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Implementing problem-based learning on sound waves improves student learning outcomes

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Abstract. Problem-based learning (PBL) is widely recommended for physics topics that students find abstract, yet much of the supporting evidence comes from designs that cannot isolate what the model itself contributes. This study asked how far students' cognitive achievement on sound-wave concepts changed across a PBL unit, and what a single-group design can legitimately establish about that change. A one-group pretest-posttest pre-experimental design was applied to one intact grade-11 class ($n = 20$) at an Indonesian Islamic senior secondary school. Achievement was measured with a ten-item test (five multiple-choice, five essay) administered before and after six 90-minute PBL sessions spread over three weeks. Scores rose from $M = 58.25$ ($SD = 19.14$) to $M = 95.00$ ($SD = 6.28$). The mean gain of 36.75 points was statistically significant, $t(19) = 8.435$, $p < .001$, $d_z = 1.89$, 95% CI $[27.63, 45.87]$, and the mean normalised gain was 0.88. The gain is large by any standard. It is also inflated: 11 of 20 posttest scores reached the ceiling of the test, which caps normalised gain at unity and compresses posttest variance. Absent a comparison group, the improvement cannot be attributed to PBL alone, and the estimate should be read as an upper bound.

Keywords: cognitive achievement, N-gain, physics learning outcomes, pre-experimental design, problem-based learning, sound waves

1. Introduction

Learning outcomes are the measurable residue of instruction: what students can do afterwards that they could not do before. Adijaya et al. [1] treat them as accomplishments earned through deliberate effort and then quantified, assessed, and reported in numerical or verbal terms. In everyday school practice they function more modestly, as evidence of how far students have mastered the material at hand [23]. Candrasa and Cen [14] add a diagnostic function: by comparing behaviour before and after teaching, outcomes let teachers locate individual strengths and gaps. Whichever function is emphasised, outcomes remain the primary evidence by which instruction is judged. They are also multiply determined. Burke, Montross and Dianova [13] distinguish internal influences, such as physical fitness, sensory functioning, intelligence, attitudes, interest, and motivation, from external ones arising in the family, the school, and the wider community. Among the external influences, the instructional model is the one a teacher actually controls [49], which is why choosing it well matters. An instructional model is a systematic plan for classroom work, specifying objectives, activities, and the management of the room [41, 44].

Problem-based learning (PBL) is one such model, and it has an unusually clear rationale. Instruction begins with an authentic problem rather than with an exposition, so that inquiry is provoked before it is guided [57]. Students learn by working on the problem, and the problem-solving they do requires them to process the conceptual content rather than store it [18]. Because the problems are drawn from the world outside the classroom, students must generate solutions and then connect those solutions to the theory that explains them [53]. The problem stays in view throughout, serving as

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the reference point from which concepts and theories are extracted [29, 43]. Hmelo-Silver [24] identifies the mechanisms this arrangement is supposed to engage: flexible knowledge, self-directed learning, and collaboration around a shared object of inquiry. A systematic review of PBL in physics specifically reports consistent benefits for conceptual understanding and reasoning [40], and the model is routinely credited with developing the critical and creative thinking that school curricula now foreground [62].

Sound waves are a promising place to test that rationale, because they sit close to students' daily experience and yet are persistently poorly understood. Hrepic, Zollman and Rebello [25] show that students hold durable alternative models of how sound travels, blending wave and particle intuitions in ways formal instruction rarely dislodges. Preservice physics teachers show comparable weaknesses on mechanical waves [42]: propagation, frequency, amplitude, and superposition are all reported as abstract and cognitively demanding. Traditional teaching, which delivers the content deductively, tends to leave these intuitions intact, whereas experience-based approaches improve both retention and skill [3]. Recent studies point the same way. Watuna et al. [64] used PBL worksheets on the sound wave topic itself and reported improved mathematical representation; Yolanda, Nasir and Fakhruddin [70] combined PBL with virtual laboratories and found gains in critical thinking and written communication; Sari, Sudarti and Siswati [51] reported improved scientific writing among undergraduates taught through experiment-based PBL; Basri et al. [11] reported improved physics outcomes from PBL with AI-assisted media; and Mustajab, Bahri and Fatmala [39] documented better conceptual understanding of simple machines among grade-8 students. Comparable results are reported outside physics, in chemistry [4] and among preservice physics teachers [27]. Encouragingly consistent, this body of work is also methodologically uniform: most of it rests on single-group or unmatched designs. Lestari and Widayati [31] obtained gains of a similar magnitude using a quite different cooperative model, Teams-Games-Tournament, which is a useful reminder that improvements of this size are not diagnostic of PBL in particular.

That is the gap this study addresses. The point is not to add another affirmative result but to report one carefully, with the design's limits made explicit rather than acknowledged in passing. The study therefore asks: how much does students' cognitive achievement on sound-wave concepts change across a PBL unit, and how much of that change can a one-group pretest-posttest design actually attribute to the intervention? The working hypothesis was that posttest achievement would exceed pretest achievement by a statistically significant margin. The complementary aim, pursued through the analysis rather than a separate hypothesis, was to quantify how far measurement artefacts inflate that margin.

2. Literature review

2.1. Physics learning outcomes

Physics learning outcomes are ordinarily described as capabilities that students possess after instruction and not before [63]. They index mastery of scientific content together with change in knowledge, attitude, and behaviour [46], and they serve two distinct purposes: diagnosing whether teaching worked, and checking that what is taught aligns with what the curriculum intends [72]. The familiar tripartite division into cognitive, affective, and psychomotor domains remains a useful organising lens. The cognitive domain carries scientific reasoning, including the analysis and evaluation that revised Bloom taxonomies place at the upper levels [6]. The affective domain governs motivation and the gradual internalisation of scientific norms [60]. The psychomotor domain covers the procedural skill built through hands-on experimental work [34]. The domains are interdependent, and instruction that addresses only one of them produces a correspondingly narrow result [37]. It is worth noting that the present study measures the cognitive domain alone; that choice bounds what its findings can claim.

2.2. Problem-based learning

PBL is best understood as a framework rather than a technique. It places learners at the centre of the work and asks them to reason and talk their way through problems that resist a single correct procedure [68]. Its epistemology is constructivist: knowledge is built, not transmitted, and subject mastery is pursued alongside the capacity to keep learning [38]. The problems themselves do the pedagogical work. Because they are complex and ill-structured, they sustain engagement, force theory into contact with application, and invite hypothesis generation and evidence-based argument [24, 40]. Procedurally, PBL is usually described in five phases: orienting students to the problem, organising them for inquiry, supporting investigation, developing and presenting an artefact, and evaluating the process and its outcome [54]. The sequence is recursive rather than linear, which is part of why it suits physics, where modelling and analysis proceed by iteration. Alongside content, the arrangement develops autonomy, teamwork, and communication [2], and meta-analytic work on inquiry-based approaches more broadly finds consistent gains in higher-order thinking [5]. The contrast is with expository instruction, which continues to dominate practice in many systems [16, 66]. Project-based approaches share the constructivist premises but differ in the status of the end product, and evidence for the two should not be pooled without comment [19, 20, 48, 50, 56]. Hybrid forms combining problem-based and project-based elements are also common [26].

2.3. Sound waves

Sound waves are mechanical longitudinal waves: they need a material medium, and they propagate as compressions and rarefactions along the direction of travel [71]. By frequency they are conventionally divided into infrasonic (< 20 Hz), audible (20–20,000 Hz), and ultrasonic (> 20,000 Hz) bands. The division matters pedagogically, because students frequently fail to distinguish the regimes or to see why the boundaries fall where they do. Four behaviours account for most everyday acoustic phenomena: reflection, which produces echoes and reverberation; refraction, which bends a wave when its speed changes between regions of the medium; diffraction, which bends it around obstacles; and interference, in which superposed waves reinforce or cancel [28]. The refraction case is worth stating precisely, since it is easy to get wrong. In an ideal gas the speed of sound depends on temperature alone; the pressure and density on which it appears to depend enter only as a ratio that temperature fixes. The greater audibility of distant sounds at night is therefore a consequence of nocturnal temperature inversion, which refracts sound downwards, and not of any change in air density. Applications run from the diagnostic to the domestic. Ultrasound imaging exploits the differing reflectivity of tissues [32], ultrasonic testing supports quality control and homogenisation in food and manufacturing, and high-frequency sound is used in pest control, therapeutic treatment of musculoskeletal injury, and ultrasonic cleaning [69].

3. Method

3.1. Research design

This is a quantitative study using a one-group pretest-posttest design. Such a design is pre-experimental rather than quasi-experimental: it has neither random assignment nor a comparison group, and consequently it cannot rule out the rival explanations that a comparison group would control [52]. It was adopted for a practical reason. The school could make one intact class available for the unit and could not release a second class to serve as a control without disrupting the timetable. The design's inferential cost is real and is not offset by that convenience; it is stated here rather than deferred to the limitations, and it shapes how the results below are worded. Within the single group, achievement was measured before instruction (pretest), the PBL unit was taught, and achievement was measured again afterwards (posttest) using the same instrument.

3.2. Participants

Participants were the 20 students of one intact class, Class XI IPA 2 (grade 11, natural-sciences stream), at a Madrasah Aliyah Negeri, a state Islamic senior secondary school, in the Sleman region of Yogyakarta, Indonesia. Every student in the class took part, so the sample is a census of that class rather than a selection of individuals from within it; in sampling terms this is an intact-group, non-probability sample [55]. Two things recommended the class. Sound waves fell due in its physics sequence during the study window, and the researcher was its regular physics teacher. The second of these cuts both ways. It kept implementation faithful to the intended model; it also introduces a confound, examined in section 5.3.

A group of 20 constrains precision, and it is more honest to state the constraint numerically than to argue the number is adequate. With $n = 20$, $\alpha = .05$, and a two-tailed paired test, the study could detect a within-subject effect of $d_z \approx 0.66$ with 80% power. Effects smaller than that would probably have gone undetected. Effects at least that large, which is what was in fact observed, are detectable but are estimated with wide uncertainty, as the confidence interval reported in section 4 shows.

3.3. Instrument

Achievement was measured with a single written test administered on both occasions. It contained ten items: five multiple-choice and five short-essay questions on sound waves, covering the definition and types of sound waves, their classification, propagation, properties, and everyday applications. The same items were used at pretest and posttest, a decision that permits direct comparison but that also carries a cost discussed in section 5.3. Each item was worth 10 points, with 5 points available for a partially correct essay response, giving a total score on a 0–100 scale. Table 1 sets out the item specification.

The instrument was built to match the curricular outcome and the sub-topics taught, but no formal validation evidence is available for it: no content-validity index was computed, no reliability coefficient was estimated, and the essay responses were scored by the teacher alone without a second rater. This is a genuine weakness of the study and is listed among its limitations rather than passed over.

3.4. Data collection procedure

Data collection had three stages: pretest, instruction, posttest. The pretest established what students already knew about sound waves before any teaching on the topic, providing the baseline against which the later measurement is read. The PBL unit followed. Its content was sound waves, treated through the sub-topics listed in table 1, and its structure is described in section 3.6 below. The posttest, using the same instrument, was administered after the final session. Students were asked not to discuss the pretest items with one another; compliance could not be verified, which is one reason the repeated-instrument problem is taken up in section 5.3.

3.5. Data analysis technique

Change in achievement was summarised with the normalised gain, g, which expresses the observed improvement as a fraction of the improvement that was available to a student given their starting score [22]:

$$g = \frac{\text{posttest score} - \text{pretest score}}{\text{maximum score} - \text{pretest score}} \tag{1}$$

Two estimators can be built from equation 1, and they are not identical: one averages the individual g values, the other computes g from the class mean scores [9]. The averaged individual gains are reported here, and the alternative is given alongside for comparison. Interpretive bands for g follow Hake [22] and are shown in table 2, together with the percentage effectiveness bands that are widely

Table 1
Specification of the pretest and posttest instrument. All items address the same curricular outcome: students can apply the concepts and principles of sound waves in solving problems. Items 1–5 are multiple-choice; items 6–10 are short essay. Cognitive levels follow the revised Bloom taxonomy as applied to Indonesian physics items by Aprillia, Qadar and Efwinda [6].

Sub-material	Question indicator	Cognitive level	Item number	Expected answer
Definition and types of sound waves	Given several statements, identifies the meaning and types of sound waves	C1	1, 2	D; C
Classification of sound waves	Identifies the frequency range of a class of sound waves	C1	3, 4	A; A
Propagation speed of sound waves	Given a propagation phenomenon, explains how sound travels through a solid	C2	5	C
Properties of sound waves	Gives examples of the reflection of sound	C1	6	Shouting in an empty room or a cave (or an equivalent example)
Properties of sound waves	Given the definition of one property of sound waves, identifies which property it is	C2	7	Interference
Application of sound waves	Gives examples of applications of sound waves	C1	8	Ultrasound imaging, milk homogenisation, ultrasonic therapy, or similar
Sound source	Explains what is meant by a sound source	C1	9	The body or object that produces the vibration
Characteristics of sound waves	States the conditions under which sound can be heard	C2	10	A source, a medium, and a receiver

applied in the Indonesian literature [45, 58]. These two scales are not independent evidence: the percentage is simply $g \times 100$, so a single value places a study in one band on each scale. They are presented together only for comparability with prior reports.

Inferential testing used the paired-samples t-test, which evaluates whether the mean of a set of paired differences departs from zero [47]. Because the test assumes approximately normal differences, the distribution of the 20 difference scores was checked with the Shapiro-Wilk test before the t-test was interpreted, and a Wilcoxon signed-rank test was run as a distribution-free check on the same comparison. The null hypothesis was that achievement would not differ between the two occasions; the alternative was that posttest achievement would be higher. Effect size is reported as d_z, the standardised mean difference for paired data, with a 95% confidence interval on the raw mean difference, following the reporting conventions set out by Lakens [30]. Analyses were run in SPSS.

3.6. Implementation of problem-based learning in the sound wave unit

PBL studies are often criticised for describing the model while leaving the teaching opaque. This section sets out what was actually done. The detail is deliberate. Without it a reader cannot judge whether what happened in this classroom resembles what happens elsewhere under the same label,

Table 2
Interpretive bands for the normalised gain. The percentage bands are applied to $g \times 100$ and therefore restate the same quantity on a second scale.

Normalised gain	Category
$g > 0.7$	High
$0.3 \leq g \leq 0.7$	Moderate
$g < 0.3$	Low
Effectiveness (%)	**Interpretation**
< 40	Ineffective
40–55	Less effective
56–75	Quite effective
> 76	Effective

and comparisons across studies become comparisons of names. Implementation followed the five-phase syntax described by Arends [7] and elaborated for STEM contexts by Smith et al. [54]. The unit ran for six sessions of 2×45 minutes across three weeks of the academic term. Figure 1 shows the phase structure as applied to sound waves.

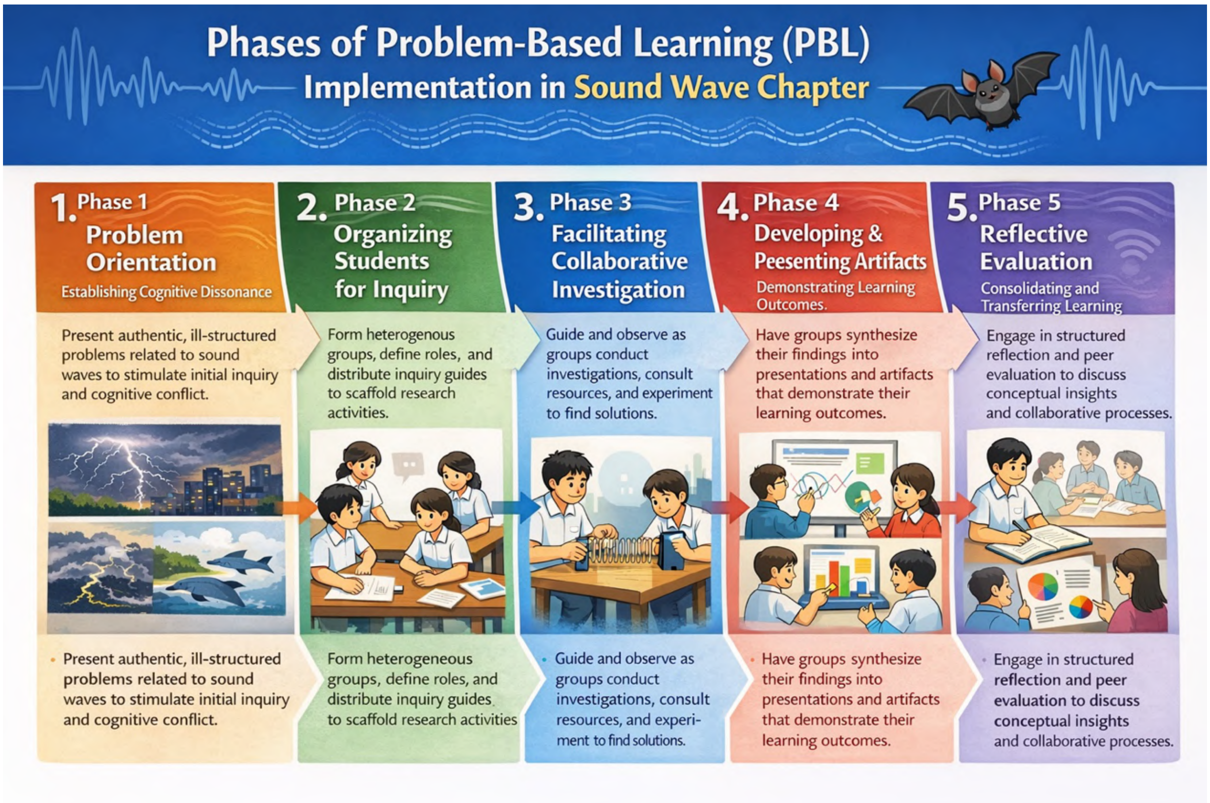

Figure 1: Phase diagram of sound wave learning based on the PBL model.

Phase 1: Orienting students to the problem

Three ill-structured problems were presented, each chosen to connect with something students had already noticed and to unsettle their explanation of it. The first was the behaviour of thunder: "Why does thunder sound louder and last longer at night than during the day, even when the strike is the same distance away?" A short video of thunder recorded at different times accompanied the question, and students were asked to explain what they heard. The second problem was the room they were sitting in: "Our classroom has poor acoustics. Students at the back often cannot hear the teacher, while those at the front find the sound overwhelming. How could we redesign the room to distribute sound better, without expensive renovation?" The third moved to biology: "Bats navigate in complete darkness, avoiding obstacles and catching insects. Dolphins communicate across kilometres of ocean. How do these animals use sound to 'see', and what physics makes that possible?" The teacher's role in this phase was deliberately non-directive. Instead of explaining, the teacher asked what students already knew that might bear on the phenomenon, what patterns they noticed, and what further information they would need. Students recorded initial hypotheses in learning journals, working individually and then in think-pair-share pairs.

Phase 2: Organising students for inquiry

Students formed five groups of four, balanced for prior achievement, gender, and observed working style. The three problems were distributed across the five groups, so that two of the problems were investigated by two groups independently, which later allowed the class to compare competing accounts of the same phenomenon. Within each group, students negotiated roles. A leader coordinated the work and managed time; a recorder kept the inquiry log, noting sources consulted and findings as they emerged; a spokesperson prepared the oral presentation and fielded questions; a resource manager handled access to textbooks, articles, and the school tablets. Roles rotated in later cycles so that every student practised each one. Structured peer roles of this kind are a well-documented way of making group work productive in physics classes [12]. The teacher supplied inquiry guides that structured the work without prescribing an answer: restate the problem in your own words, separate what you know from what you need to find out, formulate the questions that follow, record your sources, draft a preliminary explanation, and plan the artefact you will build.

Phase 3: Supporting collaborative investigation

Investigation was the longest phase, occupying three sessions. Groups worked largely on their own, drawing on resources the teacher had placed within reach. The thunder groups worked on refraction, atmospheric temperature gradients, and propagation through media of differing temperature; they used textbooks for the underlying principles, interactive simulations to watch wave behaviour respond to changed variables, and meteorological material on atmospheric structure. Their methods varied: one group built physical models with slinkies to make compression and rarefaction visible, another used PhET simulations to manipulate the variables governing wave speed and direction [8]. The classroom-acoustics groups worked on reflection, absorption, transmission, and interference. They measured the room, estimated reverberation time with an online calculator, and researched the acoustic properties of available materials; one group built a cardboard scale model of the classroom and tested sound distribution in it with a smartphone decibel-meter application. The echolocation group worked on frequency ranges, reflection, and the relation between wavelength and the smallest detectable obstacle, consulting biological sources on animal anatomy alongside physics texts on the inverse relation between frequency and wavelength. Several groups produced comparative charts of the frequency bands different animals exploit.

The teacher's role shifted from instruction to scaffolding. When a group stalled, the response was a question rather than an answer. Students struggling with why sound travels faster in warm air were asked what happens to air molecules as temperature rises, and how molecular motion might affect the speed at which a disturbance propagates. The teacher also monitored group dynamics and intervened where participation had become uneven.

Phase 4: Developing and presenting artefacts

Each group turned its investigation into a presentation that tied its findings to the physics that explained them. Multiple representational formats were encouraged: verbal explanation, mathematical relations, diagrams, and physical demonstration. The two thunder groups presented in sequence on refraction through atmospheric layers, with diagrams of bending wavefronts and the relation between temperature gradient and sound speed, both arriving at the conclusion that a cooler layer near the ground bends the sound path back towards the listener and so carries thunder further at night; because they had reached it by different routes, one through physical models and one through simulation, the class could compare two accounts of the same phenomenon. Of the two classroom-acoustics groups, the one that had built the scale model presented it, explaining the materials chosen to represent absorbing and reflecting surfaces and reporting measured sound pressure levels at several positions in the room, while the other presented its survey of material properties; both closed with recommendations for modifying the room. The echolocation group produced a comparative poster on bats, dolphins, and humans, with frequency-range comparisons, an account of how wavelength sets the minimum detectable object size, and a demonstration using an ultrasonic sensor and a microcontroller, an instance of the low-cost instrumentation now widely available for school physics [59]. Peer groups questioned the presenters, and the teacher kept the questioning constructive and focused on the concepts at issue.

Phase 5: Analysing and evaluating the process

The final phase turned attention back on the work itself. In a whole-class discussion the teacher drew the three problem contexts together, connecting them to the properties they shared: the relations among frequency, wavelength, amplitude, and speed, and the behaviours of reflection, refraction, diffraction, and interference. Students then completed written reflections recording what they had first thought, how that changed during the investigation, what remained unresolved, and what they had contributed to the group; explicit metacognitive prompting of this kind has been used to good effect in classroom interventions [15]. Peer assessment captured each member's contribution. The teacher returned written feedback on both the group presentations and the individual reflections. These reflections and peer assessments were used formatively and were not scored or analysed as data; the study's outcome measure is the written test alone.

4. Results

Individual pretest and posttest scores, with the normalised gain for each student, are given in table 3. Student identifiers have been replaced with codes.

Every student improved. Raw gains ranged from 10 to 85 points, and no student scored lower at posttest than at pretest. Pretest scores averaged 58.25 ($SD = 19.14$, median 55, range 15–90); posttest scores averaged 95.00 ($SD = 6.28$, median 100, range 80–100). At pretest, 11 of the 20 students scored below 60 and five below 50; at posttest, none scored below 80. The two standard deviations are as informative as the two means: posttest variance is roughly a tenth of pretest variance, so the class did not simply shift upwards but converged near the top of the scale. The scores had spanned 75 points at pretest and spanned only 20 at posttest, so the instrument that had separated these students at the outset barely separated them at the end. The posttest distribution makes the same point directly. Of the 20 scores, 11 were 100, one was 95, six were 90, one 85, and one 80; 18 of 20 students scored 90 or above.

The mean normalised gain was 0.88 ($SD = 0.15$, range 0.56–1.00), which falls in the high band of table 2, and 88.10% on the percentage scale, which falls in the effective band. Individually, 17 of the 20 gains fall in the high band and the remaining three in the moderate band; none is low. As noted in section 3.5, these are one result reported twice rather than two. The alternative estimator, computed from the class means rather than by averaging individual gains, gives 0.880, so the choice of estimator makes no material difference here. Eleven of the 20 normalised gains are exactly 1.00, and in every case this is because the student reached the 100-point maximum, which forces g to unity irrespective of how much was learned beyond the point where the test stopped discriminating.

Table 3
Pretest and posttest scores with normalised gain, by student.

Student	Pretest score	Posttest score	Normalised gain	Gain (%)
S1	35	100	1.00	100.00
S2	90	100	1.00	100.00
S3	85	100	1.00	100.00
S4	75	90	0.60	60.00
S5	80	100	1.00	100.00
S6	55	80	0.56	55.56
S7	90	100	1.00	100.00
S8	60	90	0.75	75.00
S9	50	90	0.80	80.00
S10	70	95	0.83	83.33
S11	45	90	0.82	81.82
S12	40	100	1.00	100.00
S13	15	100	1.00	100.00
S14	60	100	1.00	100.00
S15	60	100	1.00	100.00
S16	55	90	0.78	77.78
S17	50	100	1.00	100.00
S18	45	90	0.82	81.82
S19	55	85	0.67	66.67
S20	50	100	1.00	100.00
Mean	58.25	95.00	0.88	88.10

The 20 difference scores were approximately normal (Shapiro-Wilk $W = .954$, $p = .43$), so the paired-samples t-test was interpretable. Results are given in table 4. Posttest scores exceeded pretest scores by a mean of 36.75 points ($SD = 19.49$, $SE = 4.36$), $t(19) = 8.435$, $p < .001$. The computed value exceeds the critical value of 2.093 for $df = 19$ at $\alpha = .05$ (two-tailed), so the null hypothesis of no difference is rejected. The effect is large, $d_z = 1.89$, and the 95% confidence interval on the mean difference runs from 27.63 to 45.87 points, which is wide, as an n of 20 dictates. A Wilcoxon signed-rank test on the same comparison agrees ($p < .001$), so the conclusion does not depend on the normality assumption.

Table 4
Paired-samples t-test for the difference between posttest and pretest scores.

Comparison	Mean difference	Std. dev	Std. error mean	95% CI	$t(19)$	Sig. (2-tailed)
Posttest − pretest	36.75	19.49	4.36	[27.63, 45.87]	8.435	$< .001$

One further relationship in table 3 bears on how the gains should be read. Raw gain is almost perfectly inversely related to pretest score ($r = -.95$): the lower a student started, the more points they gained. Normalised gain, by contrast, is essentially unrelated to pretest score ($r = .01$). Normalisation therefore does what it is designed to do, removing the dependence of raw improvement on starting position, but it does so within a scale that has a hard upper bound, and 11 students reached that bound. The interpretation of both figures is taken up next.

5. Discussion

Students finished the unit knowing substantially more about sound waves than they began it with. The mean gain of 36.75 points is statistically unambiguous and large in standardised terms, and the mean normalised gain of 0.88 sits well inside the high band. Taken at face value these numbers describe an unusually successful unit. The remainder of this section argues that they should not be taken entirely at face value: part of their magnitude is attributable to the instrument and the design rather than to what students learned, and the size of that part can be partly estimated from the data themselves.

5.1. The test ceiling and what it does to normalised gain

The clearest measurement problem is that the test ran out of room. Eleven of 20 students scored the maximum at posttest and 18 of 20 scored 90 or above, while posttest standard deviation fell to a third of the pretest value. Under those conditions the normalised gain behaves poorly. Because g is defined as the fraction of available improvement actually realised, any student who reaches the maximum records $g = 1.00$ by construction, whether they mastered the topic comprehensively or merely cleared a low bar. The statistic cannot distinguish those cases, and with 55% of the sample at the ceiling the class mean is pushed upwards by arithmetic rather than by learning. Marx and Cummings [33] identify precisely this behaviour as a limitation of normalised gain and propose normalised change as a partial remedy; Bao [9] shows how sensitive averaged gain measures are to the distribution of scores. The comparison with published figures points the same way. Watuna et al. [64] reported a normalised gain of 0.68 for PBL worksheets on wave content and Basri et al. [11] 0.66 for PBL with AI-assisted media, both in the moderate band and both from studies using instruments that did not saturate. The present 0.88 is the outlier, and the simplest explanation is not that this unit was markedly better taught but that this test was markedly easier to top out. The practical implication is that 0.88 should be read as an upper bound on the unit's effect, and that a test with more headroom, more items, or harder items would very likely have returned a lower figure. That a ten-item test scored in 5-point increments produced 11 perfect scores is itself evidence that the instrument was too easy for the post-instruction range it needed to measure. The remedy is straightforward and worth stating for anyone replicating this design. Ten items scored in 5-point steps give only 21 distinct possible scores, which is too coarse to register differences among students who have all learned a good deal. A longer test, with items reaching the analysis and evaluation levels rather than concentrating at recall and understanding as table 1 shows this one did, would both raise the ceiling and let normalised gain do the work it was designed for.

5.2. Baseline dependence and regression to the mean

The near-perfect inverse relation between pretest score and raw gain ($r = -.95$) has the same dual explanation. Part of it is arithmetic: a student who scores 90 at pretest can gain at most 10 points, so large gains are available only to those who started low. Part of it, however, is the pattern expected from measurement error alone. In any single-group pre-post comparison, students whose pretest scores fell unusually low relative to their true standing will tend to score closer to that standing on retesting, and the movement will look like improvement [10]. The student who scored 15 at pretest and 100 at posttest is the case in point; a single unusually poor pretest performance is at least as plausible an account of part of that jump as an 85-point gain in understanding. Without a comparison group there is no way to separate the two contributions. The one reassurance the data offer is that normalised gain is uncorrelated with pretest score ($r = .01$), so the aggregate normalised figure is not simply an artefact of who started where. It remains vulnerable to the ceiling, which is a separate problem.

5.3. Threats to internal validity

Beyond measurement, the design leaves several rival explanations open, and none can be excluded here [52]. The first is the teacher. The researcher designed the unit, believed in the model, and taught it, and teacher expectations are known to influence student outcomes in ways that are difficult to separate from the instruction itself [61]. Implementation was probably better than a teacher encountering PBL for the first time would achieve, which means the result speaks to PBL taught well by a committed practitioner rather than to PBL as such. The second is novelty. In a setting where teacher-centred instruction predominates, an unfamiliar student-centred unit may raise attention and effort for reasons unrelated to its pedagogical structure; the systematic review by McCambridge, Witton and Elbourne [35] finds such research-participation effects to be real but heterogeneous and hard to size. Six sessions over three weeks is too short to show whether engagement would persist. The third is the test itself. The same ten items were used twice, so students had seen every question before, and the pretest may also have functioned as instruction by directing attention to what mattered. Willson and Putnam [67] estimate pretest sensitisation effects meta-analytically and find them small on average but non-negligible, and the present design offers no way to check the size of the effect here; parallel forms at the two occasions would have. Fourth, three weeks allows some maturation, and students may have encountered sound-wave content outside the classroom. These last two are usually minor over such an interval, but a comparison group would have absorbed them, and there was none.

None of this implies the unit did not work. It implies that the study establishes that substantial learning occurred during a PBL unit, and not that PBL caused it. That is a weaker claim than the numbers alone suggest, and it is the claim the design supports.

5.4. Why the observed gain is nonetheless plausible

Set against those qualifications, the mechanisms PBL is supposed to engage were visibly engaged in this unit, which makes a genuine instructional contribution plausible even if it cannot be isolated. Hmelo-Silver [24] characterises PBL as working through flexible knowledge construction, self-directed inquiry, and collaboration around a shared problem. The three problems used here were built to require exactly that. Explaining nocturnal thunder cannot be done by recalling a definition; it requires connecting temperature, sound speed, and refraction, which is why the thunder groups arrived at atmospheric inversion rather than at a formula. The classroom-acoustics problem forced abstraction into contact with measurement, since a recommendation about the room had to survive a decibel meter. The echolocation problem required students to reason from the inverse relation between frequency and wavelength to the size of a detectable object. These are the kinds of task on which conceptual understanding of waves is known to be weak [25, 42], and the unit addressed them directly rather than through exposition. The gain observed is consistent with the review evidence on PBL in physics [40] and with meta-analytic findings on its effects on critical thinking [21] and problem-solving [17, 65], all of which report positive but more modest effects than the present figure, as one would expect from designs with comparison groups.

A second mechanism deserves comment, with a caveat attached. PBL is a collaborative model, and the theoretical accounts of why it works place considerable weight on students constructing explanations for one another rather than receiving them from a teacher [24]. The design of this unit made that structure explicit: heterogeneous groups, assigned and rotated roles, two groups working the same problem independently so that competing accounts had to be reconciled in front of the class. Whether that structure contributed to the measured gain is, however, not something this study can show. Group processes were not recorded, the peer assessments were formative and unanalysed, and the outcome measure was an individual written test. The collaborative arrangement is therefore reported here as a feature of the intervention, which the description in section 3.6 documents, and not as an explanation the data support.

5.5. Limitations and implications

The limitations are those set out above, stated once more in summary. The design is pre-experimental, so causal attribution is not available. The sample is 20 students in one intact class at one school, which limits both precision and generalisation, and the researcher-as-teacher role ties the result to a single implementer. The instrument has no validity or reliability evidence, was used in identical form twice, and was too easy to measure the upper range of post-instruction achievement. Only the cognitive domain was assessed: the reflections and peer assessments described in section 3.6 were formative and were not analysed, so the study says nothing about collaboration, metacognition, or motivation, and no such claim should be read into it. The posttest was immediate, so retention and transfer are untested.

What follows for practice is correspondingly modest, and it is worth separating from what follows for research. The unit described in section 3.6 is reproducible, and the account there is detailed enough for a teacher to try it and judge the outcome in their own setting; that is a more useful contribution than the effect size. Three features of it seem worth carrying over independently of the numbers. The problems were chosen to name a phenomenon students had already noticed but could not explain, which is a more demanding criterion than authenticity alone. The teacher's default response to a stuck group was a question about mechanism rather than an answer, which requires preparation of a kind conventional lesson planning does not develop. And the artefact requirement forced each group to commit to an explanation publicly, where peers could contest it. Teachers adopting PBL are often advised to begin with a single unit rather than a whole course; the resource demands here, in problem design, in facilitation, and in the range of materials groups needed, support that advice. For research, the priorities are a comparison group, parallel test forms, an instrument with sufficient ceiling, and a delayed posttest. Any of the four would materially strengthen what a study of this kind can conclude, and the first would change its status entirely; the accumulated evidence on school interventions comes overwhelmingly from designs that include one [36].

6. Conclusions

Students' achievement on sound-wave concepts improved substantially across a six-session problem-based learning unit. Pretest scores averaged 58.25 and posttest scores 95.00; the mean difference of 36.75 points was statistically significant, $t(19) = 8.435$, $p < .001$, with a large standardised effect ($d_z = 1.89$) and a mean normalised gain of 0.88.

Those figures should be read with two qualifications that the data themselves supply. More than half the class reached the ceiling of the test, which inflates normalised gain and indicates that the instrument could not measure the top of the achieved range; and raw gains were almost perfectly inversely related to starting scores, a pattern that regression to the mean would partly produce on its own. Combined with the absence of a comparison group, this means the study documents that considerable learning took place during the unit without establishing that problem-based learning caused it.

The study's more durable contribution is the account of implementation in section 3.6. Reports of PBL frequently describe the model without describing the teaching, which makes results hard to interpret and harder to reproduce. Here the three problems, the group structure, the scaffolding moves, and the artefacts are all specified, so a teacher can run the unit and a researcher can test it against a control. That test is the obvious next step: the same unit with a comparison group, parallel pretest and posttest forms, an instrument with adequate headroom, and a delayed posttest would establish what this design cannot.

Ethics approval

The study was carried out within the normal conditions of the educational process. The sound wave unit was already scheduled in the school's physics sequence, the lessons were taught by the students' own subject teacher, and the pretest and posttest were administered as ordinary classroom assessment; no measurement was taken beyond what teaching and its assessment required, and no student received less than the standard curriculum. Permission to conduct the study and to report its results was granted by the head of the participating Madrasah Aliyah Negeri.

Informed consent

Participants were aged 16–17 and took part in activities that fell entirely within the regular curriculum. No personally identifying information was collected or retained. Participant-level scores are reported under the codes S1–S20 in table 3, and the school is identified only by type and region.

Consent for publication

No identifiable individual or institution is named in this article.

Author contributions

The author is the sole contributor to this work: the study design, the teaching of the unit, the data collection and analysis, and the writing of the manuscript are all the author's own. The author has read and agreed to the published version of the manuscript.

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Data availability statement

The complete dataset analysed in this study is reproduced in table 3: pretest and posttest scores for all 20 participants, under anonymised codes. Every descriptive and inferential statistic reported in section 4 can be recomputed from that table.

Conflicts of interest

The author declares no conflict of interest. The author taught the class that took part in the study and was also its investigator; the consequences of that dual role for the interpretation of the findings are discussed in section 5.3.

Declaration on Generative AI

In preparing the manuscript, the author used ChatGPT (OpenAI) to draft and expand parts of the literature review and the discussion and to improve the English of the text. The author has reviewed the manuscript and takes full responsibility for its content.

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