

Development Of A Stem-Based Multi-Role Project (Mrp) Model To Enhance 21st-Century Skills In Integrated Science Learning At Junior High Schools

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Abstract: This study aimed to develop a STEM-based Multi-Role Project (MRP) learning model to enhance 21st-century skills in integrated science instruction at the junior high school level. The need for innovative instructional models is increasingly crucial to address gaps in creativity, collaboration, critical thinking, and problem-solving competencies among students. A design-based research methodology was applied through iterative development, expert review, and classroom trials of the STEM-based MRP model. Its effectiveness was evaluated using a quasi-experimental pretest-posttest control group design with 96 eighth-grade students. The experimental group used the MRP-STEM learning design, while the control group received conventional instruction. Data were obtained from 21st-century skills assessments, learning outcome tests, classroom observations, and response questionnaires. Expert validation demonstrated that the model met “very valid” criteria in content, construct, and technical components (average validity score: 0.92). Classroom trials revealed high practicality, as evidenced by positive teacher responses (91.2%) and student responses (89.7%). Effectiveness results indicated significant improvement in students’ 21st-century skills, with N-Gain scores in the moderate-to-high category (0.47–0.72). Learning outcomes also increased significantly across multiple learning cycles ($p < 0.05$). The STEM-based MRP model is valid, practical, and effective for improving 21st-century skills in integrated science learning. The model is appropriate for supporting competency-based curricula and strengthening STEM integration in Indonesian junior high schools.

Keywords: STEM education; Multi-role project; 21st-century skills; integrated science; instructional development.

I. INTRODUCTION

The accelerating shift toward the Industrial Revolution 4.0 and Society 5.0 has reshaped global educational landscapes, emphasizing the need for learners to master essential twenty-first-century competencies such as critical thinking, creativity, collaboration, and communication (4C). These competencies are critical for enabling students to adapt to rapid technological changes, engage in scientific reasoning, and solve complex real-world problems. In science education, strengthening scientific literacy and higher-order thinking skills is increasingly recognized as fundamental to preparing students for future demands (1–3).

Despite national curriculum reforms, science learning in Indonesia remains below international benchmarks. Global assessments consistently show that Indonesian students demonstrate low levels of scientific literacy and struggle with analytical and inquiry-based tasks. Classroom practices largely remain teacher-centered, emphasizing

memorization rather than conceptual understanding or authentic investigation (4,5). Although Project-Based Learning (PjBL) is promoted within the national curriculum, its implementation in schools is often limited by insufficient assessment tools, weak interdisciplinary integration, and challenges in monitoring individual contributions within group work (6,7). As a consequence, many students can't fully engage in collaborative learning, and disparities in participation persist during group projects.

Integrating STEM (Science, Technology, Engineering, and Mathematics) into project-based learning has been widely reported to enhance conceptual understanding, engagement, and problem-solving skills (8–10). However, STEM-based PjBL implementations frequently lack structured role distribution, resulting in some students dominating the work while others participate minimally. Research highlights that clear collaborative structures and role assignment are essential for promoting accountability, improving communication, and ensuring equitable learning opportunities (11–13). Without these structures, group projects often fail to develop the full spectrum of 4C competencies.

Addressing these challenges requires the development of a more systematic, comprehensive, and student-centered instructional model. The Project-Based Learning Multi-Role Project based on STEM (PjBL-MRP-STEM) model integrates the authentic processes of PjBL (14), deliberate multi-role assignment to ensure accountability and balanced participation (15,16), and interdisciplinary STEM approaches that promote real-world problem solving (17,18). This model ensures that every learner contributes meaningfully to the project, facilitates deeper understanding of scientific concepts, and strengthens collaborative, creative, and communicative capacities essential for the twenty-first century.

Given the demands of modern education and the persistent challenges observed in science classrooms, the development and validation of the PjBL-MRP-STEM model represent a significant contribution to improving the quality of science learning. It aligns teaching practices with curriculum expectations, elevates students' scientific literacy, and supports the holistic development of 4C competencies through authentic, project-driven inquiry (19,20).

II. METHODE

A. Research Design

This study employed a Research and Development (RnD) methodology to systematically develop, refine, and evaluate the Project-Based Learning Multi-Role Project integrated with STEM (PjBL-MRP-STEM) model for Integrated Science instruction at the junior high school level. RnD is widely recognized for its ability to support iterative cycles of innovation development in real educational contexts, enabling researchers to bridge the gap between theory and practice through a structured process of design, implementation, analysis, and redesign (21,22).

The development framework adopted Plomp's three-phase model, which consists of preliminary research, prototyping, and assessment, a model frequently used in educational technology and instructional model development due to its iterative and formative nature (23,24). The study also incorporated a quasi-experimental design with a non-equivalent control group to evaluate the model's effectiveness, a design that is commonly used in educational intervention research to compare learning outcomes between treatment and control groups when random assignment is not feasible (25,26).

B. Research Setting and Participants

The research was conducted in public junior high schools in Sawahlunto, Indonesia, and participants were selected using purposive sampling to ensure alignment between instructional needs and research objectives (27). Participants included three science

teachers and nine students during the preliminary and small-group stages, while field testing involved intact classes of approximately 30 students each in Grades VII, VIII, and IX.

Prior to the intervention, equivalence between the experimental and control groups was established through pretesting of 4C competencies (critical thinking, creativity, collaboration, and communication), and statistical tests indicated no significant differences between groups, confirming baseline comparability (28). The development of the PjBL-MRP-STEM model followed a structured process beginning with a comprehensive needs analysis, curriculum examination, and review of existing literature on PBL, STEM, and role-based collaborative learning. These analyses revealed challenges related to student engagement, group accountability, and limited interdisciplinary integration—issues also documented in prior research on STEM-based project learning (29).

C. Model Development Procedures

1. Preliminary Research Phase

During the preliminary stage, needs analysis, curriculum examination, and literature review were conducted to develop the theoretical and practical foundation of the model.

2. Prototyping Phase

During the prototyping phase, the initial model was translated into instructional materials, including teacher guidebooks, student project books, STEM project tasks, multi-role collaboration guidelines, and 4C assessment rubrics. The model emphasized explicit role distribution (engineer, analyst, designer, communicator) to promote accountability and reduce free-rider behavior; a structure supported by research on collaborative learning dynamics (16). Expert validation was conducted with eight specialists in science education, pedagogy, and assessment using a validated rubric to evaluate content validity, construct validity, practicality, and linguistic clarity. Revisions were incorporated iteratively, informing the development of Prototype 2 and subsequently Prototype 3 following small-group and one-to-one evaluations with teachers and students. This iterative refinement aligns with best practices in DBR, where expert consultation and user feedback are key mechanisms for improving instructional design effectiveness (30).

3. Assessment Phase

The assessment phase involved a full classroom implementation of the model using a pretest–posttest control group design across three project cycles, each integrating STEM inquiry, engineering design, prototyping, and structured communication tasks. Projects included water filtration engineering (Grade VII), plant technology and hydroponics (Grade VIII), and traditional biotechnology through fermentation (Grade IX). Data collection instruments included a validated 4C competency test, a structured classroom observation protocol, practicality questionnaires, semi-structured interviews, and project product rubrics. Observation protocols focused on teacher facilitation, student engagement, role execution, STEM integration, and fidelity of implementation, with inter-rater reliability exceeding 85%, which meets recommended standards for observational research in STEM education (31).

D. Data Analysis Procedures

Quantitative data were analyzed using descriptive statistics, normalized gain scores, paired and independent t-tests, ANOVA, and Cohen's d effect size to assess the magnitude of the intervention's impact. These statistical procedures are widely used in evaluating

educational interventions where the goal is to capture both significance and practical effectiveness (32,33). Qualitative data from interviews, reflections, and observations were analyzed using thematic coding through a six-step process, supported by triangulation, peer debriefing, and audit trails to enhance trustworthiness. This mixed-methods integration enabled a deeper understanding of how and why the PjBL-MRP-STEM model influenced student learning processes, consistent with convergent parallel mixed-methods designs recommended in contemporary educational research (34,35).

E. Ethical Considerations

Ethical considerations were strictly observed. All participants and school authorities provided informed consent, participation was voluntary, data confidentiality was maintained, and procedures adhered to institutional and national research ethics guidelines. Ethical compliance ensured transparency, safety, and research integrity throughout the study, consistent with international standards for human-participant research (36).

III. RESULTS

A. Model Validity

To ensure the feasibility and quality of the developed instructional materials, the PjBL-MRP-STEM products—comprising the Model Book, Teacher Guide, and Student Book—were evaluated by expert reviewers in content, language, and visual design. The validation process focused on relevance to curriculum standards, conceptual accuracy, clarity of explanation, linguistic readability, and usability in classroom implementation. In addition to the validity assessment, the reliability of expert judgments was examined using the Intraclass Correlation Coefficient (ICC). A summary of the validity and reliability results is presented in Table 1.

TABLE 1. Summary of Product Validation and Reliability of PjBL-MRP-STEM Learning Materials

Product	Expert Group	Mean Validity (Aiken's V)	Category	ICC	Reliability Category	Overall Validation Score
Model Book	Content	0.89	Very High	0.74	Moderate-High	0.89 (Very High)
	Language	0.91	Very High	0.76	Moderate-High	
	Design	0.75–1.00	High–Very High	–	High (internal)	
Teacher Guide	Content	0.86	Very High	0.75	Moderate-High	0.86 (Very High)
	Language	0.87	Very High	0.83	High	
	Design	0.75–1.00	High–Very High	–	High (internal)	
Student Book	Content	0.88	Very High	0.88	High	0.88 (Very High)
	Language	0.86–0.88	Very High	0.84	High	
	Design	0.75–1.00	High–Very High	–	High (internal)	

NOTE. Validity scale: 1.00–1.80 = Very Low; 1.81–2.60 = Low; 2.61–3.40 = Moderate; 3.41–4.20 = High; 4.21–5.00 = Very High. Reliability interpretation (ICC): <0.50 = Poor; 0.50–0.74 = Moderate; 0.75–0.90 = High; >0.90 = Very High (Koo & Li, 2016; Nasiri et al., 2023).

Reliability testing using the Intraclass Correlation Coefficient (ICC) revealed moderate–high consistency among material and language experts (0.74–0.88) and high consistency for design experts. These findings confirm that the assessment indicators were valid and consistently applied.

To ensure that the data collected in the development and implementation of the PjBL-MRP-STEM model were valid and trustworthy, all research instruments used in the needs assessment, practicality test, and effectiveness evaluation underwent expert validation. The assessment involved specialists in STEM education, instructional evaluation, and learning assessment, focusing on content relevance, linguistic clarity, construct representation, and applicability for classroom use. The summary of the instrument validation results is presented in Table 2.

TABLE 2. Summary of Instrument Validity for the PjBL-MRP-STEM Research

Instrument Category	Method	Validity Score	Category
Needs analysis questionnaires	Aiken's V	0.92–0.93	Very High
Teacher & student practicality questionnaires	Aiken's V	0.90–0.94	Very High
Self-evaluation & interview protocols	Cohen's Kappa	0.89	Very High
21st-century skills performance rubrics (4C)	Aiken's V	0.89–0.94	Very High

NOTE. Validity scale: Aiken's V ≥ 0.80 = Very High; Cohen's Kappa ≥ 0.81 = Strong Agreement.

B. Model Practicality

Practicality was examined through three stages: one-to-one evaluation, small-group evaluation, and field testing.

C. One-to-One Evaluation

Three students—representing high, medium, and low academic ability—provided feedback indicating that:

- High-achieving students understood the content clearly and suggested adding digital media features.
- Medium-achieving students requested simplification of scientific terminology.
- Low-achieving students required more visual support and simplified instructions.

Revisions were made to the language, clarity of technical instructions, and inclusion of additional visual media.

D. Small Group Evaluation

Teachers reported that the model syntax was clear and easy to implement, while students found the Student Book engaging, easy to follow, and relevant to real-world project activities. Table 3 provides a concise summary of teacher and student feedback during the small-group evaluation.

TABLE 3. Summary of Practicality in Small Group Evaluation

Aspect	Teacher	Student
Syntax	Clear	Easy to follow
Roles	Effective	Increases responsibility
Media	Adequate	Attractive
Motivation	High	Very High

NOTE. Higher ratings indicate stronger clarity, relevance, and usability of the instructional components during the small-group evaluation.

E. Field Test

The field test confirmed the high practicality of the PjBL-MRP-STEM model in classroom implementation. Practicality ratings from teachers (0.90) and students (0.93) were classified as Very High, and classroom observations yielded a score of 3.71 (Very Good), indicating strong student engagement and active participation throughout the learning process.

F. Model Effectiveness

Effectiveness was examined by comparing experimental and control classes across Grades VII, VIII, and IX. Four components of 21st Century Skills (4C)—Critical Thinking, Creativity, Collaboration, and Communication—served as the main indicators.

G. Distribution of 4C Performance

Table 4 presents the distribution of 4C skill categories in the experimental and control groups, illustrating differences in students' achievement levels across Critical Thinking, Creativity, Collaboration, and Communication.

TABLE 4. Summary of 4C Categories (Experimental vs. Control)

Skill	Experimental		Control	
CT	89.53%	high-very high	67.44%	medium
CR	88.38%	high-very high	66.67%	medium
COL	93.03%	high-very high	65.12%	medium
COM	90.70%	high-very high	66.67%	medium

NOTE. CT = Critical Thinking, CR = Creativity, COL = Collaboration, and COM = Communication. Category classification: $\leq 59\%$ = Low; 60–74% = Medium; 75–89% = High; $\geq 90\%$ = Very High. Percentages represent the proportion of students achieving each competency level in both groups.

H. Pretest-Posttest Improvement

The PjBL-MRP-STEM model produced significant improvements across all grade levels. The experimental classes showed increases of +31–35 points, while control classes improved only +11–17 points. Table 5 displays mean pretest, posttest, and improvement scores for both experimental and control classes.

TABLE 5. Mean Pretest and Posttest Scores

Class	Pretest	Posttest	Gain
7.1 (Exp)	49.4	81.0	+31.6
7.2 (Ctrl)	49.8	66.6	+16.8

8.1 (Exp)	49.3	80.8	+31.5
8.3 (Ctrl)	47.3	64.2	+16.9
9.1 (Exp)	49.4	84.8	+35.4
9.3 (Ctrl)	49.3	60.8	+11.5

NOTE. Gain = Posttest – Pretest. Gains ≥ 30 indicate strong improvement; gains < 20 indicate limited improvement.

I. N-Gain Analysis

To further examine the consistency of learning gains across grade levels, the N-Gain scores for Critical Thinking, Creativity, Collaboration, and Communication were analyzed for each class. These results provide a detailed comparison of learning improvement between experimental and control groups participating in different project implementations. Table 6 summarizes the mean scores, sample sizes, and standard deviations for each competency across Grades 7, 8, and 9.

TABLE 6. N-Gain Scores of 21st-Century Competencies Across Grade Levels

Report					
Kelas		N-Gain Critical Thinking	N-Gain Creativity	N-Gain Collaboration	N-Gain Communication
7.1	Mean	.6871	.5544	.6058	.5995
	N	29	29	29	29
	Std. Deviation	.18163	.20082	.17439	.21845
7.2	Mean	.3493	.3605	.3177	.3202
	N	29	29	29	29
	Std. Deviation	.18014	.17388	.18096	.20362
8.1	Mean	.6595	.5730	.6385	.5934
	N	27	27	27	27
	Std. Deviation	.15317	.20841	.13934	.19824
8.3	Mean	.3184	.3378	.3138	.2922
	N	27	27	27	27
	Std. Deviation	.16420	.15010	.12885	.15677
9.1	Mean	.6939	.6589	.7432	.6826
	N	30	30	30	30
	Std. Deviation	.16752	.09451	.12795	.13485
9.3	Mean	.4894	.2787	.3488	.2652
	N	30	30	30	30
	Std. Deviation	.20545	.14669	.18497	.20731
Total	Mean	.5346	.4608	.4957	.4594
	N	172	172	172	172
	Std. Deviation	.23392	.21684	.23411	.25278

Note. N-Gain interpretation: ≥ 0.70 = High; $0.30-0.69$ = Medium; < 0.30 = Low

J. Inferential Statistics

1. Normality and Homogeneity Tests

Normality tests (Shapiro–Wilk) confirmed that most data met the normal distribution assumption ($p > 0.05$). Homogeneity tests revealed that three variables (CT, COL, COM) met the homogeneity assumption, while Creativity (CR) did not.

2. Anova

To determine whether the differences in learning improvement between experimental and control classes were statistically significant, an ANOVA test was conducted for the N-Gain scores of the four competencies (Critical Thinking, Creativity, Collaboration, and Communication). The results are summarized in Table 7.

TABLE 7. One-Way ANOVA Results for 21st-Century Competencies Across Classes

		ANOVA				
		Sum of Squares	df	Mean Square	F	Sig.
N-Gain Critical Thinking	Between Groups	4.175	5	.835	26.755	.000
	Within Groups	5.181	166	.031		
	Total	9.357	171			
N-Gain Creativity	Between Groups	3.467	5	.693	25.162	.000
	Within Groups	4.574	166	.028		
	Total	8.040	171			
N-Gain Collaboration	Between Groups	5.200	5	1.040	41.386	.000
	Within Groups	4.172	166	.025		
	Total	9.372	171			
N-Gain Communication	Between Groups	4.995	5	.999	27.960	.000
	Within Groups	5.932	166	.036		
	Total	10.927	171			

Note. All competencies show significant differences between groups ($p < .05$)

3. Kruskal–Wallis (Creativity)

The Kruskal–Wallis test revealed a significant difference in students' Creativity scores across the classes ($p < 0.001$). The highest mean rank was obtained by Class 9.1 (135.93), indicating superior improvement in creative performance, whereas Class 9.3 showed the lowest mean rank (43.85), suggesting comparatively limited enhancement.

4. Independent Samples t-test and

To test the effectiveness of the PjBL–MRP–STEM model in improving 21st-century student competencies, an independent sample t-test was conducted at three grade levels (VII, VIII, and IX). This test compared the N-Gain scores of the experimental class receiving the PjBL–MRP–STEM intervention and the control class receiving conventional instruction. In addition, an effect size (Cohen's d) was calculated to measure the magnitude of the intervention's impact. The results are summarized in Table 8

TABLE 8. m Independent Samples t-Test Summary for N-Gain of 21st-Century Skills

Grade	Skill	Exp. Mean 	Ctrl. Mean 	t- value	df	Sig. (p) 	Cohen's d	Effect Size
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VII	CT	.6871	.3493	7.111	56	.000	1.89	Very Large
	CR	.5544	.3605	3.931	56	.000	1.05	Large
	COL	.6058	.3177	6.174	56	.000	1.64	Very Large
	COM	.5995	.3202	5.035	56	.000	1.34	Very Large
VIII	CT	.6595	.3184	7.892	52	.000	2.18	Very Large
	CR	.5730	.3378	4.759	52	.000	1.33	Very Large
	COL	.6385	.3138	8.891	52	.000	2.46	Very Large
	COM	.5934	.2922	6.192	52	.000	1.71	Very Large
IX	CT	.6939	.4894	4.225	58	.000	1.11	Large
	CR	.6589	.2787	11.934	58	.000	3.13	Very Large
	COL	.7432	.3488	9.606	58	.000	2.52	Very Large
	COM	.6826	.2652	9.243	58	.000	2.42	Very Large

NOTE. Effect size interpretation follows Cohen (1988): Small (0.20–0.49), Medium (0.50–0.79), Large (0.80–1.19), and Very Large (≥ 1.20). CT = Critical Thinking, CR = Creativity, COL = Collaboration, and COM = Communication. All comparisons reveal statistically significant improvement ($p < .05$) favoring the PjBL–MRP–STEM model.

The following figure presents the effect size trends of the PjBL–MRP–STEM model on students' 21st-century competencies (Critical Thinking, Creativity, Collaboration, and Communication) across Grades VII, VIII, and IX. The visualization shows that all competencies achieved large to very large effects, with the strongest impacts observed in Creativity and Collaboration, particularly in Grade IX. This pattern indicates that the influence of the model becomes more substantial at higher grade levels, where project complexity and students' ability to carry out role-based STEM tasks are more advanced.

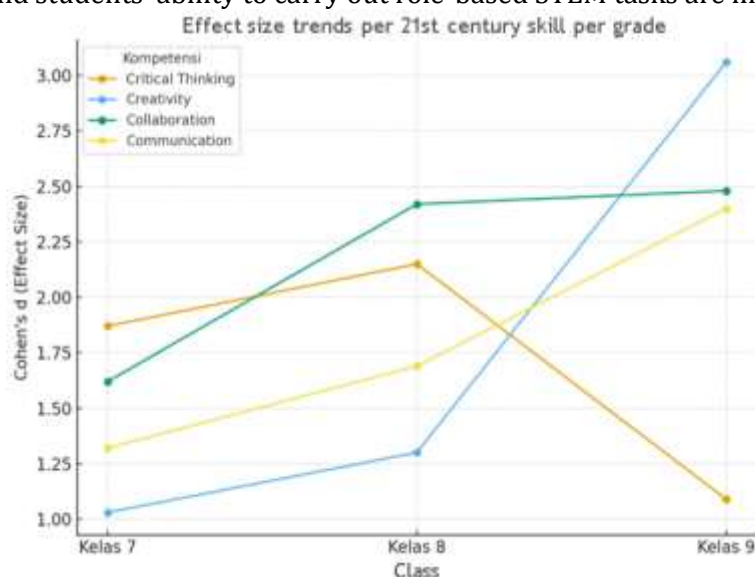


Fig 1. Trends in Effect Size of 21st Century Skills in Grades 7–9 Students

The results clearly show that the PjBL–MRP–STEM model produced consistently higher impacts across all skills and grade levels, with the strongest improvements in collaboration and creativity among Grade IX students.

K. Discussion

The findings of this study demonstrate that the STEM-based Multi-Role Project (MRP) model is effective in enhancing junior high school students' 21st-century competencies in

integrated science learning. The model fulfilled all development criteria—validity, practicality, and effectiveness—indicating its feasibility as a pedagogical innovation for strengthening STEM integration and student-centered learning in Indonesian secondary education.

1. *Validity of the STEM-Based Multi-Role Project Model*

The model's validity results, categorized as very high across content, construct, linguistic, and technical aspects, highlight the clarity, alignment, and theoretical soundness of its instructional design. The strong reliability of expert ratings, indicated by moderate-to-high ICC values, confirms consistency in expert judgments. This demonstrates that the framework is theoretically well-grounded in inquiry-based STEM learning, engineering design processes, and project-based pedagogy. These findings align with international research asserting that well-structured STEM-PBL models must provide clear interdisciplinary links and authentic problem-solving contexts to support higher-order learning outcomes(5,10,14).

2. *Practicality in Classroom Implementation*

Teacher and student responses indicated very high practicality, and classroom observations confirmed active engagement, indicating that the MRP structure is accessible for teachers and motivating for students. The explicit distribution of roles (e.g., designer, analyst, communicator, engineer) promoted accountability, reducing the typical "free rider" problem in group projects. Previous studies similarly emphasize that collaborative learning becomes more equitable and productive when roles are clearly assigned and monitored(37,38). Students' suggestions for simplified terminology and digital media enhancements also demonstrate their active engagement with the materials, supporting iterative refinement consistent with design-based research principles(30).

3. *Effectiveness in Enhancing 21st-Century Skills*

A consistent pattern of superior learning gains was observed in experimental groups across grade levels, particularly in Creativity, Collaboration, and Communication. N-Gain and effect size analyses confirm highly significant improvements, with very large effects ($d \geq 1.20$) across multiple competencies. The results corroborate prior evidence that STEM-based project learning fosters divergent thinking, scientific reasoning, and cooperation through design iteration, experimentation, and communal sense-making (11,19,39). The highest mean ranks in creativity found in Grade IX further suggest that older students benefit from advanced engineering-based design challenges, strengthening cognitive imagination and innovation through real-world problem-solving tasks.

4. *The Role of Multi-Role Distribution in Enhancing Collaboration*

The model's unique pedagogical contribution lies in its structured multi-role system, ensuring balanced participation among group members. This feature is rarely emphasized in traditional PjBL approaches and directly addresses participation inequality observed in previous studies (29). Assigning interdependent roles requires students to rely on one another to complete the project, fostering interdependent collaboration and communication. This supports socio-constructivist perspectives, particularly Vygotsky's notion that knowledge is constructed through socially mediated interaction and shared tasks (40).

5. *Implications for Science Education and Curriculum Implementation*

The results indicate that the PjBL-MRP-STEM model aligns with competency-based curricula by fostering literacy, reasoning, and problem-solving beyond content memorization. These competencies are crucial for addressing current gaps in Indonesian science education, especially deficiencies in inquiry skills and interdisciplinary reasoning reported in global assessments. The model's applicability to three different science project themes (water filtration, hydroponics, and biotechnology) demonstrates its flexibility and relevance to local contexts and science standards, further strengthening its curricular usability.

6. Limitations and Recommendations

Although effective, the model requires teachers to possess strong classroom management, familiarity with STEM inquiry, and ability to assess performance-based tasks. Future studies should evaluate teacher training frameworks for scalable implementation and investigate longitudinal impacts on scientific literacy and career readiness. Additionally, integrating digital design tools, online collaboration platforms, and assessment analytics may further optimize student engagement and performance monitoring.

IV. CONCLUSION

This research confirms that the STEM-based Multi-Role Project (MRP) model is a rigorously validated, highly practical, and strongly impactful instructional innovation for developing 21st-century competencies in junior high school integrated science learning. The model achieved very high validity across content, construct, and technical dimensions, indicating that its pedagogical foundations are conceptually robust and aligned with competency-based science curricula. Its high practicality scores demonstrate that both teachers and students can implement the model effectively, even within diverse school infrastructures and limited learning resources.

The model's effectiveness is evidenced by consistently large to very large effect sizes in critical thinking, creativity, collaboration, and communication across multiple grade levels. These results highlight the strategic value of structured multi-role distribution within STEM project tasks, which ensures equitable participation, promotes deep conceptual reasoning, and maximizes individual responsibility in group learning. The integration

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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