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Optimization of Project-Based Learning with Inquiry Approach in Rotational Dynamics Study

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Abstract – *Rotational dynamics is frequently taught as an abstract, equation-centered topic, which can reduce engagement and hinder the growth of inquiry and process skills. This study aimed to optimize project-based learning (PjBL) through an open-inquiry approach to improve students' learning outcomes, classroom activity, and science process skills in rotational dynamics. A quasi-experimental nonequivalent control-group design was conducted at MAN 2 Kepulauan Meranti with 55 eleventh-grade students (experimental n=26; control n=29). The experimental class learned through PjBL integrated with open inquiry by designing and building a mini gear-based machine prototype from recycled cardboard as an investigative medium, while the control class received conventional instruction. Data were gathered using pretest–posttest cognitive tests, classroom activity observations, science process skills rubrics, and student response questionnaires. The experimental class demonstrated higher overall activity (75%) than the control class (57%). Student responses indicated the intervention was enjoyable (77%) and helped understanding (69%). Science process skills in the experimental class were rated good, with strong performance in using tools/materials and communicating results (mean score 4.0 each), and adequate performance in project design (3.2), conducting experiments (3.0), interpreting data (3.0), and reporting. Cognitive achievement also improved: the experimental class reached a higher posttest mean (79.6) than the control class (73.9) and a higher normalized gain (N-gain=0.74 vs 0.67). The novelty of this study lies in a low-cost, scalable PjBL–open inquiry sequence that leverages recycled materials to produce tangible prototypes that make rotational concepts observable and testable. In conclusion, optimizing PjBL with open inquiry can enhance engagement, process skills, and conceptual mastery, offering a practical contribution to physics education for more meaningful and skills-oriented instruction.*

Keywords: *open inquiry; physics education; project-based learning; rotational dynamics; science process skills*

I. INTRODUCTION

Science can be seen both as a product and a process. As a product, science includes the accumulated knowledge about natural phenomena, shared as facts, concepts, principles, laws, and theories. As a process, science involves the systematic activities and methods used to create that knowledge through observation, experimentation, measurement, analysis, and logical reasoning. This dual view shows that learning science isn't just about acquiring scientific facts, but also about developing students' ability to think and act scientifically. This includes asking questions, testing ideas, interpreting evidence, and communicating conclusions (García-Carmona & Acevedo-Díaz, 2018; Lederman, 2019). In short, science education aims to build students' scientific understanding along with the skills and attitudes necessary for scientific inquiry.

From this perspective, scientific knowledge does not form instantly; it is built through a series of discovery processes that utilize scientific methods and are guided by a scientific mindset. Narut and Supardi (2019) highlight that the core of science involves science as a process, science as a product, and science as an attitude. These three aspects are interconnected: scientific products (such as concepts and principles) are created through scientific processes (like observation and experimentation), and both are supported by attitudes such as curiosity, objectivity, carefulness, openness to evidence, and a willingness to revise explanations. Therefore, science learning that only emphasizes outcomes (such as formulas or definitions) may weaken students' process skills and attitudes. Conversely, learning experiences that intentionally focus on processes and attitudes can enhance students' understanding and their ability to apply knowledge in real-world situations.

A key implication for instruction is that science learning should provide students with opportunities to engage in problem-solving and inquiry activities that reflect how science is practiced. Problem-solving helps learners identify issues, formulate questions, propose explanations, plan strategies, test options, and evaluate outcomes. These actions align with the development of science process skills and offer a natural way to build conceptual understanding. Learning through direct experience also matches how students learn effectively from a young age; experiencing, exploring, and manipulating objects or situations can be a strong foundation for deeper reasoning (Kožuchová et al., 2023). Therefore, science teaching that incorporates experience-based tasks and organized opportunities for investigation is more likely to foster meaningful learning than approaches focused solely on explanation and memorization.

In relation to these needs, Project-Based Learning (PjBL) is widely recognized as a student-centered approach that supports the development of higher-order thinking, collaboration, and authentic engagement (Bao & Koenig, 2019; Espinosa et al., 2019). In PjBL, students work over an extended period to explore and respond to a meaningful problem or challenge, ending with the creation of a product. Importantly, the value of PjBL goes beyond the final product; it lies in the learning process how students identify problems, design plans, seek information, conduct trials, revise designs, and justify decisions. This process strongly aligns with science as both a process and an attitude, as students are required to demonstrate persistence, curiosity, responsibility, and evidence-based reasoning while completing the project. Therefore, PjBL can foster an instructional environment that encourages students to learn actively and independently, while still being guided through purposeful tasks that connect scientific concepts to real-world situations. Meta-analytic evidence shows that PjBL can produce a medium-to-large positive effect on students' academic achievement compared with traditional instruction.

Previous research has reported positive contributions of project-based approaches to key competencies in science learning. Evidence from STEM settings suggests that PjBL can benefit achievement across diverse student groups, including lower-achieving students (Han & Capraro, 2015). Pratama et al. (2024) reported that PjBL positively affects scientific and digital literacy skills. This indicates that projects may provide contexts that help students integrate scientific reasoning with the use of information and technology. Similarly, Nurjanah et al. (2021) reported that PjBL improves science process skills. These findings suggest that when students engage in planning, investigating, and producing a tangible output, they are more likely to practice the procedural and reasoning components associated with scientific work. Nevertheless, the effectiveness of PjBL depends on the quality of implementation, including the clarity of learning goals, the appropriateness of project tasks, and the degree to which students are supported in performing inquiry rather than merely completing tasks mechanically (Markula & Aksela, 2022).

To strengthen the inquiry character of project work, many science educators integrate PjBL with an inquiry-based learning (IBL) approach. Inquiry is an active learning method in which students develop knowledge or solve problems by following procedures comparable to the scientific method used by researchers. Students are encouraged to explore issues, ask questions, generate and test ideas, collect and analyze evidence, and communicate findings. In this approach, learning shifts away from memorizing scientific facts and rules toward constructing understanding through doing. The teacher's role becomes facilitative: providing scaffolding, resources, and feedback that support students' learning processes, rather than delivering information as the primary source of knowledge (Belland et al., 2017; Lehtinen & Viiri, 2017; Zacharia et al., 2015). Sokołowska (2020) explains that inquiry-based learning is associated with creativity, enhancement of critical thinking and reasoning, and development of research skills grounded in learners' curiosity and inquisition. Because inquiry-based learning is student-centered, it can also promote greater independence and responsibility in learning.

Inquiry-based learning further supports comprehensive development across cognitive, psychomotor, and affective domains, particularly when learners are authentically engaged. When students plan investigations, manipulate materials, collect data, and interpret outcomes, they simultaneously practice thinking and hands-on skills and develop attitudes such as persistence and carefulness. In this sense, inquiry learning supports the development of competence, comprising content knowledge, skills, and attitudes (Sokołowska, 2020). This multidimensional outcome is particularly relevant to science education, where the goals typically include not only mastering concepts but also developing scientific habits of mind. Therefore, integrating inquiry into PjBL can create stronger alignment with the nature of science, while also supporting outcomes such as science process skills and learning achievement. Inquiry-based laboratory environments have also been shown to improve students' conceptual understanding and thinking skills compared with traditional instruction (Thacker, 2023).

Figure 1. Inquiry-based learning cycle

The inquiry process is commonly represented as a learning cycle, which in this study is illustrated in Figure 1 (Pedaste et al., 2015). Although inquiry cycles may be described with different labels across frameworks, the general pattern involves iterative stages such as identifying problems, questioning, planning investigations, collecting evidence, analyzing results, constructing explanations, and communicating or reflecting on findings. In practice, inquiry can be implemented at different levels: structured inquiry, guided inquiry, and open inquiry. In structured inquiry, students follow procedures designed by the teacher; in guided inquiry, students investigate teacher-provided questions with more autonomy in procedures; and in open inquiry, students play a greater role in formulating questions, designing methods, and making decisions about how to investigate. In the present research, an open inquiry approach was adopted within a PjBL framework to maximize students' engagement, ownership, and scientific thinking. Open inquiry has also been implemented within project-based laboratory curricula to support students' experimental design and data analysis skills (DeStefano & Widenhorn, 2024).

However, implementing open inquiry and PjBL in real classrooms requires careful consideration of contextual constraints. Schools may face limitations in laboratory equipment, instructional media, and students' socioeconomic backgrounds. Due to the limitations of the facilities and the economic level at the location where this research was conducted, this study used simple materials as the project's raw materials. From a pedagogical perspective, the use of recycled or readily available materials can be advantageous because it encourages creativity, supports contextual learning, and reduces dependence on expensive resources. At the same time, to ensure that learning remains scientifically meaningful, the design of projects must still provide sufficient opportunity for students to observe, test, measure, compare, and reason using evidence. This emphasis aligns with maker-centred perspectives that highlight learning through designing and making artifacts in authentic contexts (Wang et al., 2019). Similar constraints have motivated the development of low-cost, inquiry-oriented laboratories in contexts with limited facilities (Husnaini & Chen, 2019).

A further issue concerns who designs and controls the learning media used in project and inquiry activities. Existing research on the utilization of recycled materials as instructional media has largely adopted a teacher-centered approach. As reported by Suyamto (2022), Sunandar et al. (2024), and Nuwairah et al. 2018), learning media are designed and prepared by teachers. When media are fully prepared by the teacher, students may benefit from well-structured tools, but may have limited opportunity to practice design thinking, creativity, and ownership of learning. Students may become media users rather than creators, potentially limiting the development of planning, revising, and evaluating design skills closely connected to inquiry and problem-solving.

To address this gap, the current study positions students not only as learners but also as creators of learning media by giving them the opportunity and responsibility to design and produce their own instructional tools using simple materials. This focus is expected to boost student ownership and engagement while promoting the use of inquiry processes in planning, constructing, and testing the media. By combining PjBL with an open inquiry approach and placing students in an active role as designers, this study aims to enhance learning experiences that reflect science as a process, product, and attitude, aligning with the view of science education as an active path toward meaningful knowledge building and experiential learning.

II. METHODS

This research was conducted at MAN 2 Kepulauan Meranti involving two grade XI classes, namely XI F 2A and XI F 2B. A quasi-experimental design was employed. The experimental group was class XI F 2A (26 students), which received the treatment, while class XI F 2B served as the control group (29 students).

Due to limitations in laboratory equipment, the learning intervention used simple recycled materials, particularly cardboard boxes. Students were challenged to design and construct a mini machine prototype as a project within a PjBL framework integrated with an inquiry approach. The inquiry level applied in this study was open inquiry because each student group was given broad opportunities to determine the design and development of their product. This activity was intended to help students discover key concepts in rotational dynamics. Five core concepts were targeted in the learning process: (1) the definition of torque, (2) the definition of inertia, (3) the relationship between torque and angular acceleration, (4) physical quantities in gear connections, and (5) the concept of rotational kinetic energy.

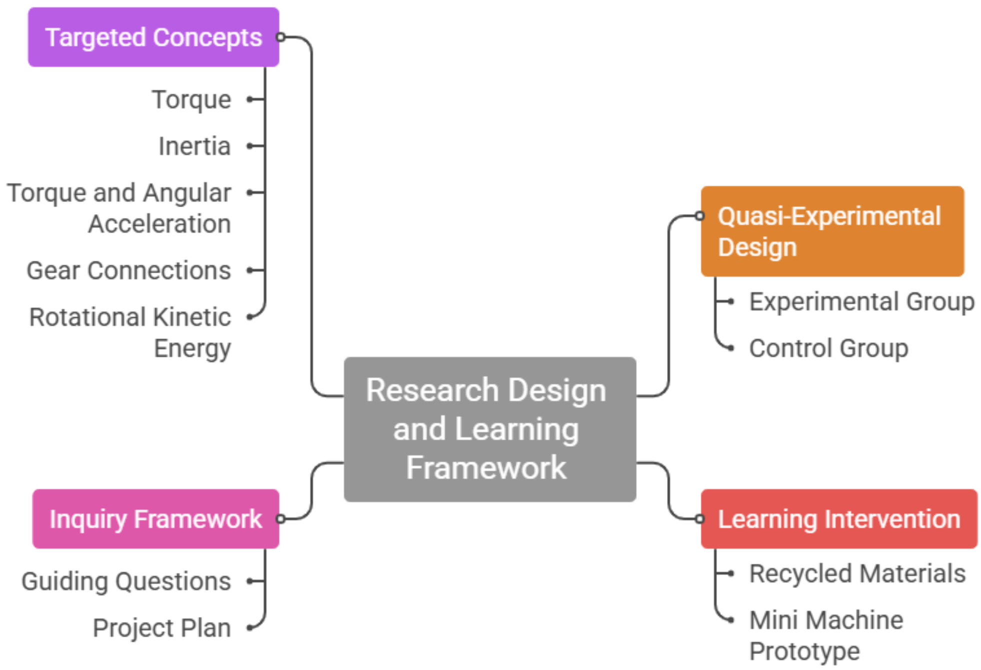

Figure 2. Research design and learning framework

To guide students' inquiry processes, structured guiding questions were provided in Table 1. These questions were designed to help students discover and construct the five targeted concepts as they completed project activities. Students carried out exploration as part of the project-based inquiry process. At the start of PjBL, students were instructed to create a mini machine prototype using simple recycled materials. Students were divided into five study groups, and each group was required to prepare a project plan including the mini machine design, required tools and materials, relevant equations used in the mini machine, estimated cost, and a project timeline. The teacher monitored all stages of implementation, including project development, testing, assessment, and evaluation of the overall process. During project work, students were also asked to respond to the prepared guiding questions to construct knowledge in accordance with inquiry principles.

Table 1. The list of questions to guide students in discovering the concept

Questions	Targeted concept
How do force, position and angle affect torque?	1
How do torque affect angular acceleration	2
How does adding particles to gears affect movement?	3
What is the physical quantity that connects gears 1 and gear 2?	4
Where does rotational kinetic energy come from?	5

During the learning process, the teacher observed students and completed observation forms on student activities and science process skills to determine students' levels. After the learning intervention was completed, cognitive learning outcomes were assessed using a written test comprising 20 reasoning-based questions. The N-gain value was calculated to indicate the effectiveness of the learning intervention by measuring proportional improvement from pretest to posttest. Student activities and cognitive learning outcomes in the experimental and control classes were compared to assess the treatment's success. The comparison included the average written test scores and the percentage of student activity (A). Student activity percentage was calculated using the following equation:

$$A = \frac{S}{S_{maks}} x\ 100\ \% \qquad 1)$$

where S is the total student activity score (1–4) and S_maks is the maximum obtainable score. The scoring criteria were: 1 = insufficient, 2 = sufficient, 3 = good, and 4 = very good. Five aspects were observed: students' attention to the lesson, collaboration in groups, activeness during the project, accuracy and speed in answering questions, and students' ability to convey opinions. A similar approach was used to calculate the percentage scores for student activity and science process skills, using a rubric-based performance scale and converting results into mastery percentages.

In this research, the assessment of science process skills focused on five key skills: designing projects, using tools and materials, planning and conducting experiments (including variable control), interpreting data, and communicating results. Data were gathered using multiple instruments, such as student activity observation sheets, science process skills observation rubrics, and cognitive learning outcome tests. Student activities and science process skills were observed during the learning process, while cognitive learning outcomes were measured afterward using a written test.

To improve methodological rigor, all research instruments underwent content validity testing through expert judgment. The instruments were reviewed by two physics education experts and one experienced physics teacher to ensure they aligned with learning objectives, indicators, and assessed competencies. Revisions were made based on expert feedback before implementation. Instrument reliability was tested with a pilot study conducted with students outside the research sample. The reliability of the cognitive learning outcome test was calculated using Cronbach's Alpha and yielded a coefficient above 0.70, indicating acceptable reliability. Observation instruments for student activities and science process skills showed consistent inter-rater agreement, supporting the reliability of behavioral measures measurements.

Science process skills in this study refer to students' abilities to apply scientific methods and reasoning during project-based inquiry activities. Five skills were evaluated: (1) designing projects (students' ability to generate project ideas and create prototypes based on physics concepts), (2) using tools and materials (selecting and using them appropriately and safely), (3) planning and conducting experiments (developing procedures, controlling variables, and executing systematic investigations), (4) interpreting data (analyzing results and relating findings to relevant concepts), and (5) communicating results (presenting outcomes both orally and in writing). Each skill was assessed with a performance-based rubric using a four-point scale (1 = insufficient, 2 = sufficient, 3 = good, 4 = very good). Scores for each skill were converted into percentages to determine mastery levels.

III. RESULTS

In this study, students were given creative freedom in their projects. The experimental class successfully developed five different simple projects based on gear applications using recycled cardboard: a miniature windmill (group A), a miniature noodle-making machine (group B), a miniature rice field plowing machine (group C), a miniature treadmill (group D), and a miniature chopper (group E).

The treatment used in the experimental class boosted students' motivation to learn. According to the student questionnaire, two areas were assessed: whether the learning process was enjoyable and whether the physics concepts were easy to grasp. The results, as shown in Figure 3, show that about 77% of students agreed that learning became more enjoyable, and 69%

stated that the concepts of rotational dynamics were easier to understand. These responses suggest that students received the treatment positively.

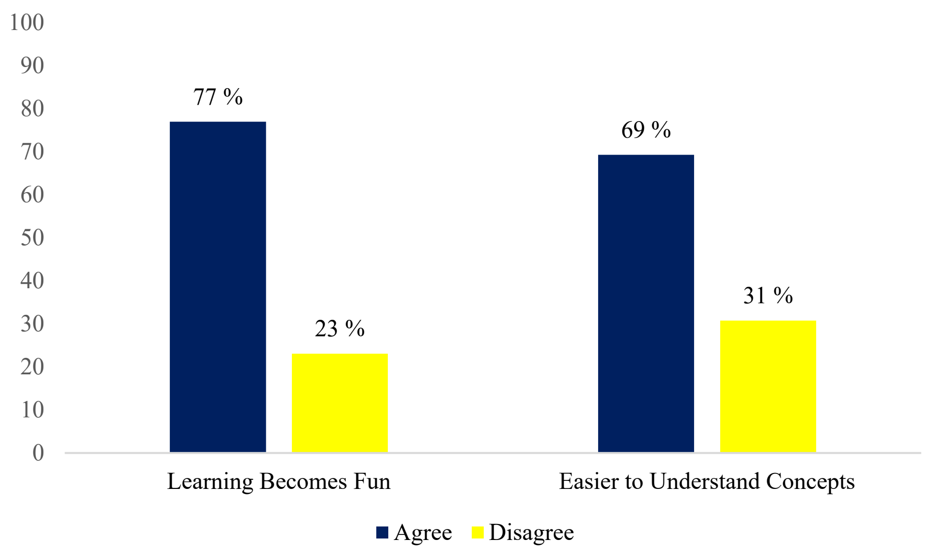

Figure 3. Student response to treatment

The classroom atmosphere in the experimental class is presented in Figure 4. Based on brief interviews, several students stated that they were more enthusiastic during learning, less sleepy, found it easier to understand several physics concepts, and were interested in conducting similar projects for other topics in the future.

Figure 4. The atmosphere of the experiment class

Students' enthusiasm was also reflected in their classroom activities. Five activity aspects were observed: students' attention to the lesson (aspect 1), collaboration in groups (aspect 2), activeness in project work (aspect 3), accuracy and speed in answering spontaneous questions (aspect 4), and students' ability to convey opinions (aspect 5).

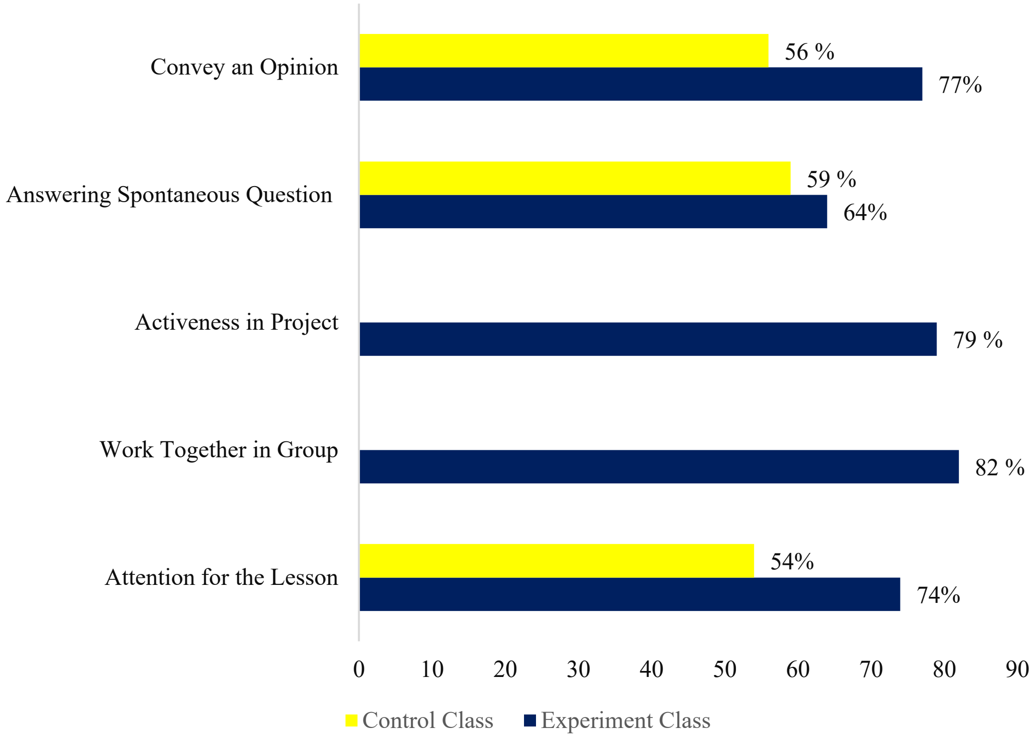

Figure 5. The activity percentage in the experiment class

Figure 5 illustrates the activity percentage impact in the experimental class (0.9) concerning the aspect of conveying opinions, demonstrating that the learning intervention effectively encouraged students to articulate their ideas. The subsequent most significant impact was observed in the accuracy and speed of responses to spontaneous questions (0.8), indicating an enhanced understanding of rotational dynamics. An improvement of 0.7 was noted in students' attentiveness to the lesson, reflecting a positive contribution to maintaining focus. The aspects of collaboration within groups and project activities could not be compared with the control class, as the control class did not engage in PjBL within study groups.

The activity values for both classes, by observed aspect, are shown in Figure 5 (in percentages). Overall, the results indicate that PjBL with an inquiry approach increased student activity in class. For students' attention to the lesson, accuracy, speed in answering spontaneous questions, and conveying opinions, the differences between the experimental and control classes were 20%, 5%, 21%, and 21%, respectively. The smallest difference occurred in accuracy and speed when answering spontaneous questions. The overall activity percentage across aspects was 75% for the experimental class and 57% for the control class.

Table 2. Student activity observation

Aspect	Experiment class	Control class
1	3,3,4,4,3,3,3,3,3,2,2,4,4, 3,4,3,3,2,3,1,2,4,4,2,3,2	2,2,3,4,4,3,2,1,1,4,3,1,4,1,1, 4,2,1,1,1,1,1,3,3,2,1,3,2,2
2	3,4,4,3,4,3,4,4,4,2,3,4,4, 4,4,2,3,3,4,4,1,2,4,2,4,2	-
3	4,4,4,4,2,2,4,3,4,1,4,4,4, 4,4,3,3,2,3,4,1,3,4,1,4,1	-
4	1,4,4,4,4,2,3,3,2,1,2,4,3, 3,4,3,4,1,3,1,1,3,3,1,2,1	2,1,1,4,3,3,3,1,1,3,2,1,4,2,2, 4,3,1,1,1,2,2,3,3,4,3,4,3,2
5	2,3,4,4,4,2,4,3,1,4,3,4,4, 4,2,4,4,3,4,2,2,2,3,2,4,2	3,1,2,4,3,4,2,1,1,3,2,1,3,1,2, 4,4,1,1,1,3,3,2,4,3,2,1,1,2

In this study, five science process skills were assessed using an assessment rubric and a Likert scale: designing projects, using tools and materials, planning and conducting experiments (including controlling variables), interpreting data, and communicating results. The results for each group are displayed in Figure 6.

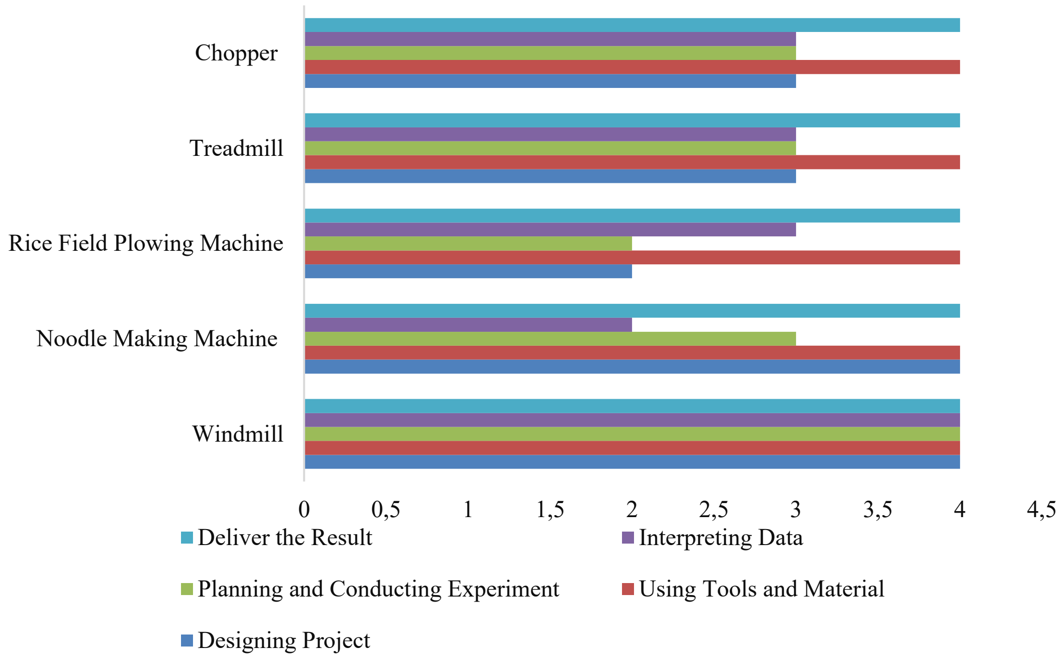

Figure 6. Science process skills

The mean scores for each skill were as follows: 3.2 for designing projects, 4.0 for utilizing tools and materials, 3.0 for planning and executing experiments (including variable control), 3.0 for data interpretation, and 4.0 for communicating results. The inquiry-based approach was incorporated within PjBL to facilitate students in understanding the concepts of torque, the relationship between torque and angular acceleration, moment of inertia, gear connections, and rotational kinetic energy. An analysis of students' mastery of these concepts in the experimental cohort was derived from post-test results, as depicted in Figure 6.

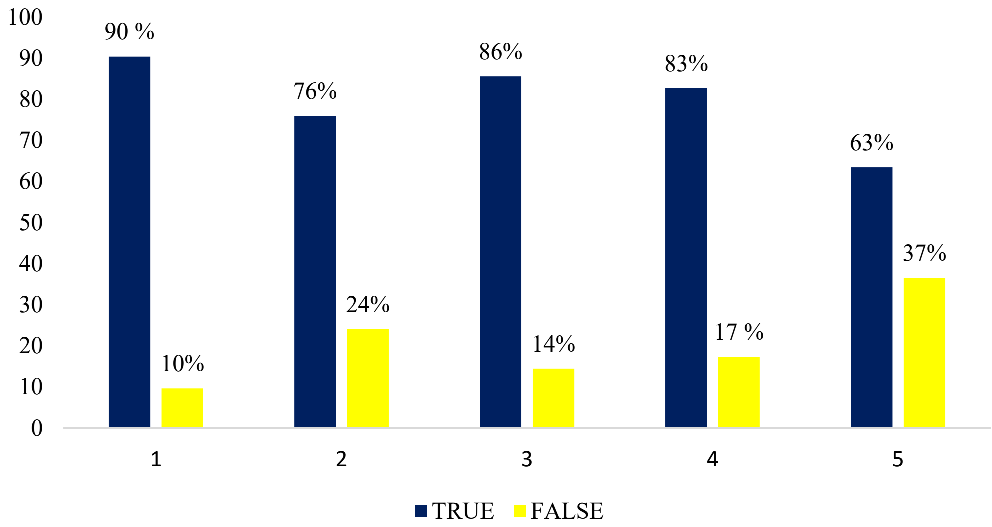

Figure 6. Ratio true and false for each aspect

Figure 6 illustrates the ratio of correct (TRUE) to incorrect (FALSE) responses across five evaluated facets of rotational dynamics. The percentages of correct responses are as follows: aspect 1 (torque) at 90%, aspect 2 (the relationship between torque and angular acceleration) at 76%, aspect 3 (moment of inertia) at 86%, aspect 4 (gear connection) at 83%, and aspect 5 (rotational kinetic energy) at 63%. These findings suggest that students' comprehension of the concepts varied among the evaluated aspects.

Table 3. Learning outcome categories

Test score range	Categories
00–59	Very low
60–69	Low
70–79	Medium
80–89	High
90–100	Very ligh

Table 3 categorizes learning outcomes into five achievement levels based on score ranges: very low (00–59), low (60–69), medium (70–79), high (80–89), and very high (90–100). This categorization is employed to interpret the levels of concept mastery depicted in Figure 6 in a standardized and systematic manner. Referring to Figure 6 and the learning outcome categories in Table 3, the concept with the highest mastery is torque (90%), which is classified within the very high category. Mastery of the moment of inertia (86%) and gear connection (83%) is designated as high. The relationship between torque and angular acceleration (76%) is categorized as medium, whereas rotational kinetic energy (63%) is classified as low.

The differences in mastery levels may be affected by the relative difficulty of each concept. For example, rotational kinetic energy often requires combining multiple prerequisite ideas (such as torque, angular motion, and inertia) along with stronger quantitative reasoning, which could explain the lower performance. Overall mastery is about 80%, which is considered high, indicating that using an inquiry approach within PjBL has positively supported students' understanding of rotational dynamics concepts.

Table 5. Analysis of creative thinking ability in an experimental class

No	Pretest score	Posttest score	N-gain score
1	25	70	0.60
2	25	85	0.80
3	20	85	0.81
4	20	80	0.75
5	30	80	0.71
6	10	75	0.72
7	15	80	0.76
8	15	85	0.82
9	35	80	0.69
10	10	70	0.67
11	15	75	0.71
12	15	85	0.82
13	20	85	0.81
14	25	85	0.80
15	20	90	0.87
16	25	75	0.67
17	30	85	0.79
18	35	75	0.62
19	30	75	0.64
20	25	70	0.60
21	15	75	0.71
22	15	85	0.82
23	10	90	0.89
24	5	85	0.84
25	10	70	0.67
26	15	75	0.71
Average	**19.8**	**79.6**	**0.74**

Table 5 displays the pretest, posttest, and N-gain scores of 26 students in the experimental group who participated in PjBL with an inquiry approach using simple materials. The average pretest score was 19.8, while the average posttest score rose to 79.6. The mean N-gain of 0.74 indicates significant improvement in students' cognitive achievement, reflecting a considerable proportional increase from the initial (pretest) to the final (posttest) assessment. Overall, the data reveal that most students consistently improved after the intervention, with individual N-gain values mostly falling within the medium-to-high range.

Table 6. Analysis of creative thinking ability in the control class

No	Pretest score	Posttest score	N-gain score
1	20	65	0.56
2	25	70	0.60
3	15	65	0.59
4	10	85	0.83
5	30	80	0.71
6	35	75	0.62
7	30	85	0.79
8	25	80	0.73
9	25	75	0.67
10	15	70	0.65
11	25	65	0.53
12	15	65	0.59
13	20	80	0.75
14	15	75	0.71
15	15	65	0.59
16	20	90	0.90
17	25	85	0.80
18	35	70	0.54
19	25	65	0.53
20	30	70	0.57
21	15	70	0.65
22	5	70	0.68
23	10	70	0.67
24	5	90	0.89
25	10	80	0.78
26	10	75	0.72
27	15	70	0.65
28	25	70	0.60
29	20	70	0.62
Average	**19.7**	**73.9**	**0.67**

Table 6 shows the pretest, posttest, and N-gain results of 29 students in the control class who learned using a traditional teaching method. The average pretest score was 19.7, and the average posttest score increased to 73.9. The mean N-gain of 0.67 indicates that learning outcomes improved; however, the level of improvement was less than that of the experimental class. Although the control group also made progress, the proportional gain from pretest to posttest was not as significant as in the experimental group, suggesting that the experimental intervention provided additional benefits to students' cognitive achievement.

The comparison of cognitive learning outcomes between the two classes is reflected in both the mean scores and the N-gain values. The experimental class achieved a mean post-test score of 79.6, whereas the control class attained 73.9, resulting in a difference of approximately 7.7%

(73.9 → 79.6). Furthermore, the experimental class demonstrated a higher N-gain value of 0.74 compared to the control class, which recorded 0.67. These findings affirm that the implementation of an inquiry-based approach within PjBL utilizing simple materials was more effective than traditional instruction in enhancing cognitive learning outcomes related to rotational dynamics. Although the disparity in post-test means is modest, the pattern of improvement indicated by the N-gain values substantiates the conclusion that the intervention exerted a positive influence. Based on the categorization of N-gain effectiveness, the intervention may be regarded as efficacious in improving students' cognitive learning outcomes.

IV. DISCUSSION

The findings of this study indicate that implementing PjBL integrated with an inquiry-based approach positively influenced students' learning motivation, classroom activity, science process skills, creative thinking, and cognitive learning outcomes in rotational dynamics. Although the improvement in cognitive achievement between the experimental and control classes was relatively moderate (7.7%), the results still demonstrate the instructional value of inquiry-oriented projects, particularly when learning resources are limited, and instruction relies on simple and recycled materials.

From a theoretical standpoint, these outcomes align with fundamental principles of inquiry-based learning, which emphasize that students develop understanding through active knowledge construction—questioning, exploring, experimenting, analyzing evidence, and reflecting on results. During the project activities, students designed and built functional models of gear applications and were required to connect observable changes in their models with abstract physics concepts such as torque, moment of inertia, angular acceleration, and rotational kinetic energy. Such experiences are consistent with a constructivist view of learning, in which conceptual understanding is strengthened when learners interact with concrete phenomena and negotiate meaning through collaboration. In this study, inquiry tasks embedded in the project appear to have shifted students from passive reception to active investigation, as reflected in improved activity and science process skills.

The PjBL framework also supports cognitive engagement by placing learning within authentic and meaningful tasks. Students were not merely asked to solve textbook problems; instead, they had to plan, design, test, revise, and communicate their solutions by creating prototypes. This process demands sustained attention, decision-making, and justification of ideas, which are closely associated with higher-order thinking. The high performance in the observed aspect of conveying opinions (0.9) suggests that the learning environment successfully encouraged students to articulate reasoning and share ideas, which are important features of student-centered instruction. In addition, increased classroom activity indicates that the project context promoted learner autonomy and participation, both of which are often linked to deeper engagement in science learning.

These findings are consistent with several prior studies reporting that inquiry-oriented and project-based environments can enhance conceptual understanding and scientific competencies when learning is appropriately scaffolded. Belland et al. (2017) synthesized empirical research on computer-based scaffolding in STEM education and reported that structured scaffolds can support learners' performance and learning outcomes. Similarly, Zhang and Ma (2023) concluded in their meta-analysis that inquiry-based learning positively contributes to students' academic achievement, affective attitudes, and thinking skills. In the context of physics education, Sari et al. (2018) and Gunawan et al. (2020) reported that inquiry-based and project-based models, particularly those supported by hands-on activities, improve conceptual mastery and scientific skills. Kokotsaki and Wiggins (2016) further noted that PjBL fosters motivation and engagement, which are key factors that can facilitate cognitive achievement. Meta-analytic findings also show that PjBL tends to outperform traditional instruction in terms of academic achievement (Chen & Yang, 2019; Masita, 2021; Nashiroh et al., 2020).

At the same time, the moderate difference in cognitive outcomes observed in this study is also consistent with the literature, suggesting that cognitive gains from inquiry and project-based approaches may not always be large in short-term implementations. de Jong et al. (2021) emphasized that designing and implementing digital inquiry learning materials is demanding and that learning benefits depend on well-aligned scaffolds and sufficient time for reflection and consolidation. In the present study, several factors may explain why the cognitive improvement, although positive, was not substantially higher.

First, rotational dynamics is conceptually demanding and often requires integration of multiple related ideas. The results show lower mastery of rotational kinetic energy than of torque or moment of inertia, suggesting that students may have needed additional time or repeated inquiry cycles to connect experimental observations to more abstract representations. Concepts involving energy typically require students to coordinate qualitative understanding with mathematical relationships and system-level reasoning, which may not fully develop within a single project cycle.

Second, the duration of the intervention may have limited the depth of conceptual change. Inquiry-based PjBL generally requires extended instructional time for iterative experimentation, revising designs, and reflective discussion. When time is limited, students may prioritize completing the physical product over engaging in deeper conceptual reasoning. Therefore, longer exposure combined with structured reflection sessions may be necessary to maximize cognitive learning outcomes in future implementations.

Third, students' prior learning experiences may influence the extent to which they benefit from inquiry-based projects. Learners accustomed to teacher-centered instruction may initially interpret project work as a production task rather than a conceptual inquiry task. This may lead them to focus on assembling prototypes while only superficially engaging with underlying physics principles. This challenge aligns with evidence summarized by Lazonder and Harmsen (2016), who found that inquiry-based learning is more effective when learners receive adequate guidance. While the present study used guiding questions, stronger scaffolding, such as worked examples, concept mapping, or structured checkpoints for explanation, may further help students connect project activities with formal conceptual understanding.

Despite these limitations, the results provide important pedagogical implications. The substantial improvements in motivation, classroom activity, science process skills, and creative thinking suggest that inquiry-based PjBL contributes to holistic learning development, not only to test performance. These competencies are central to scientific literacy and are increasingly emphasized in 21st-century education, where students are expected to communicate ideas, collaborate, solve problems, and think creatively. Thus, even when immediate cognitive gains are moderate, the broader learning benefits may support sustained conceptual growth over time.

Overall, this study supports integrating inquiry-based learning within a project-based framework as a meaningful strategy for teaching physics concepts, especially in contexts with limited laboratory facilities. To further enhance cognitive outcomes, future practice should incorporate stronger instructional scaffolding (Belland et al., 2017; Zacharia et al., 2015), explicit reflection and discussion of core concepts, and longer implementation durations. In summary, inquiry-based project learning may not always yield large short-term gains in cognitive scores, but it plays a crucial role in strengthening students' engagement, scientific reasoning, and creative capacities, which form the foundation for deeper and more durable conceptual understanding.

V. CONCLUSION AND SUGGESTION

The findings of this study show that integrating PjBL with an inquiry-based approach is effective for teaching rotational dynamics in physics. The intervention improved students' learning motivation and engagement, reflected in a positive response rate of 73%. It also increased classroom activity from 57% to 75% and strengthened students' science process skills during learning. In addition, the experimental class demonstrated higher cognitive learning outcomes than the control class (79.6 vs. 73.9), representing a 7.7% improvement. The N-gain value of 0.74

further indicates that the inquiry-based PjBL treatment was effective in supporting students' cognitive achievement, even when the learning projects relied on simple, recycled materials rather than on complete laboratory equipment.

Despite these positive results, this study has several limitations. First, the quasi-experimental design and the relatively small sample size in a single-school setting may limit the extent to which the findings generalize to broader populations. Second, the length of the intervention may not have been sufficient to achieve maximal conceptual gains, especially for complex topics like rotational kinetic energy, which showed lower mastery than other concepts. Future research should explore the long-term effects of inquiry-based PjBL on conceptual retention and higher-order thinking skills, test the model across different physics topics and educational levels, and compare outcomes over longer implementation periods. Additional studies are also needed to see how more robust scaffolding (for example, structured reflection sessions) or integration with digital or virtual laboratory tools could improve understanding. Overall, this study adds to physics education by showing that inquiry-based project learning can enhance both cognitive and process skills and offers a practical teaching approach for schools with limited laboratory resources.

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