Difficulties in understanding mechanical waves: Remediated by problem-based instruction

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(Received 21 January 2022; accepted 4 April 2022; published 2 June 2022)

This study aimed at analyzing the impact of problem-based learning (PBL) in improving physics students' conceptual understanding of mechanical waves. This study used a quasiexperimental, pretest–post-test control group design with PBL instruction as a teaching intervention. The participants of this study were 239 physics students from 19 secondary schools in Western Uganda. We analyzed data with SPSS v.23.0 using repeated two-way analysis of variance tests. We found that unlike the superposition of mechanical waves concepts, PBL effectively improves students' understanding of propagation, reflection, and standing waves more than the usual or traditional teaching method. Teachers were recommended to teach with PBL to assess students' difficulties to remedy them and uplift their understanding.

DOI: 10.1103/PhysRevPhysEducRes.18.010140

I. INTRODUCTION

Students find dealing with different physics concepts difficult, including mechanical waves [1]. The reports of national experiments in Uganda showed a lack of this understanding, particularly among physics students [2]. As a result, students may drop out of science subjects as they advance to higher levels, increasing the shortage of skilled labor in science, technology, engineering, and mathematics fields. Previous researchers have linked students' inability to properly handle these concepts with the teaching methods used, which primarily involve teachers teaching in front of students with material primarily from textbooks [3]. This method reduces opportunities for students to develop a free exchange of ideas and does not promote active learning. A study by Hake [4] showed that involving students in interactive engagement strategies increased their conceptual understanding. As Wittmann [5] points out, examining students' understanding of concepts taught in the classroom provides the basis for creating instructional materials that are most effective in increasing students' actual understanding. Thus, to overtake the current passive mode of teaching and actively involve students in the learning process, problem-based learning (PBL) instruction was considered a prerequisite for this study. In this regard, the present study sought to analyze the impact of PBL in enhancing students' conceptual understanding of mechanical waves in physics among secondary schools in Mitooma district–Southwestern Uganda. On the other hand, most of the studies found in the literature concentrate on students' difficulty in a particular subconcept, but this study investigates a full topic of waves by using the mechanical waves conceptual survey (MWCS) by Tongchai *et al.* [6].

A. Students' difficulties with mechanical wave concepts

Learning is a mental process, and students' prior knowledge about the concept plays an important role in the learning process. When students face a new learning environment, they generate meaning based on their prior knowledge. Therefore, if teachers are able to teach new knowledge effectively, they need first to investigate what students already know and whether it supports or contradicts the expected scientific realities [7]. Hence the term "difficulty" was generally used interchangeably with "misconception" in this study to represent all misunderstandings students possess about a concept.

Students generally perceive wave studies as difficult, abstract, uninteresting, and a subject only suitable for very gifted and gifted students [8]. High school teachers pointed out that students misidentified radio waves as longitudinal sound waves rather than transverse mechanical waves [9]. Wittmann [10] found that students' interpretations do not focus exclusively on the event-driven nature of wave phenomena but provide objectlike descriptions. Richardson [11] found that many students tend to focus on problem-solving strategies without being aware

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of the underlying concepts; instead of building a conceptual understanding of waves in physics to solve word problems, students use a formula-focused translation strategy. If student difficulties are not addressed early enough, they can persist and worsen as topics reappear in more advanced courses [12].

B. Theoretical framework

Currently, the way teachers teach in the classroom is considered an important factor influencing learning outcomes [13]. Classroom methods for teachers are usually based on the type of teaching and learning they experience as a student, the methods promoted in teacher education as defined in the curriculum, other teachers, and learning theory [14]. The adequacy of this method depends on students' goals, context, and needs, available materials and personalities, teacher strengths, and style [15]. However, recent curriculum reforms have promoted a shift from conventional learning approaches to active learning strategies that encourage students to participate in learning [14]. In this approach, students are actively involved in activities that involve analysis, synthesis, evaluation, and developing skills, values, and attitudes [16]. Jacobsen [15] argued that active learning discusses learning activities in which students gain considerable autonomy and control over learning activities, including guidelines for experimentation and problem solving. Philosophers of education, including pragmatists, advocate for humans to learn via solving real-life problems [17]. Problem-based learning instruction came to light originating from the constructivism school of thought to achieve this [18]. Allchin [19] defines PBL as a teaching method where learners solve problems based on real-life situations. Learners in PBL engage in intriguing real and relevant intellectual inquiry based on real-life cases [20]. The process of PBL starts with forming groups among students in which they work collaboratively as they identify or create a problem based on the prevalent context and then suggest possible solutions to the problem employing all available tools [21], enabling them to develop new and relevant knowledge [22].

Students instructed under PBL can easily share their views with others, employ various approaches to analyze circumstances, and explore different ways of solving a problem [23]. They can also explicitly reflect on their experience and thus deepen their understanding of scientific practices [19]. PBL supports the development of critical and reflective thinking about the process itself and emotional aspects such as curiosity [24]. In PBL, the teacher only facilitates the problem-solving process [22] through monitoring group discussions and presentations and may appropriately ask questions that probe accuracy, relevance, depth of information and analyses, raise new issues that ought to be considered, and also foster students' participation [25]. The study thus aimed at incorporating PBL elements to develop the intellectual ability of learners [26]. Problem-based learning activities enable learners to construct meaning at an intrapersonal level and relate this meaning with the interpersonal physical world.

One important thing is that teachers as educationists cannot just transfer knowledge to learners. However, instead, learners need to actively construct the knowledge within their minds, which they generate from interaction with their experiences and ideas [27]. Because of this, our study adopted the social constructivism learning theory associated with a famous psychologist, Jean Piaget, who proposed that individuals can build new knowledge from their experiences through the processes of accommodation and assimilation. Social constructivists believe that individuals seek to understand the world they live and work in. According to this theory, the teacher's role is that of a facilitator; to help learners understand the content by formulating aims of learning based on reliable tasks with specific objectives [26]. The adoption of PBL in this study was based on this theory of social constructivism to incorporate the fact that learning can only be complete if instruction uses a hands-on approach.

C. Aim of the study

Our previous paper [28] evaluated the PBL in mechanical waves as a whole and measured students' performance. The present study aimed at analyzing the impact of problem-based learning on physics students' understanding of mechanical waves. Actually, we identified difficulties (in pretest), then gave instruction, and then reexamined the resistant difficulties. We need to clarify that we instructed PBL in general, not specifically identified difficulties. Specifically, it tended to answer the following research questions:

1. Does problem-based learning instruction improve physics students' understanding of main topics in mechanical waves?
2. What are students' difficulties within mechanical waves before and after learning through traditional or PBL methods?

II. METHODOLOGY

A. Design of the study

The study followed a quantitative research approach with a quasiexperimental design employing cross-sectional survey techniques [29]. Precisely, our study used a pretest and post-test control group experimental design where PBL as an intervention and traditional teaching methods (TTM) were used on the experimental and control groups, respectively.

B. Target population and sampling methods

In this study, the population of senior six (grade 13) physics students in the Mitooma district–Southwestern

Uganda was considered. A total of 239 physics students from 12 schools were randomly selected. The average was around 22 students per physics class. All physics students in grade 13 were used as an entire class. As a result, when we wanted to recruit students from various schools, we asked for all those doing physics in grade 13. Allocation of schools to the treatment and comparison groups was also based on simple random sampling. Cluster sampling technique was employed in this study where intact classes were used as units of analysis. Two hundred and thirty-nine (239) students participated in a group that performed both pre-and post-test (where 132 were taught via PBL while 107 were taught via TTM).

C. Ethical considerations and data collection methods

The study did not consider particular groups such as those living with HIV or persons with special education needs. Thus, the study was blind to whether a participant was a member of one of those groups. All participants were required to first consent. Each participant was given a code and was referred to only by that code. No monetary compensation was given to participants. Participants were free to withdraw from the study at any time without penalty and were also free not to answer any questions or respond to any research situations if they chose so. Prior to data collection, a research proposal was sent to the University of Rwanda College of Education (URCE) for evaluation, where the unit of research and innovation offered us an ethical clearance.

Teachers were first trained on planning and implementing a PBL lesson. Quantitative data on determining the impact of problem-based learning on students' conceptual understanding in mechanical waves were collected using a mechanical wave conceptual survey (MWCS) designed by Tongchai *et al.* [6] for high school students available at physport [30]. The survey covers four main topics in mechanical waves: propagation of waves (question 1–8), superposition (question 9–12), reflection (question 13–16), and standing waves (question 17–22) as described in Barniol and Zavala [31,32] and Tongchai *et al.* [6] It contains multiple-choice questions that enable the researchers to extract detailed and varied responses from a wide range of students. It also helps to identify the students' difficulties with mechanical waves. MWCS questions 1–3, 5, and 12 have four answer choices (A–D); questions 4, 9, 11, and 20 have six choices (A–F); questions 6, and 13–16 have five choices (A–E); questions 7–8 have eight choices (A–H); questions 10, 17–19, and 21–22 have three choices (A–C). In addition to questions 17–19 and 21–22 choices, four reasons are attached to questions 17–19, while five choices for a reason are attached to questions 21–22.

We first pretested the survey on the students before the administration of teaching activity to identify homogeneity among participating groups. After the intervention was

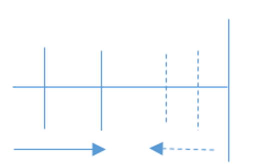
	Traditional teaching method (TTM) class	**Problem-based learning (PBL) class**
What did the teacher do? **(typical examples of what was done related to mechanical waves)**	On reflection of waves, the teacher had written down notes which he dictated for students to write down; he then drew different diagrams on the board to illustrate the reflection of plane waves on a plane surface and a circular surface. The ullustration below shows plane waves on a plane surface are reflected as plane waves  	- Students had previously been given an activity to discuss the reflection of waves using appropriate examples and demonstrations - Groups of 5 to 6 students had been formed, each group with a presenter. - They used two mirrors (one plane and the other curved) with both upright and round objects placed in front of the mirror one at a time, and a white screen where the image would be formed, and the presenter would invite fellow students in turns to observe and trace the shape of the image formed in each case.
What did the learners do? **(typical examples of what was done related to mechanical waves)**	After copying notes and drawing diagrams as given on the board, they described the appearance of different shapes of reflected waves depending on the shape of the incident wave and the shape of the reflector.	After tracing for themselves the shapes of images formed in each case, they described how the shape of the incident wave and the shape of the reflecting surface affect the shape of the reflected waves.

FIG. 1. Intervention delivered.

delivered from January to April 2021, it was then post-tested on all the groups of students to determine how much value the treatment added to students' conceptual understanding of mechanical waves and analyze their challenges with mechanical waves. At each time of administration of the test, individual students were always allowed enough time to answer the survey items. The test was then scored using the key provided by the authors of the MWCS for further statistical analysis. Figure 1 informs what was done in control (learning via TTM) and experimental (learning via PBL) classes.

D. Trustworthiness: Validity and reliability of the study instruments

Trustworthiness was ensured by creating rapport with participants and developing a consent form assuring them of confidentiality of information and identity. More so, the samples selected were large enough, were studied in their natural setting, and techniques were employed to allow generalization and replicability of data over a bigger population. To ensure the internal content validity of the study instruments, a standardized MWCS was adopted. Before its adoption; the instrument was studied carefully with the co-authors and two other research experts to ensure that it matched the problem under investigation and covered the content of mechanical waves as given in the Ugandan national syllabus [33].

Each research instrument is considered to be reliable. In that case, we must demonstrate that if the instrument used was carried out on a similar group of participants under similar conditions; it would still give similar results [34]. Achievement of consistency assured us that the results obtained represent the conceptual understanding of the individual participants [29]. After the survey was accepted for adoption, a test–retest pilot study was carried out on a small group of those who participated in the final study. In addition, McNemar's test was run to determine a difference between the test-retest pilot results. An exact p value of 0.250 was obtained, meaning that the difference was non significant at a 95% confidence interval; hence the instrument was considered reliable.

E. Data analysis methods

Data were mostly analyzed in Statistical Package for Social Science (SPSS) software, version 23.0, to compute statistical significance. The average score for each mechanical wave topics was computed for each student in the experimental and control groups. Then, two-way analysis of variance repeated measures were used to provide results of differences between control and experimental groups at the same time before and after delivering teaching intervention across all four main topics of mechanical waves. To determine students' difficulty with mechanical waves, the difficulty analysis based on their average performance on the MWCS was computed for each question.

III. DATA PRESENTATION AND RESULTS

This section presents the results of the study aimed at analyzing the impact of PBL on students' conceptual understanding of mechanical waves gained from pretest to post-test between experimental and control groups using the MWCS. The findings were presented according to the research questions.

A. Question one: Does problem-based learning instruction improve physics students' understanding of main topics in mechanical waves?

Table I shows descriptive statistics of the pre-and post-test for each experimental and control group, among four main topics of mechanical waves. The experimental group consisted of 132, while the control group consisted of 107 students.

The performance in main topics in waves was very high statistically significant ($p < 0.001$) with 0.040 partial eta squared. This effect from pretest to post-test (main topics in waves within testing time) was also very high statistically significant ($p < 0.001$) with $\eta = 0.091$ (partial eta squared). However, the effect in main topics in waves within groups of intervention (experiment and control) was not statistically significant ($p > 0.05$) with 0.014 partial eta squared though the overall effect (main topics in waves within groups and along testing time) was highly statistically significant ($p < 0.01\eta$) with 0.028 partial eta squared. Note that partial eta-squared () indicates the percent of the variance in the dependent variable attributable to a specific independent variable. The lack of statistical significance in both experimental and control groups was caused by the fact that before teaching intervention control group was better than the experimental group in most of the topics of mechanical waves (see Fig. 2), especially in reflection. At the same time, this was inversed after the intervention.

Figure 3 shows that experimental groups performed better on the topics than the control group in the post-test. Thus, the effect canceled each other. Visually, if the experimental group that learned through problem-based learning lowly performed before learning and highly performed after learning, it means that PBL showed effect over the traditional method.

Another confirmatory factor of this effect was learning gain. Figure 4 shows that the normalized learning gains from pretest to post-test in the experimental group were higher than ones in the control group across all main topics in mechanical waves. Thus, PBL statistically raised conceptual understanding of main topics in mechanical waves than TTM did, except in superposition of waves-related concepts.

Propagation of waves was highly statistically significantly different ($p < 0.01$), superposition was not significant ($p > 0.05$), a reflection of waves was very high statistically significant ($p < 0.001$), and standing waves

TABLE I. Descriptive statistics.

Main topics in mechanical waves	Groups	Testing time	Mean (%)	Standard deviation	N
Propagation	Experimental	Pretest	15.53	11.67	132
		Post-test	61.83	13.92	132
	Control group	Pretest	17.40	12.70	107
		Post-test	56.65	15.57	107
Superposition	Experimental	Pretest	12.12	17.33	132
		Post-test	62.50	24.02	132
	Control group	Pretest	17.05	18.36	107
		Post-test	61.91	23.87	107
Reflection	Experimental	Pretest	9.84	15.05	132
		Post-test	63.44	21.26	132
	Control group	Pretest	24.06	20.29	107
		Post-test	56.07	23.99	107
Standing waves	Experimental	Pretest	23.34	12.21	132
		Post-test	60.74	14.87	132
	Control group	Pretest	26.84	12.69	107
		Post-test	55.65	17.19	107

have also shown a very high statistically significant difference ($p < 0.001$) in favor of the experimental group. Students improved their understanding in reflection ($\langle g \rangle = 0.595$) more than in other concepts. Standing waves showed the lowest learning gains ($\langle g \rangle$) among other topics ($\langle g \rangle = 0.488$ for experimental and $\langle g \rangle = 0.394$ for the control group).

B. Question two: What are students' difficulties within mechanical waves before and after learning through traditional or PBL?

To compare physics students' difficulty with MWCS between those instructed under problem-based learning and those instructed under traditional approach, the number of students who answered a single question correctly was

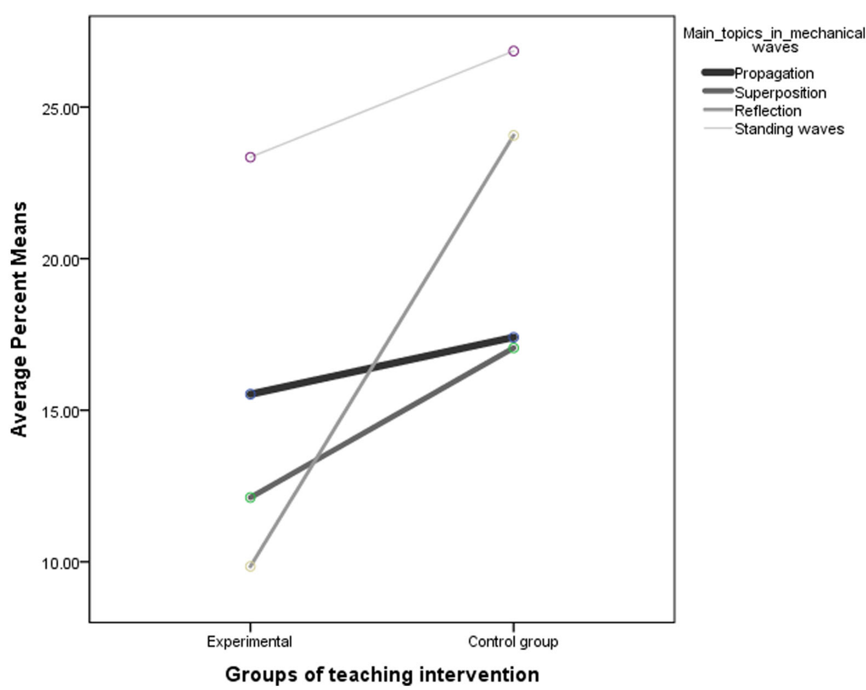


FIG. 2. Pre-test performance of experimental and control group in main topics of mechanical waves.

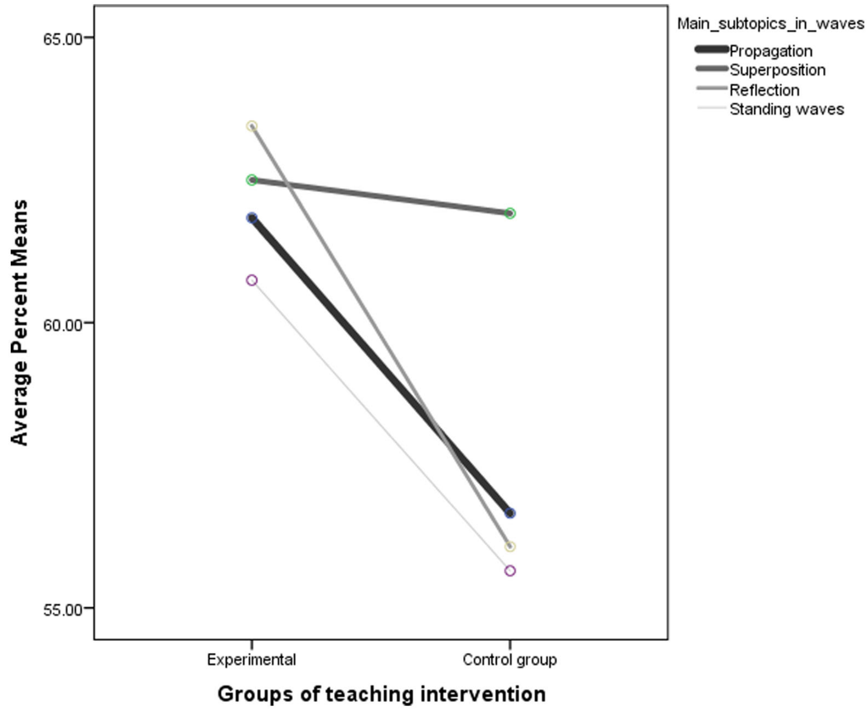


FIG. 3. Post-test performance of experimental and control group in main topics of mechanical waves.

counted. This text presents the overall number of students (in percentage) that have performed well on each question in MWCS in each teaching intervention group. It can be seen that 17% of students in the experimental group and 22% of students in the control group performed well in the pretest (students who got more than 50% scores or who got correct answers) while 62% of students in the experimental group and 57% of students in the control group performed well in the post-test. Thus, more students in the control group could perform the test well before teaching intervention; however, after learning mechanical waves, students taught with PBL increased considerably than those taught with the traditional teaching methods. This shows the potential of PBL instruction. Generally, the number of students in both control and experimental groups, as observed in Fig. 5, increased from the pretest stage. The number of students who performed each MWCS question well was below 50%. However, except for questions 5 and 22b, other questions were performed above 50% by students (see Fig. 5) after being taught (at the post-test stage).

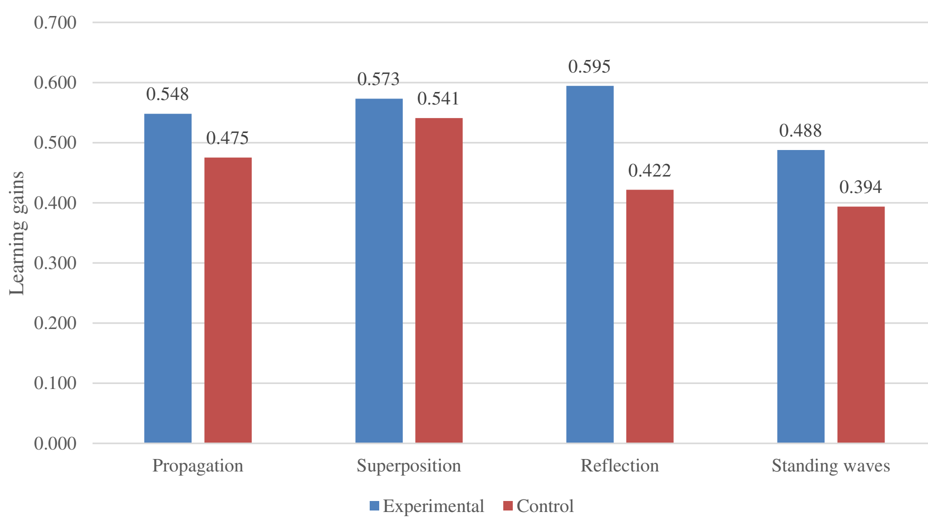


FIG. 4. Normalized learning gains across main topics in mechanical waves.

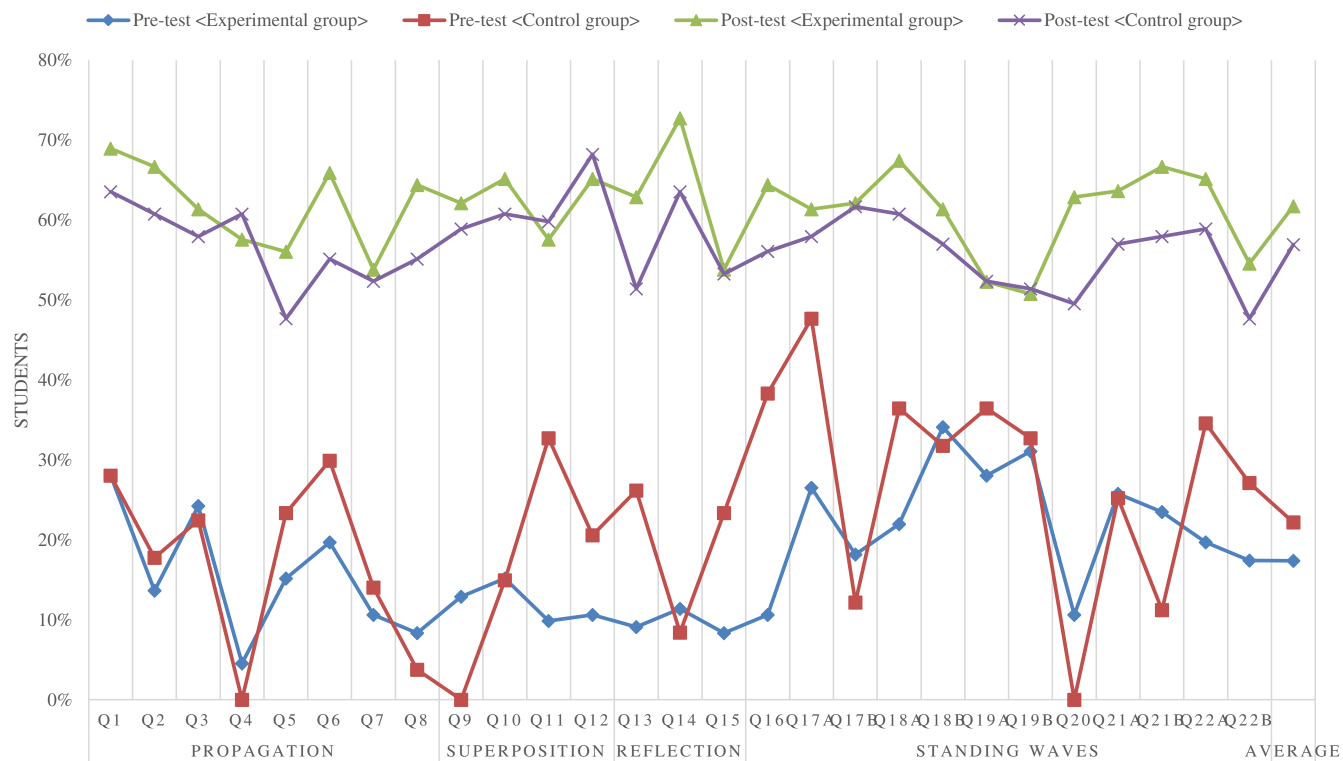


FIG. 5. A display of MWCS questions revealing students' difficulties after teaching interventions among the groups that were given both pretest and post-test.

Question 17a "how would the wavelength of the new harmonic standing wave change" was well performed by 48% of students in control group alongside 27% students in experimental group before teaching intervention. However, PBL shows its impact where the number of students in the experimental group (61%) surpassed the control group (58%) after teaching intervention.

Generally, the PBL effect was visualized across all MWCS questions except questions 4, 11, 12, and 19 (both a and b). The concepts in those questions, such as "speed independence of the changes in hand movement" (question 4), "superposition of two waves in the overlap" (question 11), "superposition of two waves after overlap" (question 12), and "how would the wavelength of the new harmonic standing wave change" (question 19) were understood despite the learning into problem-based instruction.

Among questions with follow-up of the reason of the selected answers, questions 18, 19, and 22 showed the existence of difficulties among students. A big number was able to select a correct answer but not provide the right reason attached to their answer. For instance, 67% of students in the experimental group answered that the wavelength of the new harmonic standing wave would increase (choice A, correct answer on question 18) if the mass is increased by a factor of four while everything else stays the same. However, only 61% were able to explain why the wave's speed increases when the tension increases (reason choice 3). In the same group, 52% of students were able to answer that the wavelength of the new harmonic standing wave decreases (choice B, correct answer on question 19) if a thicker (more mass) rope is used while everything else stays the same. However, only 51% were able to provide the reason that as the rope becomes heavier, the speed of the wave decreases (reason choice 3). Seemingly, question 22 raised the same confusion in providing reasons among students in the experimental group. Sixty-five percent of students answered that the pitch of the sound would become higher (choice B) if more water were added to fill the bottle to half full because the air column becomes shorter and the wavelength changes (choice "2" answered by 55%).

IV. DISCUSSION

Our study intended to outline difficulties faced by Ugandan students in mechanical wave concepts. Educationists have linked the lack of the required knowledge among students in the concepts of waves to the way they are taught [35]. Researchers such as Wittmann [10] identified the lack of cognitive aspects of knowledge given by Bloom's taxonomy [36] as one of the students' difficulties in the topic of waves. Mujasam *et al.* [37] added that difficulties exist because of teachers' failure to optimally incorporate students in terms of the learning experience as a foundation for building new knowledge. Tabor-Morris *et al.* [9] pointed out that teachers' awareness of students' difficulties in studying waves and addressing them may be essential to assisting students' learning.

Our study was unique to reveal that PBL effectively remedied misconceptions in propagation, reflection, and standing of waves. In their revisited analysis, Uwamahoro *et al.* [38] revealed that effective instruction improved students' understanding of all primary topics in geometric optics, except the behavior of lenses. Şengören *et al.* [7] highlighted that proper understanding of wave concepts such as interference, reflection, transmission, refraction, and phase difference requires students to have a proper grounding of the fundamental wave properties hence easing learning of advanced related concepts. Fazio *et al.* [39] emphasized that teachers need to employ innovative teaching approaches that lead to observable and measurable positive changes in students' learning. It was also found that usual teaching can improve students' understanding of light phenomena [40]. However, PBL did not show its effect on superposition on waves. A study by Sundar [41] concurred that students face difficulties in a superposition of waves, and therefore, instruction should be carefully planned. For instance, the author needed to introduce a pictorial representation to increase students' attention and understanding. He set up two loudspeakers and let each student walk between the speakers, changing speed, and spot the points where the volume is low and high. Thus, teaching such a concept would probably need more engaging activity such as this practice or computer simulation such as PhET simulation, which were not done in our intervention of problem-based instruction.

Problem-based learning impacts the development of thinking skills and an understanding of the nature of waves more than the conventional methods [19] hence improving academic achievement [42]. As students work on problems, they typically exercise and deepen research, analysis, interpretation, critical thinking skills, and creative thinking skills [23]. In addition, students can reflect on their experience and thus better understand scientific practice [19]. Engaging students in problem solving not only gives them a deeper layer of thinking about the generation of knowledge, the nature or quality of evidence, and about reasoning but also fosters a habit of curiosity or of questioning assumptions, and promote reflective thinking; however, the instructor has to highlight these features in student activities and assessments. Problem-based learning engages students in practicing or developing problem-solving skills through firsthand experience [19]. According to Orozco and Yangco [23], most of the students involved in PBL can share their opinions with others, employ different approaches to analysis, and explore ways to solve problems.

Students were found to experience conceptual challenges in the topic of waves at all levels, and these challenges, according to Aykutlu *et al.* [43], originated from the occurrence of errors, students' difficulties in understanding abstract concepts, lack of mathematical operational skills, and lack of time allocated to the curriculum. Mekonnen [44] noted that when students persistently face difficulties, they lose confidence in their knowledge, which affects their level of activity in the concepts of waves in physics. Therefore, teachers need to carefully design appropriate instruction such as PBL to remove possible difficulties and misconceptions in physics concepts.

V. CONCLUSION AND PRACTICAL IMPLICATIONS

Our previous studies investigated students' performance under problem-based learning instruction to embrace the opportunities brought by this instruction. The current study complemented the previous studies in a way that it tended to study (a) how PBL instruction improves physics students' understanding of mechanical wave concepts more than traditional teaching instruction and (b) students' difficulties within mechanical wave concepts. Our main results revealed that PBL makes students conceptualize the mechanical wave's content and understand it better than their colleagues taught with chalk and blackboard. Teachers are encouraged to use conceptual understanding tests to evaluate students' difficulties and select active learning methods such as PBL to remediate such alternative and poor understanding. Further studies are needed to measure the correlation between attitude and conceptual understanding in physics.

ACKNOWLEDGMENTS

S. T. K. has received financial support from the African Centre of Excellence for Innovative Teaching and Learning Mathematics and Science (ACEITLMS).

[1] F. Özdemir and A. Kargi, Electromagnetic waves and human health, in *Electromagnetic Waves*, edited by V. Prof. Zhurbenko (IntechOpen, 2011).

[2] Uganda National Examination Board, *Uganda National Examinations Board Report on Work of Candidates UCE 2016* (Kampala, Uganda, 2017).

[3] Y. J. Dori and J. Belcher, How does technology-enabled active learning affect undergraduate students' understanding of electromagnetism concepts?, J. Learn. Sci. **14**, 243 (2005).

[4] R. R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, Am. J. Phys. **66**, 64 (1998).

[5] M. Wittmann, *Making Sense of How Students Come to an Understanding of Physics: An Example from Mechanical Waves* (University of Maine, Maryland, 1998).

[6] A. Tongchai, M. Sharma, I. Johnston, and K. Arayathanitkul, Students' conceptual knowledge of mechanical waves across different backgrounds and cultures, in *Proceedings of The Australian Conference on Science and Mathematics Education* (2008), pp. 121–126.

[7] S. K. Şengören, R. Tanel, and N. Kavcar, Students' difficulties about the wave pulses propagating on a rope, J. Turkish Sci. Educ. **6**, 50 (2009).

[8] S. Y. Erinosho, How do students perceive the difficulty of physics in secondary school? An exploratory study in nigeria, Int. J. Cross-Disciplinary Subj. Edu. **3**, 1510 (2013).

[9] A. E. Tabor-Morris, T. M. Briles, and R. Schiele, Radio wave errors: Students mistaking radio transverse electromagnetic light waves as longitudinal sound waves, Int. J. Learn. Teach. Educ. Res. **16**, 37 (2017).

[10] M. C. Wittmann, The object coordination class applied to wavepulses: Analysing student reasoning in wave physics, Int. J. Sci. Educ. **24**, 97 (2002).

[11] J. Richardson, Concept inventories: Tools for uncovering STEM students' misconceptions. Assessment and education research (2004), pp. 19–26.

[12] Q. X. Ryan, B. R. Wilcox, and S. J. Pollock, Student difficulties with boundary conditions in the context of electromagnetic waves, Phys. Rev. Phys. Educ. Res. **14**, 020126 (2018).

[13] M. M. Isac, P. Dinis da Costa, L. Araújo, E. S. Calvo, and P. Albergaria-almeida, Teaching practices in primary and secondary schools in Europe: Insights from large-scale assessments in education , JRC Science and Policy Report No. EUR 27277 EN, 2015.

[14] J. Westbrook *et al.*, *Pedagogy, Curriculum, Teaching Practices and Teacher Education in Developing Countries* (Univeristy of Sussex, Sussex, 2013).

[15] D. A. Jacobsen, P. Eggen, and D. Kauchak, *Methods for Teaching*, 8th ed. (Pearson Education, Inc., Boston, 2009).

[16] O. Karamustafaoglu, Active learning strategies in physics teaching, Energy Educ. Sci. Technol. Part B Soc. Educ. Stud. **1**, 27 (2009).

[17] *Turning Points in Qualitative Research: Tying Knots in a Handkerchief*, edited by Y. S. Lincoln and N. K. Denzin (Rowman Altamira, 2003).

[18] R. un N. Awan, H. Hussain, and N. Anwar, Effects of problem based learning on students' critical thinking skills, attitudes towards learning and achievement, J. Educ. Res. **20**, 28 (2017).

[19] D. Allchin, Problem- and case-based learning in science: An introduction to distinctions, values, and outcomes, CBE Life Sci. Educ. **12**, 364 (2013).

[20] R. Fogarty, *Problem-Based Learning and Other Curriculum Models for the Multiple Intelligences Classroom* (IRI/Skylight Training and Publishing, Inc., Illinois, 1997).

[21] M. Savin-baden, *Facilitating Problem-Based Learning* (Open University Press, Buckingham, 2007).

[22] C. Chin and L. G. Chia, *Problem-Based Learning: Using Students' Questions to Drive Knowledge Construction* (Wiley Interscience, New York, 2004), Vol. 88, p. 707.

[23] J. A. Orozco and R. T. Yangco, Problem-based learning: Effects on critical and creative thinking skills in biology, Asian J. Biol. Educ. **9**, 1 (2016).

[24] I. Sadeh and M. Zion, The development of dynamic inquiry performances within an open inquiry setting: A comparison to guided inquiry setting, J. Res. Sci. Teach. **46**, 1137 (2009).

[25] D. E. Allen, R. S. Donham, and S. A. Bernhardt, Problem-based learning, New Dir. Teach. Learn. **2011**, 21 (2011).

[26] S. Olusegun, Constructivism learning theory: A paradigm for teaching and learning, Int. J. Res. Method Educ. **5**, 66 (2015).

[27] R. Duit and M. Tesch, On the role of the experiment in science teaching and learning—visions and the reality of instructional practice, in *Proceedings of the 7th International Conference on Hands-on Science* (2010), pp. 17–30.

[28] S. T. Kanyesigye, J. Uwamahoro, and I. Kemeza, The Impact of Problem-Based Learning on Students' Achievement in Mechanical Waves in Secondary Schools (2022).

[29] J. R. Fraenkel, N. E. Wallen, and H. H. Hyun, *How to Design Research in Education and Evaluate*, 8th ed. (McGraw-Hill, New York, 2012).

[30] physport.org, https://www.physport.org/assessments/assessment.cfm?A=MWCS&S=4.

[31] P. Barniol and G. Zavala, The mechanical waves conceptual survey: An analysis of university students' performance, and recommendations for instruction, Eurasia J. Math. Sci. Technol. Educ. **13**, 929 (2017).

[32] P. Barniol and G. Zavala, Mechanical waves conceptual survey: Its modification and conversion to a standard multiple-choice test, Phys. Rev. Phys. Educ. Res. **12**, 010107 (2016).

[33] Ministry of Education and Sports, *Uganda Advanced Certificate of Education: Teaching Syllabi for Physics and Mathematics* (Republic of Uganda, Kampala, 2013), Vol. 2.

[34] L. Cohen, L. Manion, and K. Morrison, *Research Methods in Education*, 6th ed. (Routledge, New York, 2007).

[35] S. M. Njiru and S. Karuku, An exploration of factors that contribute to low performance in physics: A case of a secondary school in Kenya, Innov. Sp. Sci. Res. Journals **17**, 381 (2015).

[36] B. S. Bloom, M. D. Engelhart, E. J. Furst, W. H. Hill, and D. R. Krathwohl, Taxonomy of educational objectives: the classification of educational goals: Handbook I: cognitive domain (No. 373.19 C734t). D. Mckay (1956).

[37] M. Mujasam, A. Y. T. Allo, and M. Ansaruddin, The effectiveness of experiment-based student worksheets with map concept in understanding the physics concepts of static fluid materials, J. Phys. Conf. Ser. **1157**, 032023 (2019).

[38] J. Uwamahoro, K. Ndihokubwayo, M. Ralph, and I. Ndayambaje, Physics students' conceptual understanding of geometric optics: Revisited analysis, J. Sci. Educ. Technol. **30**, 706 (2021).

[39] R. M. Mineo, C. Fazio, and G. Tarantino, An inquiry-based approach to physics teacher education: The case of sound properties (2010), https://www.semanticscholar.org/paper/An-Inquiry-Based-Approach-to-Physics-Teacher-the-of-Mineo-Fazio/6026b6d2eb95cb1b80d1955982f27c1bfca9ff6c.

[40] K. Ndihokubwayo, J. Uwamahoro, I. Ndayambaje, and M. Ralph, Light phenomena conceptual assessment: An inventory tool for teachers, Phys. Educ. **55**, 035009 (2020).

[41] N. Sungar, Teaching the superposition of waves, Phys. Teach. **34**, 236 (1996).

[42] I. A. Elvan, G. Ezgi, and M. Aydoğdu, Effect of problem solving method on science process skills and academic achievement, J. Turkish Sci. Educ. **7**, 13 (2010).

[43] I. Aykutlu, S. Bezen, and C. Bayrak, Teacher opinions about the conceptual challenges experienced in teaching physics curriculum topics, Proc. Soc. Behav. Sci. **174**, 390 (2015).

[44] S. Mekonnen, Problems challenging the academic performance of physics students in higher governmental institutions in the case of Arbaminch, Wolayita Sodo, Hawassa and Dilla Universities, Nat. Sci. **06**, 362 (2014).