but did not reach conventional statistical significance, $F(2, 56) = 3.10$, $p = .053$, indicating that although B.Sc. students showed a numerically larger mean gain, the difference in gain among the three programme groups cannot be considered statistically reliable at $\alpha = .05$. The null hypothesis H_{03} is therefore retained, albeit marginally, and this borderline result is discussed further in Section 9.

Table 4: Overall Achievement Gain by Undergraduate Programme

Programme	N	Pretest M	Posttest M	Gain M	t	p	d
B.Sc.	19	54.00	88.05	34.05	12.84	<.001	2.95
B.Sc. with Mathematics	20	60.30	85.70	25.40	11.00	<.001	2.46
B.Sc.–B.Ed.	20	50.30	76.80	26.50	8.98	<.001	2.01

9. Discussion

The results provide clear support for the effectiveness of the model-based mathematics laboratory intervention. The large overall effect size (d = 2.35) and the statistically significant gain across every one of the nine laboratory units converge with the theoretical expectation, drawn from constructivist (Piaget, 1970) and constructionist (Papert, 1980) accounts of learning, that direct manipulation of concrete or visual models strengthens the internalisation of mathematical concepts more effectively than symbolic instruction alone. The magnitude of gain observed here is broadly consistent with Hake's (1998) and Freeman et al.'s (2014) findings that interactive, hands-on engagement produces substantially larger learning gains than passive instructional formats, and with Hattie's (2009) identification of active, feedback-rich instructional strategies as comparatively powerful influences on achievement.

The unit-wise pattern of results is informative. The largest gain was recorded for Complex Numbers, a topic that is often taught through the purely symbolic manipulation of a + ib notation; visualising complex numbers on the Z- and W-planes and in polar form appears to have given students a geometric anchor for a concept they may previously have encountered only algebraically. Similarly, large gains on the Rolle's/Lagrange's/Cauchy's Mean Value Theorems unit suggest that graphical and physically-grounded demonstrations of these theorems helped make an otherwise abstract existence-theorem topic tangible. Even the smallest unit-level gain (Linear Operators, d = 1.00) remained large by conventional standards, suggesting that the laboratory format was broadly, rather than selectively, effective.

The comparison across programmes suggests that the intervention worked comparably well for students following applied science (B.Sc.), mathematics-intensive (B.Sc. with Mathematics), and teacher-education (B.Sc.–B.Ed.) pathways, which is encouraging from the standpoint of designing a common mathematics laboratory curriculum that can be used across undergraduate science and teacher-education programmes without extensive customisation. The marginally non-significant ANOVA result (p = .053) together with the numerically higher gain for B.Sc. students may reflect the somewhat lower pretest baseline in the B.Sc.–

B.Ed. group or genuine differences in prior mathematical preparation across the three colleges; this pattern merits confirmation in a larger, better-powered sample.

Overall, the pattern of results significant gains at the overall level, at the level of every individual laboratory unit, and within every programme subgroup offers converging evidence that model-based mathematics laboratory activity is an effective supplement, and potentially an effective alternative, to purely lecture-based instruction for undergraduate science students.

10. Educational Implications

- Undergraduate mathematics curricula for science and teacher-education programmes can benefit from the deliberate inclusion of model-based laboratory sessions alongside conventional lecture instruction, particularly for topics that are traditionally taught in a purely symbolic manner (e.g., complex numbers, linear operators, mean value theorems).
- Teacher educators preparing prospective science and mathematics teachers (as in the B.Sc.–B.Ed. programme) may use structured mathematics laboratory activities both to strengthen trainees' own conceptual understanding and to model activity-based pedagogy they can later use in their own classrooms.
- Institutions planning mathematics laboratory infrastructure can prioritise low-cost, high-yield activities such as those built around measurement (planimeter, simple pendulum) and visualisation (complex-plane plotting, interpolation graphs) which produced some of the largest gains in this study.
- Curriculum designers should consider unit-wise achievement data, rather than only an aggregate score, when deciding which topics most urgently require a laboratory or model-based supplement to lecture instruction.

11. Limitations of the Study

- The single-group pretest–posttest design lacks a control or comparison group; consequently, the observed gains, although statistically robust, cannot be unambiguously attributed to the laboratory intervention alone and may be partly influenced by testing effects, maturation, or concurrent classroom instruction.
- The sample ($N = 59$) was drawn purposively from three affiliated colleges in one region of Gujarat, which may limit the generalisability of the findings to other institutional or geographic contexts.
- Achievement was measured using a single researcher-developed test administered immediately before and after the intervention; longer-term retention of the gains was not assessed.
- Potential confounding variables such as students' prior mathematics achievement, study habits, and attitude toward mathematics were not statistically controlled.

12. Conclusion

This study evaluated the effectiveness of a nine-unit, model-based mathematics laboratory intervention on the academic achievement of 59 undergraduate science students drawn from three colleges in Gujarat, using a single-group pretest–posttest design. Students showed a statistically significant and practically large improvement in overall achievement ($t(58) = 18.02$, $p < .001$, $d = 2.35$), and every individual laboratory unit spanning both applied/experimental and purely mathematical topics showed a significant, large-magnitude gain. Gains were significant across all three undergraduate programmes represented in the sample. These findings support the conclusion that model-based, hands-on mathematics laboratory activity is an effective pedagogical strategy for strengthening undergraduate science students' mathematics achievement, and they provide an empirical basis for embedding structured mathematics laboratory work more systematically within undergraduate science and teacher-education curricula. Future research using randomized controlled or quasi-experimental designs with comparison groups, larger and more geographically diverse samples, and delayed retention testing would help to further strengthen the causal evidence base for this pedagogical approach.

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