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Effect of Inquiry-Based Laboratory and Self-Paced Learning Strategies on Students' Achievement in Partial Differential Equations in Ebonyi State

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ABSTRACT

The study investigated effects of integrated inquiry-based laboratory and self-paced learning strategies on undergraduate students' achievement in Partial Differential Equations (PDE) in government-owned universities in Ebonyi State. Three research questions and three null hypotheses guided the study. Quasi-experimental non-equivalent design was adopted. Population comprised 46 400-level Pure Mathematics and Mathematics Education students (34 males, 12 females) sampled by census. Partial Differential Equations Achievement Test (PDEAT) was face and content validated with reliability coefficient of 0.87 using Kuder-Richardson 20 (K-R20). Mean, standard deviation and ANCOVA at 0.05 significance level were used for analysis. Findings revealed both strategies enhanced achievement, reduced gender gap, and the interaction effect of strategy and gender was not significant. Implication is that learner-centered strategies improve learning outcomes irrespective of gender, promoting equity. It is recommendations among other things that students should adopt both strategies in learning PDE.

Keywords: Inquiry-based Laboratory Learning strategy, Self-paced Learning Strategy, Achievement, Partial Differential Equations, Gender

INTRODUCTION

Many undergraduate students experience difficulties in understanding and solving mathematical problems due to inadequate conceptual understanding and challenges in applying mathematical concepts to real-life situations. These difficulties may hinder their ability to understand and solve problems involving Partial Differential Equations (PDE), particularly those related to heat transfer, wave motion, and diffusion; thereby resulting in unsatisfactory academic achievement. Integrated Inquiry-Based Laboratory Learning strategy and Self-Paced Learning strategy facilitated through Google Classroom may enhance students' conceptual understanding by promoting practical exploration, independent learning, and active engagement that could in turn, enhance students' academic achievement. These strategies though important, the extent to which they influence undergraduate students' achievement in Partial Differential Equations, and whether their effects differ by gender, remain important empirical questions.

Partial differential equations (PDE) are mathematical equations that involve an unknown function of two or more independent variables and their partial derivatives, making them essential for modeling complex phenomena. PDE describe how quantities such as temperature, wave displacement, or quantum states change with respect to space and time; as seen in classical examples like the heat equation, wave equation, and the Schrödinger equation in quantum mechanics (Evans, 2010; Strauss, 2008; Boyce & DiPrima, 2017). Irrespective of the importance of Partial Differential Equations (PDE) in mathematics and applied sciences, students continue to experience difficulties in understanding and solving PDE problems. The researcher's preliminary survey indicates that students' achievement in PDE is poor, with high failure rates across different levels in government-owned universities in Ebonyi State.

This situation may be associated with the abstract nature of PDE concepts, the complexity of mathematical procedures, and the limitations of teacher-centred instructional approaches that emphasise memorisation rather than conceptual understanding. In addition, the inherent complexity of PDE, especially nonlinear cases with no general analytical solutions, makes learning difficult and demands numerical, graphical, and technology-supported approaches, thereby motivating recent reforms in the teaching and learning of differential equations (Bibi et al., 2017; Raissi et al., 2019). Recent research has demonstrated the potential of inquiry-based learning to improve students' mathematical achievement. For instance, Khasawneh et al. (2023) examined inquiry-based learning in undergraduate college algebra, while Kiss (2022) discussed an integrated inquiry-based approach that encourages students to explore mathematical relationships and develop deeper understanding. These findings reinforce the need for more studies on their effect in addressing students' learning difficulties in PDE.

Integrating laboratory activities with inquiry-based learning may provide students with opportunities to explore abstract PDE concepts through computer simulations, graphical representations, numerical computations, and practical investigations. For example, students can investigate heat distribution, wave propagation, and the effects of initial and boundary conditions to establish connections between mathematical expressions and real-world phenomena. Research reviews by Dah et al. (2024) and Strata et al. (2024) identified positive outcomes of inquiry-based learning, including improved conceptual understanding, motivation, thinking skills, and attitudes towards learning. Integrating laboratory activities with inquiry-based learning could therefore promote active

participation, quantitative reasoning, and persistence in solving complex mathematical problems. Nevertheless, its effectiveness in improving students' achievement, including possible differences between male and female students, requires empirical investigation in the context of PDE. This provides the rationale for adopting the Integrated Inquiry-Based Laboratory Learning Strategy (IIBLLS) in teaching and learning of Partial Differential Equations. Aside IIBLLS, another instructional approach that is likely to promote meaningful learning and cater for individual learning needs could be self-paced learning strategy (SPLS).

Self-Paced Learning Strategy (SPLS) is an approach that allows learners to regulate the speed of their study, enabling them to move through instructional content according to their individual learning needs. As noted by Agah et al. (2021), SPLS empowers learners to complete parts or the entirety of instruction at their own pace, while instructors primarily serve as guides and evaluators of progress (Castek et al., 2015). In the present study, SPLS involves students advancing through PDE content independently, supported by digital instructional resources, communication and assessments facilitated through Google Classroom. Google Classroom is a free, web-based platform developed by Google to support educational institutions in creating, organizing assignments, communicating with students and sharing resources. According to Agarwal (2020) as well as Ellis and Goodyear (2016), it is a versatile digital platform that centralizes and streamlines the learning experience. Its seamless integration with other Google tools enhances collaboration and students' participation. It also facilitates assignment management, grading and feedback in a collaborative environment, thereby improving engagement and interaction (Ellis & Goodyear, 2016). In operational terms, Google Classroom refers to the online platform employed by the researcher to deliver course materials, post learning activities, administer assignments, facilitate interactions and enable students to complete tasks at their own pace.

Several studies on Google Classroom's impact revealed that it improved students' achievement across areas (Hughes & Schuetz, 2018; Alharbi, 2019; Jalil & Hossain, 2019; Agarwal, 2020; Nashwan & Alkass, 2020; Sallam & Fawzi, 2021), thereby enhancing SPLS. Similarly, Bautista (2015) found that students exposed to SPLS performed better than those taught with conventional strategy in chemistry, while Castek et al. (2015) found that SPLS reduced fear and anxiety and improved achievement. Agah et al. (2021) found that SPLS favoured achievement in trigonometry, while Marshman and Chandralekha (2016) reported no significant effect in introductory physics. Although previous studies show SPLS and Google Classroom can enhance achievement, findings remain inconsistent and largely confined to chemistry, trigonometry and introductory physics, with little attention to advanced mathematics like PDE. Moreover, existing research examined self-paced or inquiry-based laboratory strategies independently, without simultaneously investigating their comparative effects across separate universities and with respect to gender, which the present study addresses.

Gender has long attracted scholarly attention in education, particularly in mathematics, where culturally constructed roles and expectations often shape learning experiences and outcomes (Razzak, 2013; Okorie & Ezeh, 2016; Jacob & Linus, 2017). Studies on gender differences in mathematics achievement report mixed findings, with some indicating no significant differences (Ukwueze, 2017; Ukwueze et al., 2019), others showing female advantage (Voyer, 2014), and some favouring males (Oloda, 2017). Much of the existing literature focuses on general mathematics at lower levels and rarely examines whether specific instructional strategies implemented in different universities can address gender gaps, particularly in advanced areas such as PDE (Ukwueze et al., 2024; Nwaogu & Amaechi, 2024). Consequently, there is limited empirical evidence from Nigerian universities, especially in Ebonyi State, on how IIBLLS and SPLS influence gender-related outcomes in PDE; prompting the present study to compare their effectiveness on students' achievement in PDE among undergraduate mathematics students.

Specifically, the study sought to determined:

1. the effect of integrated inquiry-based laboratory and self-paced learning strategies on undergraduate students' achievement in PDE.
2. the mean achievement scores of male and female undergraduate students in PDE.
3. the interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE

Research Questions

1. What are the mean achievement scores of undergraduate students taught PDE using integrated inquiry-based laboratory learning strategy and those taught with self-paced learning strategy?
2. What are the mean achievement scores of male and female undergraduate students in PDE?
3. What is the interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE?

Hypotheses

The following hypotheses tested at 0.05 significant level guided the study:

Ho_1: There is no significant difference in the mean achievement scores of undergraduate students taught PDE using integrated inquiry-based laboratory learning strategy and those taught with self-paced learning strategy.

Ho_2: There is no significant difference in the mean achievement scores of male and female undergraduate students in PDE.

Ho_3: There is no significant interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE.

METHODS

The design was quasi-experimental, non-equivalent design. The study was conducted in Ebonyi State, Nigeria, using all 46 400-level Mathematics students [34 males, 12 females] from Ebonyi State University, Abakaliki (n=26) and Alex Ekwueme Federal University, Ndufu-Alike, Ikwo (n=20) as sample via total enumeration technique was used due to small size of the population., organized into two intact course groups. Three instruments were used: Partial Differential Equations Achievement Test [PDEAT] – a 20-item multiple-choice test, Partial Differential Equations Quantitative Literacy Questionnaire [PDEQLQ] and Task Persistence Questionnaire [PDETPQ] – each 20-item 4-point Likert scales, adapted from Boersma et al. (2011) and Ogbu & Ugwu (2023) respectively, alongside lesson plans for Integrated Inquiry-Based Laboratory Learning Strategy and Self-Paced Learning Strategy covering wave equation, heat equation and types of PDE solutions. The instruments were face-validated by five experts from UNN and construct-validated through factor analysis (KMO = 0.81 for PDEQLQ and 0.80 for PDETPQ, $p<.001$), retaining 20 factorially pure items (≥0.35 loading) each, while trial testing yielded reliability coefficients of 0.87 [KR-20] for PDEAT, and 0.823 and 0.857 [Cronbach Alpha] for PDEQLQ and PDETPQ. Mean and standard deviation answered research questions while ANCOVA tested hypotheses at 0.05 level using SPSS version 25. A 4-week quasi-experiment [16 periods] was conducted with pre-test before treatment and post-test after treatment administered by trained research assistants using a training manual.

RESULTS

Research Question One: What are the mean achievement scores of the undergraduate students taught PDE using integrated inquiry-based laboratory learning strategy and those taught with Self-paced learning strategy?

Table 1: Mean and standard deviation of achievement scores of the students taught PDE using integrated inquiry-based laboratory learning strategy and those taught with self-paced learning strategy

Treatment		Pre-test		Post-test		Adjusted
	N	$\bar{\chi}$	SD	$\bar{\chi}$	SD	Mean
IIBLLS Group	26	41.15	9.20	63.65	7.25	60.474[a]
Self-paced group	20	33.00	7.33	55.00	11.54	55.219[a]

Table 1 data shows that the students who were taught partial differential equations using IIBL (experimental group 1) learning strategy had a pre-test mean score of 41.15 with standard deviation of 9.20 and post-test mean score of 63.65 with standard deviation of 7.25. Similarly, the students who were taught partial differential equations using SP (experimental group 2) learning strategy had a pre-test mean score of 33.00 with a standard deviation of 7.33 and a post-test mean score of 55.00 with a standard deviation of 11.54. The adjusted mean scores of 60.47 and 55.22 for the undergraduate students exposed to IIBL learning strategy and SP learning strategy respectively, imply that the undergraduate students exposed to IIBL (experimental group 1) learning strategy had higher post-test mean achievement score than those exposed to SP (experimental group 2) learning strategy. However, the post-test standard deviation of 7.25 and 11.54 for undergraduate students exposed to IIBL learning strategy and SP learning strategy respectively imply that the variation in the individual post-test scores of undergraduate students exposed to SPLS from their group mean is higher than those of the undergraduate students exposed to IIBLLS group.

Hypothesis One: There is no significant difference in the mean achievement scores of the undergraduate students taught Partial Differential Equations (PDE) using IIBLLS and those taught with SPLS.

Table 2: Analysis of Covariance (ANCOVA) of the effect of integrated inquiry-based laboratory learning strategy and self-paced learning strategy on undergraduate students' achievement in partial differential equations (PDE)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2567.668[a]	4	641.917	10.096	.000	.496
Intercept	1848.888	1	1848.888	29.080	.000	.415
Pretest	88.177	1	88.177	1.387	.246	.033
Treatment	136.331	1	136.331	2.144	.055	.050
Gender	156.178	1	156.178	2.456	.125	.057
Group * Gender	100.053	1	100.053	1.574	.217	.037
Error	2606.788	41	63.580			
Total	170175.000	46				
Corrected Total	5174.457	45				

a. R Squared = .496 (Adjusted R Squared = .447)

Table 2 shows the analysis of data with the calculated value of F(1,43) = 2.144, with associated probability value of .055 (p > .05), with a very small effect size (partial eta squared = .050) was obtained with regard to main effect of treatment on the mean achievement scores of students who were exposed to IIBLLS and those exposed to SPLS. Since the associated probability (.055) was greater than 0.05 level of significance, the null hypothesis was not rejected meaning that there is no significant difference in the mean achievement scores of students taught partial differential equations using integrated inquiry-based laboratory (IIBL) learning strategy and those taught with self-paced (SP) learning strategy, implying that both strategies impacted on students' partial differential equations achievement in similar way.

Research Question Two : What are the mean achievement scores of male and female undergraduate students in PDE?

Table 3: Mean and Standard deviation of pre-test and post-test scores of male and female undergraduate students exposed to integrated inquiry-based laboratory learning strategy and those exposed to self-paced learning strategy in partial differential equations.

Gender	N	Pre-test		Post-test		Adjusted Mean
		$\bar{\chi}$	SD	$\bar{\chi}$	SD	
Male	34	41.32	7.43	62.94	5.25	61.568[a]
Female	12	27.08	4.98	51.25	6.53	54.124[a]

Table 3 reveals the difference in the mean achievement scores of male and female undergraduate students in partial differential equations. The result showed that male undergraduate students had a pre-test mean score of 41.32 with standard deviation of 7.43 and a post-test mean score of 62.94 with a standard deviation of 5.25. On the other hand, the female undergraduate students had pre-test mean achievement of 27.08 with a standard deviation of 4.98 and post-test mean score of 51.25 with a standard deviation of 6.53. The adjusted mean scores 61.57 and 54.12 for male and female respectively, imply that male undergraduate students had a higher post-test mean score than their female counterparts. The standard deviations of 5.25 and 6.53 for male and female undergraduate students respectively, imply that variation in the individual achievement score of female undergraduate students from their group mean is higher than those of male undergraduate students.

Hypothesis Two: There is no significant difference in the mean achievement scores of male and female undergraduate students in PDE.

Table 2 reveals the calculated value of F(1,41) = 2.456 with associated probability value of .125 (p > .05) with a very small effect size (partial eta squared = .057) for the male and female students' achievement score in partial differential equations. Since the associated probability (.125) was greater than 0.05 level of significance, the null hypothesis was not rejected. Thus, there is no significant difference in the mean achievement scores of male and female students in PDE.

Research Question three

What is the interaction effect of learning strategy and gender on students' achievement in PDE?

Table 4: Mean and Standard deviation of interaction effect of (IIBL) and (SP) learning strategies and gender on undergraduate students' achievement in PDE

Mean Treatment	Gender	N	Pre-test		Post-test		Adjusted Mean
			$\bar{\chi}$	SD	$\bar{\chi}$	SD	
IIBLL Strategy	Male	18	46.39	4.79	68.61	5.35	65.979[a]
	Female	8	29.38	4.17	52.50	9.97	54.969[a]
SPL Strategy	Male	16	35.63	5.44	56.56	4.79	57.157[a]
	Female	4	22.50	2.89	48.75	7.00	53.280[a]

Table 4 reveals the interaction effect of teaching strategy and gender on students' achievement in PDE. The result showed male undergraduate students who were exposed to IIBL learning strategy had a pre-test mean score of 46.39 with a standard deviation of 4.79 and a post-test mean score of 68.61 with a standard deviation of 5.35 while the male undergraduate students who were exposed to SP learning strategy had pre-test mean score of 35.63 with standard deviation of 5.44 and a post-test mean score of 56.56 with a standard deviation of 4.79. Female undergraduate students who were exposed to IIBL learning strategy had a pre-test mean score of 29.38 with a standard deviation of 4.17 and a post-test mean score of 52.50 with a standard deviation of 9.97, while the female undergraduate students who were exposed to SP learning strategy had a pre-test mean score of 22.50 with a standard deviation of 2.89 and a post-test mean score of 48.75 with a standard deviation of 7.00. By implication, this showed that male and female undergraduate students who were exposed to IIBL learning strategy had slightly higher adjusted mean scores than the male and female undergraduate students who were exposed to SP learning strategy.

Hypothesis three: There is no significant interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE.

Data on Table 2 shows that the calculated value of F(1,41) = 1.574 for the interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE had an associated probability value of .217 (p > .05) with a small effect size (partial eta squared = .037). Since the associated probability (.217) was greater than .05 level of significance, the null hypothesis was not rejected implying that there was no significant interaction effect of teaching strategy and gender on undergraduate students' achievement in PDE. This is further shown by the interaction graph below:

Figure 5: Profile Plots for Interaction Effect of Learning Strategies and Gender on Undergraduate Students' Achievement in PDE.

The figure above explains the interaction effect of the teaching strategies and gender on undergraduate students' achievement in PDE. The parallel lines suggest that there was no interaction effect of teaching strategies and gender on undergraduate students' achievement in PDE since there is no crossing of lines connecting the means.

DISCUSSION

The findings revealed that students taught Partial Differential Equations (PDE) using the Integrated Inquiry-Based Laboratory Learning (IIBLL) strategy obtained slightly higher post-achievement mean scores than those taught using the Self-Paced (SP) learning strategy, although the difference was not statistically significant. This indicates that both strategies were effective in improving students' achievement in PDE. The hands-on activities, experimentation, and exploration of open-ended questions associated with IIBLL enhanced students' focus and motivation, while the autonomy and flexibility of SP learning encouraged independent learning, self-confidence, and deeper understanding of PDE concepts. These findings agree with Obi and Ede (2025), Adeniyi and Adewale (2024), Khasawneh, Hodge-Zickerman, York, Smith and Mayall (2023), Sichangi, Ngaruiya, Odundo and Muriithi (2023), and Salisu and Yusuf (2023), who reported positive effects of inquiry-based and laboratory learning on students' achievement. Similarly, Okonkwo and Ofoegbu (2023), Adeyemi and Bello (2022), and Eze and Ugwuanyi (2021) found that IIBLLS enhanced academic performance across different science and mathematics disciplines.

The findings also support previous studies on the effectiveness of self-paced learning in improving students' achievement across different educational levels and subject areas. Spencer (2022) found that self-paced learning improved mathematics achievement and motivation among eighth-grade students, while Ntibi and Ibok (2020) reported higher mathematics and physics achievement among students taught using self-paced learning than those taught using conventional methods. Similarly, Lee and Song (2019) found that self-paced learning improved university students' practical programming performance, while Adani, Eskay, and Onu (2012) reported significant improvement in algebra achievement among students with learning difficulties. These findings suggest that self-paced learning can support undergraduate mathematics students in addressing the abstraction, symbolic manipulation, and problem-solving demands of PDE.

The findings further support Dewey's constructivist theory of learning (1938), which emphasizes

observation, experimentation, active participation, and learning through experience, as demonstrated by the hands-on activities and collaborative experiences associated with IIBLL and the independence promoted by SP learning. They are also consistent with Piaget's cognitive learning theory (1952), which emphasizes individual learning, information processing, assimilation, and the construction of meaning. Both instructional strategies provided engaging and flexible learning experiences that supported students' understanding and achievement in PDE. Therefore, the findings affirm the potential of IIBLL and SP learning strategies to improve undergraduate students' achievement in Partial Differential Equations.

The findings revealed that male and female students taught using the integrated inquiry-based laboratory learning (IIBLL) strategy obtained slightly higher mean achievement scores in Partial Differential Equations (PDE) than those taught using the self-paced (SP) learning strategy. However, the difference in achievement between male and female students was not statistically significant. The ANCOVA results further indicated that gender had no significant influence on students' achievement in PDE, suggesting that both instructional strategies provided equal learning opportunities for students irrespective of gender. These findings agree with Ukwueze, Ugwuanyi and Ogbu (2022), Anakpa, Nzeakor and Emefo (2021), Ukwueze, Abugu and Odo (2020), Ukwueze (2017), Salami (2013), Arhin and Offoe (2015), Ajai and Imoko (2015), Amatobi (2013), and Gambari, Shittu and Taiwan (2013), who reported no significant gender differences in students' academic achievement across various subjects and instructional approaches.

However, the findings contradict Amongne (2015), who reported a statistically significant achievement difference favouring male students, and Muthukrishny (2010), who found a gender gap favouring female students in mathematics achievement. Similarly, Cooper (2018) and Wong (2017) observed that females often employ language-based strategies when solving mathematics problems, which may favour them in tasks involving recall and routine calculations rather than spatial reasoning. These conflicting findings may be attributed to differences in research contexts, populations, mathematical content, assessment instruments, and instructional practices. Consequently, gender differences in mathematics achievement may depend on the nature of the tasks and learning conditions rather than representing a universal pattern.

The non-significant gender differences observed in the present study support Dewey's constructivist theory of learning, which emphasizes problem-solving, experimentation, reflection, and active participation in the learning process. By providing male and female students with equal opportunities to explore, experiment, and solve problems through IIBLL and SP learning strategies, the study suggests that both approaches can promote achievement irrespective of gender. This interpretation is consistent with Lazonder and Harmsen (2016), who highlighted the contribution of inquiry-based learning to students' motivation, engagement, and learning outcomes.

The findings revealed that there was no significant interaction effect of learning strategies and gender on undergraduate students' achievement in Partial Differential Equations (PDE), suggesting that the observed achievement outcomes were associated with the instructional interventions rather than differences in gender. These findings agree with Asanre and Abiodun (2025), Odo (2023), Khasawneh, Hodge-Zickerman, York, Smith and Mayall (2023), and Ajai, Imoko and Okwu (2013), who reported no significant interaction effects between gender and instructional approaches on students' mathematics achievement. Similarly, Al-Samarraie, Al-Emran, and Abedalaziz (2021), Agyei and Voogt (2022), Chen, Wang, and Kirschner (2023), Nwosu and Okeke (2024), and Patel and Singh (2025) found no significant interaction effects between gender and self-paced, blended, online, or adaptive learning approaches on students' achievement in mathematics and related subjects.

The findings suggest that male and female students can benefit equally from well-structured instructional strategies that promote active participation, independent learning, and flexibility in learning pace. Therefore, the integrated inquiry-based laboratory and self-paced learning strategies used in this study appear to support achievement irrespective of gender, suggesting their potential to reduce gender disparities in mathematics achievement.

CONCLUSIONS

Based on the findings of this study, it is concluded that Integrated Inquiry-Based Laboratory and Self-paced Learning strategies increased students' achievement in partial differential equations irrespective of gender in a similar way; though, the group exposed to integrated inquiry-based laboratory learning strategy had higher achievement scores than their counterparts in in self-paced learning strategy group.

Recommendations

Based on the findings of this study, the researcher made the following recommendations:

1. Students should embrace both integrated inquiry-based laboratory and self-paced learning strategies to the learning of Mathematics as this was found to improve students' achievement in partial differential equations.
2. PDE Lecturers should embrace and employ the learning strategy such as the use of IIBLLS (guided inquiry cycles, laboratory-based exploration, collaborative problem-solving activities emphasized) and the use of SPLS (structured learning modules, individual pacing guides, self-directed tasks, and mastery-based progression) in the teaching and learning of partial differential equations.

3. Policy makers and other stakeholders in Mathematics Education should organize workshops, in-service training, conferences and seminars for Mathematics Lecturers where the guides on how to use both integrated inquiry-based laboratory and self-paced learning strategies in the teaching and learning of Mathematics can be presented.
4. Curriculum planners should consider reviewing the current Mathematics curriculum and incorporating strategies in teaching Mathematics in such a way that students' activities and teachers' activities should reflect both integrated inquiry-based laboratory and self-paced learning strategies steps, since they were found to have enhanced students' achievement in partial differential equations, and are also found to be gender friendly.

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