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Phyphox-Integrated Problem-Based E-Worksheets to Train Students' Collaborative Skills in Physics Learning

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Abstract

National educational progress relies heavily on innovative teaching methods, particularly in physics learning. This study focuses on the development and feasibility assessment of an interactive electronic student e-worksheet based on a Problem-Based Learning (PBL) approach and integrated with the Phyphox application as a virtual laboratory tool to support students' collaborative skills in physics le arning. Employing the 4D development model (Define, Design, Develop, Disseminate), the research was conducted up to the Develop stage, emphasizing product feasibility testing. Validation was carried out by subject matter and media experts, while practicality testing involved two teachers and 42 students from a public senior high school in Bandar Lampung. Data collection methods included interviews, observations, and Likert-scale questionnaires. The e-worksheet achieved high feasibility scores, 88.7% for media quality and 93.3% for content. Practicality assessments from teachers and students ranged from 93.0% to 95.2%, indicating excellent usability. The findings demonstrate that integrating Phyphox into the e-worksheet is both highly feasible and perceived as practical; however, future studies should examine its effectiveness in enhancing collaboration and learning outcomes. This research contributes to advancing technology-based interactive learning media with the potential to improve educational quality. Further investigations are recommended to evaluate the effectiveness of this tool across different academic levels and physics topics.

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INTRODUCTION

Physics fosters students' critical thinking, analytical abilities, and problem-solving skills (Putra et al., 2023; Putri et al., 2022; Wartono et al., 2017). In addition, physics learning is also expected to cultivate 21st-century competencies, particularly collaborative skills, which enable students to work effectively in teams, communicate ideas, and solve problems together (Fajri et al., 2024; Rofiudin et al., 2024). However, physics learning at the senior high school level still faces challenges, particularly in delivering abstract and complex concepts such as sound waves. Teaching methods that are still dominated by lectures and conventional exercises often result in passive student participation and difficulties in connecting concepts to real-life phenomena (Harum et al., 2020; Rahmawati et al., 2022; Ramdani et al., 2021).

A preliminary study conducted in a public senior high school in Bandar Lampung revealed that limited laboratory facilities and the minimal use of technology were the main barriers to engaging students in direct experimental activities. In addition, printed student worksheets have proven less effective in fostering students' active involvement during learning (Elvanuari et al.,

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2024; Rahma & Novita, 2024). This condition is consistent with findings from other studies highlighting the importance of innovative learning media that integrate interactive elements and digital technology to enhance students' motivation and learning outcomes (Sadik, 2008; Szymkowiak et al., 2021; Timotheou et al., 2023).

In this context, the development of interactive electronic student worksheets represents a potential solution to overcome the challenges of physics learning in the digital era. E-worksheet enables more engaging and adaptive material delivery and supports self-directed and flexible learning, aligned with the characteristics of today's digital generation (Rahma & Novita, 2024; Rahmayani & Atmazaki, 2025; Nabila & Kamaludin, 2023). Furthermore, modern learning media must also be designed to foster character values, including social responsibility and collaboration, a key competency in 21st-century education (Widiarni et al., 2024). Beyond enhancing individual understanding, physics learning also requires tools that promote collaboration during experimental activities. In this regard, the Problem-Based Learning (PBL) approach, which is student-centered and oriented toward solving real-world problems, has been proven effective in enhancing critical thinking, analytical skills, and collaboration (Aggraini et al., 2024; Huda & Khotimah, 2023). This approach aligns with constructivist theory, which emphasizes the importance of active and meaningful learning experiences in deepening the understanding of physics concepts (Astutik, 2022; Bigozzi et al., 2018; Prihandono et al., 2023).

Several studies have reported that PBL-based e-worksheets can improve students' learning outcomes and skills in physics topics such as electric circuits, redox reactions, and magnetic fields (Fadilah et al., 2023; Tunga et al., 2021). Moreover, using digital media and supporting applications such as Liveworksheets, Flip PDF, and Android-based tools has further strengthened learning effectiveness (Fadhila, 2022; Fadilah et al., 2024; Suryani, 2024). Although school physics practice is often limited by the lack of laboratory equipment and materials, the Phyphox application offers an innovative solution for sensor-based experiments. It utilizes smartphones' built-in sensors to measure real-time physical parameters like sound frequency, acceleration, and pressure (Ariyansah et al., 2021; Rakestraw et al., 2023). Its ability to present data directly allows students to observe cause–and–effect relationships, build conceptual understanding, and develop scientific skills more authentically. While PBL-based e-worksheet has shown positive impacts, its integration with Phyphox offers additional advantages by enabling data-driven experiments and facilitating group collaboration.

Phyphox enhances access and flexibility in conducting experiments and demonstrates high accuracy. Research by Staacks et al. (2022) reported up to 95% accuracy and a 30% reduction in human error, establishing Phyphox as a valid alternative laboratory tool. Moreover, integrating Phyphox into the PBL model strengthens student engagement, promotes group collaboration in experiments, and supports the development of 21st-century skills. Various studies have shown that Phyphox contributes positively to improving conceptual understanding, learning motivation, and students' active participation in physics learning (Coramik & İnanç, 2023; Pierratos & Polatoglou, 2020; Rusdin et al., 2025). Thus, Phyphox revolutionizes school laboratory practices and reinforces contextual, interactive, and data-driven learning approaches.

Within this framework, collaborative skills become a central focus, as they are one of the key competencies of the 21st century, encompassing students' abilities to work together through effective communication, role-sharing, and collective decision-making (Fajri et al., 2024; Rofiudin et al., 2024). This study adopts five leading indicators: contribution, flexibility, responsibility, productivity, and respect, measured through rubric-based observation, Likert-scale questionnaires, and group interaction analysis (Wahyudi, 2024). The selection of these indicators highlights the relevance of the instruments in comprehensively assessing students' collaborative skills.

Previous studies have highlighted the effectiveness of PBL-based e-worksheets in improving students' learning outcomes and engagement, and Phyphox has been shown to provide accurate, flexible, and interactive experimental opportunities. However, most research has treated these innovations separately, with limited attention to their integration for developing 21st-century skills. This gap underscores the urgency of creating a unified model that not only supports conceptual mastery but also explicitly trains students' collaborative abilities. Therefore, this study introduces a novel approach by developing and evaluating an interactive PBL-based e-worksheet integrated with Phyphox, specifically designed to foster collaborative skills in physics learning. The objectives are to assess its feasibility, gather teacher and student responses, and determine its attractiveness. The findings are expected to contribute an innovative solution that strengthens both conceptual understanding and active engagement through technology-driven experimental practice.

METHOD

This study employed the Research and Development (R&D) method, a systematic approach designed to produce specific educational products (Arifiyani et al., 2025; Budiarti et al., 2023; Sugiyono, 2022). The development process adapted the 4D model developed by Thiagarajan et al. (1947), which consists of four stages: Define, Design, Develop, and Disseminate. However, this study was limited to the development stage, focusing on product development and feasibility testing; therefore, the model was simplified into 3D Thiagarajan et al. (1947). Adopting the 4D model, simplified into 3D, was considered appropriate as it provides a systematic flow in designing and developing educational products while aligning with the specific needs of the development process.

Data collection in this study was conducted through structured interviews, classroom observations, and questionnaire distribution, aiming to obtain comprehensive and in-depth information regarding the needs of the developed product. Interviews were conducted with two physics teachers using pre-prepared interview guidelines to explore learning needs and understand the challenges teachers and students face in teaching-learning. Observations were carried out directly in the classroom using observation sheets to objectively examine the learning situation, including interactions among teachers, students, and the learning environment. Meanwhile, questionnaires were administered to gather data on the validity and practicality of the e-worksheet from the users' perspectives, both teachers and students. This approach provided a strong foundation for ensuring the product development was contextually relevant to field conditions and empirically validated.

In addition to observations and interviews, questionnaires were distributed to 42 students and six experts to collect quantitative data regarding their perceptions of the developed e-worksheet. The validation stage involved six experts—three media experts and three subject matter experts—who assessed the feasibility and quality of the learning media using a structured questionnaire instrument. Furthermore, students were asked to complete questionnaires to measure their perceptions of the e-worksheet regarding quality, usability, and interactivity. Figure 1 provides a detailed illustration of the 4D research procedure stages applied in this study.

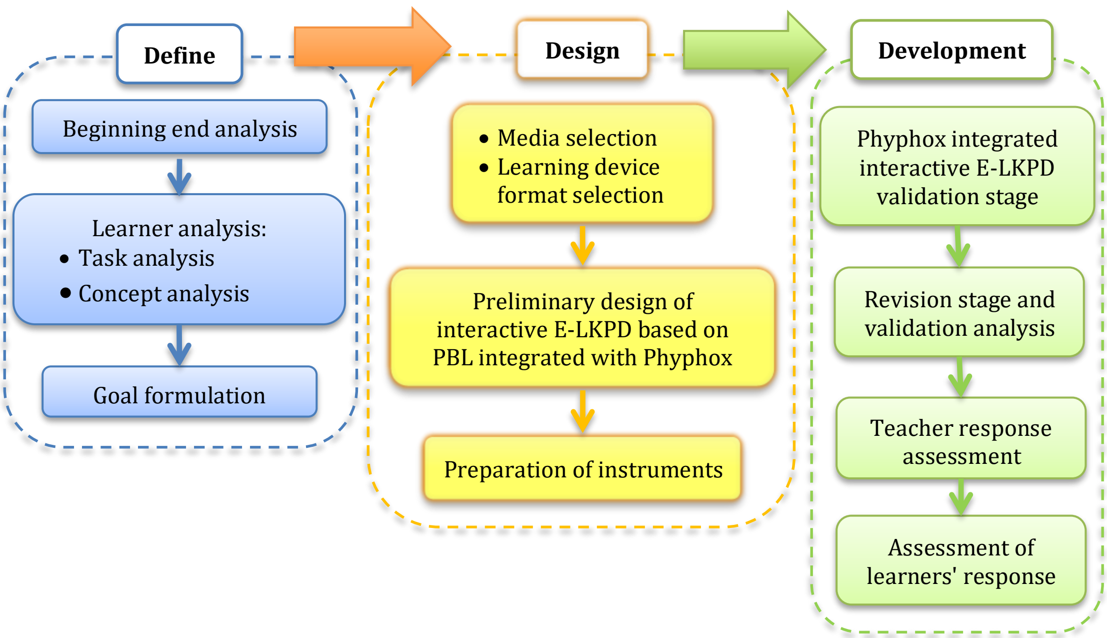


Figure 1. Research Procedure

The study participants comprised six validators, two teachers, and 42 eleventh-grade students from SMA Negeri 12 Bandar Lampung. The validators included three subject-matter experts (physics education and curriculum) and three media experts (educational technology and graphic design) who assessed the content feasibility, presentation quality, and technical aspects of the e-worksheet. Two physics teachers with more than five years of teaching experience were involved as practical validators to provide contextual input. The product trial involved 42 students selected based on specific criteria: active participation in physics lessons, ownership of digital devices, and willingness to participate. The trial was conducted in two stages: a small-scale trial (15 students) to gather initial feedback for product refinement, and a large-scale trial (27 students) to assess the feasibility and practicality of the e-worksheet. Data were collected through questionnaires that evaluated product quality, ease of use, and interactivity.

The development procedure began with the Define stage, which involved identifying learning needs through curriculum analysis, teacher interviews, and classroom observations using observation sheets. The design stage included the preparation of the e-worksheet framework based on the PBL flow, which comprised problem orientation, problem definition, investigation, presentation, analysis, and evaluation. The e-worksheet was designed using Canva with the integration of Google Forms for interactive responses, while ensuring accessibility (color contrast, font size ≥12 pt, and alternative text for images) and compatibility with both mobile and desktop devices. The development stage consisted of expert validation, initial product revision, small-scale trial, second product revision, and large-scale trial, with data collected through questionnaires assessing the quality, usability, and interactivity of the e-worksheet.

The research data were analyzed using a descriptive approach with quantitative and qualitative methods. The primary instrument was a five-point Likert scale questionnaire to assess students' needs, expert validation, and teacher and student responses to the e-worksheet. A five-point scale was chosen because larger scales (e.g., seven or thirteen points) confuse respondents and complicate data processing. In contrast, a five-point scale provides more accurate and representative results (Hertanto, 2017). Quantitative data were analyzed using descriptive statistics, including mean, standard deviation, value range, and 95% confidence intervals. The percentage scores were calculated using the formula provided Wiliyanti et al. (2019).

$$P = SMI\sum x \times 100\%$$

Where:
P = Percentage of feasibility
$\sum x$ = Total score obtained
SMI = Maximum ideal score

The percentage obtained was then used to assess the feasibility of the product based on the interpretation, as shown in Table 1 (Anisa et al., 2024).

Table 1. Product Feasibility Criteria

Interval	Criteria	Description
$0\% < x \leq 20\%$	Verry Poor	Not suitable for use
$20\% < x \leq 40\%$	Poor	Not recommended for use
$40\% < x \leq 60\%$	Fair	Needs significant revisions, not recommended
$60\% < x \leq 80\%$	Good	Suitable for use with minor revisions
$80\% < x \leq 100\%$	Very Good	Suitable for use without revisions

Qualitative data obtained through interviews were analyzed using a thematic analysis approach. Each interview transcript was systematically coded to identify patterns and key themes that reflected the needs of students, educators, and the school environment. Meanwhile, observational data were analyzed using descriptive narrative methods, emphasizing the dynamics of the learning process, the level of student participation, and the implementation of instructional media in the classroom. Both forms of analysis were then integrated to complement the quantitative findings, thereby providing a comprehensive understanding of the suitability and relevance of the Problem-Based Learning (PBL)-based e-worksheet integrated with the Phyphox application in the context of physics learning.

This study obtained approval from the Research Ethics Committee of UIN Raden Intan Lampung (Number: B-4145/Un . 16/DT.1/PP.009.7/2025). All participants, including teachers and students, were provided with informed consent detailing the purpose of the study, procedures, their rights to refuse or withdraw at any time, and the intended use of data. Participant confidentiality was safeguarded through anonymization of results and secure data storage, in accordance with research data protection standards in educational research.

RESULTS AND DISCUSSION

Define Stage

The initial stage in 4D development research is the definition stage. At this stage, the researcher collects information and data on the need for the development of PBL-based E-worksheet products with the integration of Phyphox to students' cooperative abilities in physics learning, through interviews, observations, and analysis of related documents (Tsai et al., 2010). In the Define stage, the researcher identifies several things, such as an analysis of the beginning, student study, tasks, concepts, and learning objectives.

In the final analysis, the researcher identified the issues in physics learning at SMA Negeri 12 Bandar Lampung, particularly concerning the topic of Sound Waves. Based on observations and interviews with physics teachers, it was found that the learning approach, which was still dominated by conventional theory, hindered student engagement. The limited availability of learning media and experimental tools was a significant barrier to creating an interactive learning experience. Therefore, developing an E-worksheet based on PBL with the integration of Phyphox is expected to serve as a solution to enhance student engagement and deepen their understanding of physics concepts. Student Analysis. The student analysis was conducted to study the characteristics of the learners relevant to the development of the E-worksheet. Based on observations, students at SMA Negeri 12 Bandar Lampung were found to be less engaged in physics learning, particularly in understanding abstract concepts such as Sound Waves. This issue was attributed to the limited use of teaching aids and interactive learning media. However, students demonstrated interest in using learning media that could bridge theory with practical applications. Developing a PBL-based E-worksheet integrated with Phyphox will enhance student motivation and engagement. Task Analysis

The task analysis aims to identify the key skills that students need to master in the study of Sound Waves. In developing the PBL-based E-worksheet, the material covers important topics such as the differences between transverse and longitudinal waves, wave characteristics, the speed of sound, and the Doppler effect phenomenon. Students are expected to apply these concepts in experiments and analyze the results using the Phyphox application. Concept Analysis. In the concept analysis, the researcher outlines the key concepts to be taught in the physics lesson, such as wave concepts, amplitude, frequency, wavelength, and the Doppler effect. A concept map facilitates student understanding by illustrating the relationships between the concepts and how they support each other. Learning Objective Analysis. The learning objectives analysis aims to develop an interactive E-worksheet based on PBL with Phyphox integration to enhance students' collaboration skills in physics learning. This product facilitates students' understanding of physics concepts in Sound Waves through a more interactive and applied learning approach.

The analysis in the "define" phase revealed a mismatch between the teaching approach applied and the students' needs in understanding abstract topics, such as sound wave theory. The limited availability of media to support physics experiments has also contributed to low student participation in the learning process. However, there is potential to be developed, particularly the students' interest in utilizing technology and contextual learning. Therefore, developing an E-worksheet based on Problem-Based Learning (PBL) integrated with the Phyphox application is a promising tool for effective learning. This media provides problem-solving-centered learning, enables the direct implementation of digital experiments, and encourages student collaboration, ultimately optimally enhancing their collaborative skills.

Design Stage

The second stage in the 4D development model is the Design stage, which focuses on planning the structure and components of Problem-Based Learning (PBL)-based Student Worksheets, which are integrated with the Phyphox application to improve students' cooperative skills in physics learning (Jin et al., 2019).

The media developed is a PBL-based interactive e-worksheet with Phyphox Integration of Collaboration Capabilities for high school/MA students in physics learning. The selection of formats was carried out to ensure the format of the E-worksheet preparation was developed. The format of the preparation of the E-worksheet that will be used is appropriate (Pawestri & Zulfiati, 2020), which consists of a title, basic competencies, time needed to complete, brief information, activity steps, tasks that must be completed, and reports that need to be prepared. In the same literature, the worksheet must contain implementation and preparation instructions (Melenia, 2024).

The initial design of the interactive e-worksheet based on Problem-Based Learning (PBL) integrated with the Phyphox application was carried out through two main phases: creating a storyboard and developing a product prototype. The storyboard phase involved creating an initial design that includes visual elements such as the cover page, content pages, and back cover, which serve as a guide for delivering the material over three sessions. Each session contains stages within the PBL model, such as problem orientation, student organization, etc. After completing the storyboard, a product prototype was developed to evaluate the feasibility of the design and identify potential errors before wide implementation. The e-worksheet was ready for pilot testing after revisions based on evaluation results. The media was designed using A4 paper size, Poppins font, and 1.5 spacing, and it was developed using Canva Pro to ensure visual quality and readability. These two steps ensure the developed media is effective and ready for testing. A more detailed storyboard will be explained in Table 2.

Table 2. Storyboard for the Development of an Interactive E-Worksheet Based on PBL with Phyphox Integration

Section	Description
Cover	The front page of the e-worksheet has the title, Phyphox illustration, institution logo, and author name. The cover design features a combination of green and yellow colors symbolizing the balance between nature and energy, aligned with the theme of the Sound Waves topic. The title uses modern typography to enhance readability. The main visual highlights the Phyphox application as a data collection tool in the Problem-Based Learning (PBL) process.
Preface	Acknowledgments, the purpose of creating the e-worksheet, and the benefits for students and teachers.
Table of Contents	Detailed contents of the e-worksheet that facilitate user navigation.
Introduction	e-worksheet Identity: Subject, Phase/Semester, Time Allocation, Title. e-worksheet Description: General explanation regarding content and objectives. PBL Syntax: Steps of Problem-Based Learning applied in the e-worksheet.
Instructions for Using the e-worksheet	For Teachers: How to use the e-worksheet in teaching, integration with Phyphox, and assessment strategies. For Students: How to access materials, conduct experiments, and complete exercises and evaluations.
Curriculum Content Standards	Learning Outcomes (LO): Competencies to be achieved by students. Learning Objective Flow (LOF): Sequence of lessons per the curriculum. Learning Content: Core topics to be taught. Learning Objectives: Expected learning outcomes. Pancasila Student Profile: Values developed in the learning process.
Concept Map	Diagram illustrating the relationships between the key concepts: • Speed of Sound • Sound Source • Doppler Effect
Stimulus	A phenomenon or problem that triggers concept exploration is: Why does an ambulance siren sound different when approaching or moving away?
Sound Waves	Explanation of sound waves, their mechanical properties, and how they

Section	Description
Material	propagate in different media. Learning through a video.
Properties of Sound Waves	Explanation of reflection, refraction, diffraction, interference, and propagation of sound waves.
Speed of Sound Waves	Theory and concepts: Formula for the speed of sound in different media. Experimental Activity: Using Phyphox to measure the speed of sound in air. Evaluation: Exercises based on concepts and experiments.
Sound Source Material	Theory and concepts: Sound sources and how sound is produced. Experimental Activity: Using Phyphox to analyze the frequency of different sound sources. Evaluation: Questions and reflection on the concepts.
Doppler Effect Material	Theory and concepts: The effect of frequency changes due to the movement of sound sources or listeners. Experimental Activity: Using Phyphox to observe the Doppler effect on a moving sound source.
References	Books, journals, and online sources were used to develop the e-worksheet.
Author Biography	Brief information about the developer of the e-worksheet.

The design of this interactive e-worksheet is systematically developed, following the Problem-Based Learning (PBL) model, which encompasses five main stages: orientation to the problem, organization of learning, independent and collaborative investigation, development and presentation of solutions, and evaluation and reflection of the process. Each stage is developed into interactive learning activities to enhance students' collaborative skills. The prominent uniqueness of this e-worksheet lies in integrating collaborative skill indicators in each phase of the PBL-based learning, ensuring that students not only comprehend physics concepts but also enhance their social awareness and ability to act responsibly. This main characteristic includes the integration of the PBL model into the e-worksheet. Table 3 explains the integration of the PBL learning model into the learning activities.

Table 3. Integration of the Problem-Based Learning Model into Learning Activities

PBL Model Step	Collaborative Skill Indicator	Instructional Approach	Student Activities in e-worksheet
Orientation to the Problem	Contribution	Group formation and designing an experiment using the Phyphox application	• Observing sound phenomena from digital media • Identifying relevant physics problems • Actively presenting initial ideas in group discussion forums
Organization for Learning	Flexibility	Group formation and designing an experiment using the Phyphox application	• Designing experiments related to the speed of sound, types of sounds, and the Doppler effect • Adjusting roles and responsibilities within the team • Compromising on changes to the group's strategy
Independent and Collaborative Investigation	Responsibility	Collaborative experiments with smartphone sensor-based data collection (Phyphox)	• Conducting experiments together • Taking responsibility for agreed roles • Recording and analyzing sensor data accurately

PBL Model Step	Collaborative Skill Indicator	Instructional Approach	Student Activities in e-worksheet
Development and Presentation of Results	Productivity	Preparation of experiment reports and team-based presentations	• Preparing graphs and calculations from Phyphox data • Compiling group reports • Presenting experiment results collaboratively and effectively
Evaluation and Reflection of the Process	Respectful Attitude	Collaborative process reflection and evaluation of learning challenges	• Team evaluation of experiment challenges • Giving and receiving constructive feedback • Developing team improvement plans based on reflection

The design results of the PBL-based interactive e-worksheet integrated with Phyphox are illustrated in Figure 2, which presents the main components of the teaching material, namely (a) the cover, (b) the curriculum content, and (c) the activity cover.

(a) (b) (c)

Figure 2. Design of Physics E-Worksheet Teaching Materials (a) The Cover (b) The Curriculum Content (c) The Activity Cover.

Based on Figure 2, the cover design features green and yellow colors, symbolizing the balance between nature and energy, aligned with the theme of the Sound Waves material. The title uses modern typography to enhance readability. The main visual displays the Phyphox application as a data collection tool within Problem-Based Learning (PBL). This design promotes students' collaboration skills while raising awareness of physics applications in environmental and real-life contexts. The curriculum content in this e-worksheet includes learning outcomes, learning objectives flow, learning content, learning goals, and the Pancasila student profile, all designed to develop students' competencies in understanding and solving real problems related to sound waves, through a problem-based learning approach integrated with Phyphox. The activity cover design facilitates easy identification and separates different learning activities. This e-worksheet contains three learning activities, one of which covers the topic of sound wave velocity. Figure 3 illustrates the integration of the Problem-Based Learning (PBL) model into the designed learning activities.

(a) (b) (c) (d) (e)

Figure 3. Problem-Based Learning Model into Learning Activities (a) Problem Orientation (b) Organization for Learning (c) Independent and Collaborative Investigation (d) Development and Presentation of Results (e) Analysis and Evaluation of Problem-Solving Process

Based on Figure 3, in the problem orientation stage, students are presented with a natural phenomenon as an initial stimulus and are asked to identify and analyze related problems. In this process, students are encouraged to actively participate by sharing ideas and opinions during the initial discussion, building a solid foundation for collaboration. Learning organization is the second stage in the Problem-Based Learning (PBL) model. At this stage, the teacher divides students into several groups to collaboratively design experiments using the Phyphox application. Students are expected to work efficiently, clearly divide tasks, and demonstrate adaptability and compromise skills within the team to ensure smooth experiment execution. In this third stage, students collaboratively conducted experiments and data collection related to sound propagation speed. Throughout this process, students are responsible for their respective roles, support each other as group members, and maintain an attitude of respect for the thoughts and contributions of fellow members for the smooth running of activities. At the fourth stage, students are required to analyze the collected data. After analyzing the data, students present the experimental results in groups before the class. This stage demands that students demonstrate solid teamwork and collective responsibility in delivering results, while supporting each other to achieve an effective presentation. In the final stage, students jointly evaluate the learning process, including the obstacles and challenges experienced. This evaluation process trains students to show openness, respect for criticism and input from group members, and adaptability skills for future improvement.

This e-worksheet development integrates the Problem-Based Learning (PBL) model to enhance students' understanding of physical phenomena, related explicitly to Sound Waves, through three experimental activities: Wave Speed, Sound Sources, and the Doppler Effect. In the Orientation to the Problem phase, students are introduced to the physics phenomenon of sound waves, such as sound wave velocity and the Doppler effect, using videos, articles, or Phyphox-based experiments. Students then discuss relevant physics problems and select experimental topics. This approach aligns with the research by Nicholus et al. (2023), which shows increased student engagement through group discussions. In the Organization for Learning phase, students design experiments using Phyphox to measure physical variables, such as sound speed, source frequency, and the Doppler effect, with high accuracy (Jeli & Chandra, 2025). Students work in groups to plan the experiments and distribute roles. In the Independent and Collaborative Investigation phase, students conduct experiments to collect data using Phyphox. In Activity 1, they measure sound velocity through various media, while in Activity 2, they analyze the influence of sound sources on frequency and intensity. In Activity 3, they explore frequency changes due to the Doppler effect. All experiments are conducted collaboratively, with students responsible for their respective roles.

In the Development and Presentation of Results phase, students compile experimental reports and present their findings through posters or videos to the school community. This aims to enhance students' communication and collaboration skills when explaining their findings. In the Evaluation and Reflection Process phase, students reflect on the experiments, evaluate the challenges, and give and receive constructive feedback. This process helps students refine their understanding and improve their collaborative and communication skills. By integrating the Phyphox application in this PBL-based e-worksheet, students gain a deeper understanding of physics concepts and develop collaborative, critical thinking, and problem-solving skills essential in 21st-century learning. This aligns with Nicholus et al. (2023) findings, which emphasize that the PBL model enhances student engagement in exploring physical phenomena through group discussions and using technology for experiments.

The electronic worksheet in this study was developed using a graphic design platform that allows the creation of visually appealing learning materials. This platform enables students to access the e-worksheet both during classroom learning and outside the classroom. The e-worksheet is designed to be interactive, allowing students to directly fill in their responses on the worksheet. Additionally, the e-worksheet facilitates students in studying the material and watching videos that have been systematically organized. Access via electronic devices allows students to follow the learning process more flexibly in various locations. The assessments from media and subject matter experts indicate that the e-worksheet is highly feasible for use, and the feedback from both teachers and students has been positive. These results align with the findings of Ariyansah et al. (2021), who stated that using e-worksheet can help improve students' academic achievement.

Develop Stage

The validation process of the e-worksheet involved six validators, consisting of three subject-matter experts and three media experts, who employed Likert-scale criteria to evaluate the feasibility of the design and the quality of the content. The validation results indicated an average score of 88.7% from media experts and 93.3% from subject-matter experts, placing the e-worksheet as "excellent" and "suitable for use without revision." Validators gave high ratings to aspects of visualization, the systematic organization of content, and the relevance of materials to collaborative skill indicators. From the user perspective, 95.2% of teachers, 93.0% of students in the small-scale trial, and 92.5% of students in the large-scale trial responded positively to the e-worksheet, assessing the product as easy to use, engaging, and highly relevant to the needs of modern learning. These findings support constructivist learning theory, which posits that learning resources based on active exploration can enhance students' understanding more meaningfully.

This stage aimed to refine the Interactive PBL-Based e-worksheet integrated with Phyphox to meet the feasibility and practicality criteria for use as a physics learning tool. Revisions were made based on the suggestions and feedback provided by the experts (Jin et al., 2019).

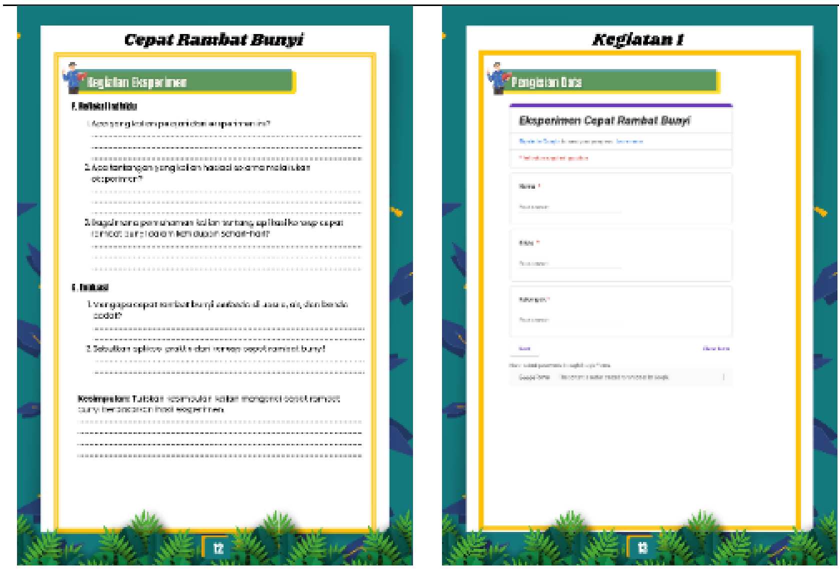
Feasibility Test of the Interactive PBL-Based e-worksheet with Phyphox Integration

The interactive Problem-Based Learning (PBL)-based e-worksheet integrated with Phyphox, which was developed to enhance student engagement and learning outcomes, underwent a feasibility test through a one-time validation process by six expert validators, consisting of three subject-matter experts and three media experts. This validation process aimed to evaluate the feasibility of the developed e-worksheet and obtain comments, suggestions, and recommendations from each validator for further improvement. Table 5 shows the validation results from subject-matter experts and media experts.

Table 4. Results of Expert Validation in Content and Media

Validation	Aspect	Percentage	Average	Category
Content Expert	Content Feasibility	96.7%	93.3%	Very Good
	Language Feasibility	93.3%		
	Presentation Feasibility	90.0%		
Media Expert	Media Size	90.0%	88.7%	Very Good
	Overall Design	83.3%		
	Cover Design	83.3%		
	Additional Information	93.3%		
	Media Content Design	86.7%		
	Ease of use	90.0%		

Before being declared feasible, the e-worksheet underwent revisions based on expert suggestions. Figures 4 illustrate the E-worksheet before and after revisions.



(a) (b)

Figure 4. E-Worksheet (a) Before Revisions (b) After Revisions

Attractiveness Test of the Interactive PBL-Based e-worksheet with Phyphox Integration

After undergoing a validation process by subject-matter and media experts, the revised e-worksheet was subsequently tested at SMAN 12 Bandar Lampung in April 2025. Twelve eleventh-grade students participated in the small-scale trial, while thirty others participated in the large-scale trial. To assess the attractiveness of using the Problem-Based Learning (PBL)-based e-worksheet, questionnaires regarding the implementation of the e-worksheet were also administered to two physics teachers.

The trial results revealed highly positive responses from both educators and students. Teachers assessed that the e-worksheet facilitated learning, enhanced student engagement, and presented more interactive and in-depth physics concepts. Students also reported that the e-worksheet was engaging, presented physics concepts more relevantly, and successfully linked them to everyday life. In addition, they expressed that the e-worksheet increased their learning motivation, effectively supported independent learning, and enhanced their sense of social responsibility. Overall, these trial results confirm that the developed physics e-worksheet is highly practical and aligns well with the needs of technology-based learning in today's context. To provide a clearer overview, the results of educator and student responses regarding the practicality and effectiveness of the developed e-worksheet are summarized in Table 6.

Table 5. Results of Educator and Student Responses

Validation	Aspect	Percentage	Average	Category
Educator Response	Content Quality of e-worksheet	94.5%	95.2%	Verry Good
	Curriculum Alignment	95.0%		
	Language Quality	96.0%		
Small-Scale Student Response	Appearance	94.3%	93.0%	Verry Good
	Content	93.1%		
	Language Quality	91.3%		
	Technical Quality	93.3%		
Large-Scale Student Response	Appearance	91.6%	92.5%	Verry Good
	Content	88.1%		
	Language Quality	88.5%		
	Technical Quality	91.8%		

Based on the trial results conducted with educators and students, the interactive physics e-worksheet was assessed as highly engaging, practical, effective, and aligned with the needs of modern learning. The average response rate from educators reached 95%, while students in the small-scale trial provided a score of 93% and those in the large-scale trial 92.5%, all of which fall into the "feasible" category. Therefore, no revisions were required, as the product has already met expectations in supporting the development of students' collaborative skills and facilitating interactive, technology-based learning.

The findings of this study indicate that the interactive e-worksheet based on Problem-Based Learning (PBL) integrated with the Phyphox application is considered feasible, engaging, and practical for use in physics learning. Assessments from experts, teachers, and students consistently yielded high scores in terms of engagement and collaboration, suggesting the product's strong potential to support students' conceptual understanding of sound waves and collaborative activities through authentic experiments. Nevertheless, the effectiveness of enhancing collaborative skills has not yet been tested through a quantitative design or standardized instruments, which should be addressed in future research. These findings are consistent with the study by Staacks et al. (2022), which demonstrated that Phyphox, as a smartphone-based experimental application, simplifies real-time data collection and enriches students' scientific analysis processes. Similarly, Carroll & Lincoln (2020) emphasized that Phyphox supports remote learning through its interactive mini-lab features and facilitates group work. In addition, Staacks et al. (2018) highlighted that Phyphox's capability to conduct direct and wireless kinematic measurements simplifies the execution of physics practicum. These results suggest that developing e-worksheet with a PBL approach and digital technology support, such as Phyphox, contributes positively to achieving more contextual, collaborative, and 21st-century-oriented physics learning.

Despite these promising results, several limitations should be noted when implementing this e-worksheet. First, the scope of the study was limited to a single school, making the findings not fully generalizable to broader and more diverse populations. Second, although the topic of sound waves was successfully and effectively integrated into this e-worksheet, its application to other physics concepts has not yet been implemented, thereby requiring further exploration to expand the range of content. Third, although indicators of collaborative skills were integrated into the learning design, this study did not quantitatively measure the contribution of the e-worksheet to improving these skills using more specific and structured instruments. Therefore, further research is needed with a broader scope regarding the number of schools, variation of physics topics, and the application of more comprehensive evaluation instruments to assess the effectiveness of the e-worksheet in enhancing students' collaborative skills more accurately.

Despite these limitations, the development of this e-worksheet provides a meaningful contribution by presenting teaching materials that bridge physics learning with the reinforcement of students' collaborative skills. Although the present study did not specifically aim to test the effectiveness of the product quantitatively, the development process has demonstrated strong potential in raising students' awareness of the importance of cooperation and responsibility in solving real-world problems. Integrating various physical phenomena and real-life events into problem-based learning activities allows students to understand concepts practically and practice critical thinking skills in linking theory with everyday life realities. Therefore, this approach enriches students' learning experiences while strengthening the relevance of physics learning in a broader and more meaningful context.

This study contributes to the body of research on the use of digital technology in contextual and collaborative learning. Unlike previous studies that focused more generally on e-worksheet, this study introduces an innovation by combining the Problem-Based Learning (PBL) approach with the Phyphox application. Such integration enhances students' practical understanding of sound wave concepts and encourages active participation and the development of social responsibility through group work and data-driven decision-making. The present research was limited to the development stage of the 4D model, without progressing to the dissemination stage. The focus was on product development and feasibility testing through expert validation and small-scale and large-scale trials.

LIMITATIONS

This study has several limitations. First, its scope was restricted to a single school (SMA Negeri 12 Bandar Lampung), limiting the findings' generalizability. Second, the developed e-worksheet focused exclusively on sound waves, meaning its application to other physics concepts requires further development. Third, although collaborative skill indicators were integrated into the instructional design, this study did not use standardized instruments to conduct an in-depth quantitative assessment. Fourth, the research only reached the product development and acceptance-testing stages without advancing to the dissemination phase, leaving the long-term effectiveness of the e-worksheet untested.

For future research, it is necessary to expand the context to multiple schools with diverse characteristics and to develop content across a broader range of physics topics. Studies employing quasi-experimental designs or randomized controlled trials (RCTs) with pretest–posttest structures are recommended to assess effectiveness more objectively. Sample sizes should ideally be determined through power analysis to ensure statistical validity. In addition, standardized instruments should be applied to evaluate collaborative skills and cognitive learning outcomes. Further research should also include dissemination and longitudinal evaluation stages to assess the sustainability of e-worksheet use in classroom practice.

CONCLUSION

This study developed an interactive e-worksheet based on Problem-Based Learning (PBL) integrated with the Phyphox application, demonstrating high feasibility as an instructional medium for sound waves. Expert validation and small-scale and large-scale trials confirmed that the product was feasible and well-received, with an average evaluation score of 92.5%. The product shows potential to support student engagement and facilitate practice-oriented learning, although the study was limited to the Development stage of the 4D model.

Further studies are needed to comprehensively evaluate this e-worksheet's effectiveness, particularly in enhancing students' collaborative skills and conceptual understanding. Experimental research designs with larger sample sizes and implementation across various physics topics are recommended to ensure consistency and generalizability of the results.

AUTHOR CONTRIBUTIONS

A.A. prepared the background, research methods, results, and discussion sections. A.A. also conducted revisions and corrections to the title and background. S.L., S., and M.S.A. reviewed and improved the methods, results, and discussion sections. A.A., S.L., S., and M.S.A. collaboratively performed the calculations. All authors contributed to the discussion and refinement of the final manuscript.

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