Contextual STEM Mathematical Modeling Using a Small Scale Savonius Wind Turbine for Public High School Education

Yayuk Badriatuz Zahroh[1a], Nuryazid Muhibah[2b], Moch. Kalam Mollah[3c], Fairus Atika Redanto Putri[3d], and Zain Lillahulhaq[3e]

SMAN 1 Kedungwaru[1], SMKN 2 Boyolangu[2], Institut Teknologi Adhi Tama Surabaya[3]

e-mail: yayukbadriatuzzahroh@18guru. sma.belajar .id[a], nuryazidmuhibah21@guru.smk.belajar.id[b] , kalam@itats.ac.id[c], fairus@itats.ac.id[d], zain@itats.ac.id[e]

ABSTRACT

This study develops a contextual STEM mathematical modeling framework using a small-scale Savonius wind turbine as an engineering context for public high school education. The framework structures the modeling process from a physical renewable-energy phenomenon to technological context, engineering parameters, mathematical formulation, numerical exploration, graphical representation, and contextual interpretation. A rotor diameter of 0.25 m and a height of 0.30 m were used to define a projected swept area of 0.075 m², while wind velocity was varied from 0.5 to 3.0 m/s. The resulting model, $P(V)=0.04594(V)^3$, illustrates how an engineering relationship can be transformed into a school-level cubic function and explored through calculations, ratios, tables, and graphs. The calculated available wind power increased from 0.0057 to 1.2403 W across the modeled range, illustrating the nonlinear effect of wind velocity. The contribution of the study lies in the structured integration of science, technology, engineering, and mathematics through a single modeling sequence rather than in proposing a new wind-power equation. The calculated values represent theoretical free-stream wind power, not actual turbine output, and the framework has not yet been evaluated through classroom intervention.

Keywords: *cubic function, mathematical modeling, renewable energy, Savonius wind turbine, STEM education.*

ABSTRAK

Penelitian ini mengembangkan kerangka pemodelan matematis STEM kontekstual dengan menggunakan turbin angin Savonius skala kecil sebagai konteks rekayasa untuk pendidikan sekolah menengah atas. Kerangka ini menyusun proses pemodelan mulai dari fenomena fisik energi terbarukan, konteks teknologi, parameter rekayasa, formulasi matematis, eksplorasi numerik, representasi grafik, hingga interpretasi kontekstual. Rotor berdiameter 0,25 m dan tinggi 0,30 m digunakan untuk menentukan luas sapuan sebesar 0,075 m², sedangkan kecepatan angin divariasikan dari 0,5 hingga 3,0 m/s. Model yang dihasilkan, ($P(V)=0{,}04594V^3$, menunjukkan bagaimana hubungan rekayasa dapat ditransformasikan menjadi fungsi kubik pada tingkat sekolah dan dieksplorasi melalui perhitungan, rasio, tabel, dan grafik. Daya angin tersedia yang dihitung meningkat dari 0,0057 menjadi 1,2403 W pada rentang pemodelan tersebut, yang menggambarkan pengaruh nonlinier kecepatan angin. Kontribusi penelitian ini terletak pada integrasi terstruktur antara sains, teknologi, rekayasa, dan matematika dalam satu rangkaian pemodelan, bukan pada pengusulan persamaan daya angin yang baru. Nilai yang dihitung merepresentasikan daya angin bebas secara teoretis, bukan keluaran aktual turbin, dan kerangka ini belum diuji melalui intervensi pembelajaran di kelas.

INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) education integrates disciplinary knowledge through problems connected to real phenomena and technological applications. Renewable energy is particularly suitable because it combines scientific principles, engineering parameters, technology, and quantitative reasoning. In Indonesian senior high schools, however, renewable energy learning is often conceptual or only partially integrated, while limitations in facilities, instructional resources, teacher readiness, time, and assessment may restrict more complex STEM activities [14], [20], [23]–[25].

Within integrated STEM, mathematics provides the quantitative language for translating physical phenomena into variables, functions, tables, graphs, and models. Engineering contexts are useful because measurable parameters can be transformed into mathematical representations without losing their physical meaning. This approach is consistent with contextual mathematics and Engineering Design Process frameworks that connect mathematical reasoning with authentic technical problems [15], [16], [21], [24], [25].

Renewable energy has been used in secondary STEM activities to support scientific creativity, multiliteracy, critical thinking, collaboration, and problem solving [17]–[20], [22], [24]. In Indonesia, Jamaludin et al. reported a windmill based STEM activity at SMA Negeri 57 Maluku Tengah [19]. These studies demonstrate the educational relevance of renewable energy, but most emphasize instructional implementation, project development, or learning outcomes rather than the explicit transformation of an engineering energy relationship into a structured mathematical modeling sequence.

ISSN 2775-5630

A small scale Savonius wind turbine provides a suitable engineering context for such modeling. The Savonius rotor is a drag based vertical axis wind turbine with relatively simple geometry, and contemporary research has largely focused on aerodynamic behavior, rotor geometry, numerical simulation, flow modification, and performance enhancement [1], [3]–[13]. For a rotor with diameter D and height H, the available wind power can be represented by $P_wind = 1/2\ \rho DHV^3$, where ρ is air density and V is wind velocity [2], [12]. When geometry and air density are fixed, the relationship reduces to the cubic form $P(V) = kV^3$. This transformation provides a mathematically accessible representation of a real renewable energy system without assuming measured turbine efficiency, torque, or rotational performance.

From an educational perspective, the value of the wind-power relationship is not limited to demonstrating that power varies cubically with wind velocity. More importantly, the relationship provides a pathway for translating an engineering system into a mathematical model. Rotor dimensions define the swept area, wind velocity becomes the independent variable, and available wind power becomes the dependent variable. These quantities can then be transformed into equations, numerical comparisons, ratios, tables, and graphs before being interpreted again within the original renewable-energy context.

Existing Savonius turbine studies primarily use mathematical and numerical models to investigate aerodynamic performance, rotor geometry, flow behavior, and performance enhancement [1]–[13]. In contrast, STEM education studies commonly employ renewable-energy contexts to support project-based learning, scientific creativity, multiliteracy, critical thinking, and other learning outcomes [14]–[25]. However, the connection between these two perspectives remains insufficiently articulated. In particular, limited attention has been given to explicitly structuring how measurable parameters of a real renewable-energy system can be translated into mathematical representations and then interpreted again in their engineering context at the public high school level.

Accordingly, this study develops a contextual STEM mathematical modeling framework using a small scale Savonius wind turbine as an engineering context. A rotor diameter of 0.25 m and height of 0.30 m are used, and wind velocities from 0.5 to 3.0 m/s are evaluated to demonstrate the cubic relationship between wind velocity and available wind power. The study focuses on mathematical formulation, numerical comparison, graphical interpretation, and STEM integration; it does not evaluate turbine aerodynamic performance or student learning outcomes.

METHOD

Research Design

This study employed deterministic mathematical modeling within a contextual STEM framework using a small scale Savonius wind turbine as the engineering context. The objective was to translate a fundamental wind energy relationship into a structured mathematical sequence for public high school education rather than to evaluate turbine aerodynamic performance. The procedure comprised four stages: definition of engineering parameters, formulation of the wind power model, numerical and graphical exploration, and contextual STEM interpretation. No wind tunnel, torque, rotational, or classroom measurements were conducted. Therefore, all calculated quantities are theoretical model based values.

Engineering Context and Model Parameters

The rotor was defined by diameter D = 0.25 m and height H = 0.30 m. Air density was assumed constant at 1.225 kg/m³, while wind velocity was varied from 0.5 to 3.0 m/s in 0.5 m/s increments. This range was selected solely for mathematical exploration and does not represent an experimentally validated operating or self-starting range of the Savonius turbine. Model parameters are summarized in Table 1.

Table 1. Parameters used in the mathematical model

Parameter	Symbol	Value
Rotor height	H	0.30 m
Rotor diameter	D	0.25 m
Swept area	A	0.075 m²
Air density	ρ	1.225 kg/m³
Wind velocity	V	0.5 to 3.0 m/s
Velocity interval	ΔV	0.5 m/s

Using the selected rotor dimensions, the projected swept area was calculated from

$$A = DH \tag{1}$$

The model was formulated under several simplifying assumptions. Air density was held constant at 1.225 kg/m³, rotor geometry was fixed at (D = 0.25) m and (H = 0.30) m, and wind velocity was treated as a prescribed free-stream input for mathematical exploration. Aerodynamic efficiency, power coefficient, torque, rotational speed, and electrical conversion were not included in the calculation. Consequently, the model estimates only the kinetic power available in the airflow across the projected rotor area and should not be interpreted as the mechanical shaft power or electrical output of the Savonius turbine.

Mathematical Modeling and Analysis

The available free-stream wind power was calculated using Eq. (2), where P_{wind} is the kinetic power available in the airflow, ρ is air density, A is the projected rotor swept area, and V is wind velocity [2], [12]. The equation is used here because the purpose of the model is to translate the Savonius rotor geometry and wind-energy relationship into an accessible mathematical representation, rather than to predict aerodynamic turbine performance. Therefore, P_{wind} represents the theoretical energy available in the airflow and not the power actually extracted by the rotor. [2], [12].

$$P_{\text{wind}} = 1/2\ \rho A V^3 \quad (2)$$

Substituting the fixed values of air density and swept area gives the principal mathematical model in Eq. (3).

$$P(V) = 0.04594V^3 \quad (3)$$

Wind velocity was treated as the independent variable and available wind power as the dependent variable. Equation (3) was evaluated for all six prescribed velocity conditions.

Because air density and swept area remain constant, the relative change in power between two wind velocity conditions can be evaluated using Eq. (4).

The ratio demonstrates that doubling wind velocity increases available power by a factor of eight, whereas tripling wind velocity increases it by a factor of 27.

$$P_2/P_1 = (V_2/V_1)^3 \quad (4)$$

Results were presented as numerical values, relative ratios, and a graph. Inferential statistical analysis was not applied because all values were deterministically generated from the governing equations.

Contextual STEM Mathematical Modeling Framework

The mathematical model was mapped to the four STEM domains. Science was represented by wind kinetic energy, technology by the Savonius turbine, engineering by rotor dimensions and swept area, and mathematics by area calculation, cubic functions, ratios, tables, and graphs [14]–[16]. The relationship among the modeling stages is summarized in Table 2.

The procedure followed five stages: identification of the physical phenomenon, introduction of the technological context, definition of engineering parameters, formulation and exploration of the mathematical model, and interpretation of the result within the original renewable energy context. The framework is intended as a mathematical modeling resource rather than a complete Engineering Design Process or a classroom effectiveness test.

Table 2. Contextual STEM mathematical modeling framework

Modeling Stage	STEM Domain	Learning and Mathematical Activity
Identify wind as an energy source	Science	Identify wind velocity and available energy
Introduce the Savonius turbine	Technology	Connect the model with renewable energy technology
Define D and H; calculate A = DH	Engineering and Mathematics	Apply geometry and numerical substitution
Formulate P_wind = 1/2 ρAV³	Science and Mathematics	Translate a physical relationship into an equation
Derive P(V) = 0.04594V³	Mathematics	Construct a cubic function
Calculate, compare, and plot	Mathematics	Evaluate values, ratios, and a nonlinear graph
Interpret the result	Integrated STEM	Relate mathematical behavior to renewable energy

The research procedure used to develop the contextual STEM mathematical modeling framework is illustrated in Fig. 1.

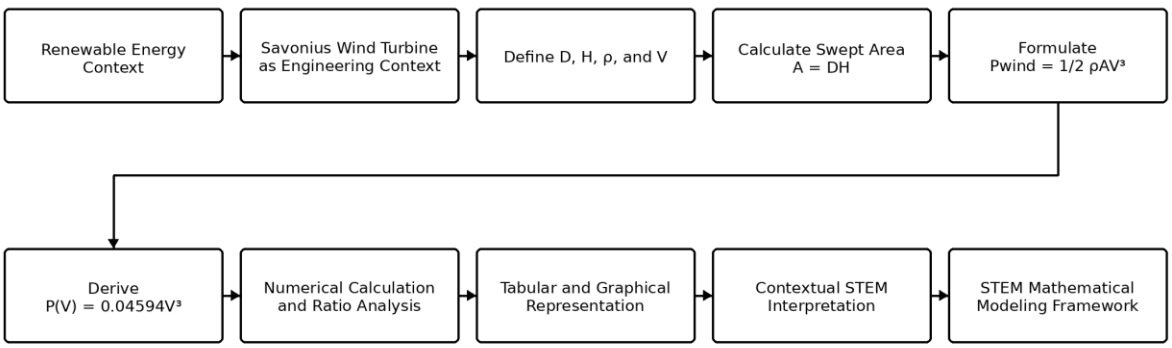

Fig. 1. Contextual STEM mathematical modeling procedure using the Savonius wind turbine as an engineering context.

RESULTS AND DISCUSSION

Mathematical Characteristics of the Savonius Wind Energy Context

The model was evaluated at wind velocities from 0.5 to 3.0 m/s using a constant swept area of 0.075 m² and air density of 1.225 kg/m³. Table 3 presents the calculated available wind power and its relative value with respect to V = 1.0 m/s.

ISSN 2775-5630

Table 3. Mathematical relationship between wind velocity and available wind power

V (m/s)	V^3	P_wind (W)	Relative power ($P/P_{(V=1)}$)
0.5	0.125	0.0057	0.125
1.0	1.000	0.0459	1.000
1.5	3.375	0.1550	3.375
2.0	8.000	0.3675	8.000
2.5	15.625	0.7177	15.625
3.0	27.000	1.2403	27.000

Available wind power increased from 0.0057 W at 0.5 m/s to 1.2403 W at 3.0 m/s (Table 3). The nonlinear trend follows directly from Eq. (3), in which wind velocity is raised to the third power.

As shown in Fig. 2, the curve becomes progressively steeper as wind velocity increases. This behavior is consistent with the fundamental free stream wind power formulation used in Savonius turbine analysis [2], [12].

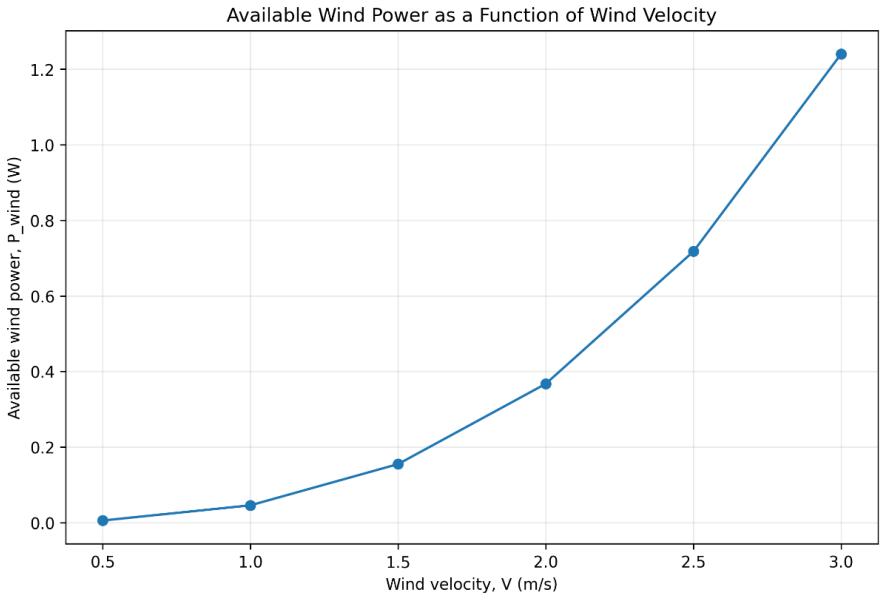

Fig. 2. Available wind power as a function of wind velocity.

The ratio analysis illustrates the cubic response. Doubling wind velocity from 1.0 to 2.0 m/s increases available power from 0.0459 to 0.3675 W, corresponding to a factor of eight. Tripling wind velocity from 1.0 to 3.0 m/s increases available power by a factor of 27. Across the complete modeled range, velocity increases by a factor of six while available power increases by a factor of 216. These comparisons demonstrate the difference between linear and cubic reasoning.

[The calculated values in Table 3 and Fig. 2 should be interpreted strictly as theoretical free-stream wind power rather than as Savonius turbine output. A real turbine extracts only part of the kinetic energy available in the airflow, and its mechanical performance additionally depends on factors such as the power coefficient, aerodynamic torque, rotational speed, rotor geometry, and operating conditions [12]. These performance parameters were neither measured nor modeled in the present study because the objective is mathematical modeling for an educational context rather than aerodynamic performance prediction. Accordingly, the calculated P_{wind} values should not be interpreted or directly compared as measured mechanical or electrical turbine output.

Although the wind power equation is generally applicable to wind energy systems, the Savonius specific context is introduced through its vertical axis rotor geometry, for which the projected swept area is represented by A = DH. The turbine is therefore used as a geometric and technological context rather than an aerodynamic performance model.

Contextual STEM Mathematical Modeling Framework

The second outcome is the structured integration of the mathematical model with the four STEM domains. Science is represented by wind kinetic energy, technology by the Savonius turbine, engineering by rotor geometry, and mathematics by functions, ratios, tables, and graphs. The sequence therefore moves from a physical phenomenon to engineering parameters, mathematical abstraction, and quantitative interpretation.

This organization is consistent with STEM based mathematics research in which engineering phenomena are used to understand equations and functions and to develop mathematical models [15]. It also aligns with engineering based STEM approaches that connect scientific understanding with real world problem solving [16].
For public high school education, the framework provides an analytical activity that can begin from predefined physical parameters without requiring immediate turbine construction or wind tunnel testing. Students can identify variables, calculate swept area, evaluate a cubic function, compare ratios, construct a graph, and interpret the result within the energy context. This responds to the need for explicit and realistic renewable energy STEM resources identified in Indonesian senior high schools [14].
The framework should not be interpreted as a complete Engineering Design Process because it does not include prototype construction, iterative testing, or optimization. Likewise, no classroom intervention was conducted, so the study does not claim improvements in numeracy, critical thinking, or STEM competency.
The principal outcome is therefore a structured mathematical modeling framework that uses the Savonius wind turbine as an authentic renewable energy context rather than a prediction of turbine performance.

CONCLUSION

This study developed a contextual STEM mathematical modeling framework using a small-scale Savonius wind turbine as an engineering context for public high school education. The framework connects a physical renewable-energy phenomenon with rotor geometry, mathematical formulation, numerical exploration, graphical representation, and contextual interpretation. For the selected rotor dimensions, the available wind power followed the expected cubic relationship with wind velocity, increasing from 0.0057 W at 0.5 m/s to 1.2403 W at 3.0 m/s. Doubling the wind velocity resulted in an eightfold increase in available wind power, while tripling it increased the available power by a factor of 27. The principal contribution of the study is therefore the structured translation of a renewable-energy system into an integrated STEM mathematical modeling sequence rather than the introduction of a new wind-power relationship. The calculated values represent theoretical free-stream wind power and should not be interpreted as actual turbine output. Because no classroom intervention was conducted, the effectiveness of the proposed framework for improving student learning remains to be evaluated in future studies.

REFERENCES

[1] N. Cuevas-Carvajal, J. S. Cortes-Ramirez, J. A. Norato, C. Hernandez, and M. F. Montoya-Vallejo, “Effect of geometrical parameters on the performance of conventional Savonius VAWT: A review,” Renewable and Sustainable Energy Reviews, vol. 161, Art. no. 112314, 2022, doi: 10.1016/j.rser.2022.112314.
[2] A. Dewan, S. S. Tomar, A. K. Bishnoi, and T. P. Singh, “Computational fluid dynamics and turbulence modelling in various blades of Savonius turbines for wind and hydro energy: Progress and perspectives,” Ocean Engineering, vol. 283, Art. no. 115168, 2023, doi: 10.1016/j.oceaneng.2023.115168.
[3] S. Torres, A. Marulanda, M. F. Montoya, and C. Hernandez, “Geometric design optimization of a Savonius wind turbine,” Energy Conversion and Management, vol. 262, Art. no. 115679, 2022, doi: 10.1016/j.enconman.2022.115679.
[4] I. Farozan, T. A. F. Soelaiman, P. Soetikno, and Y. S. Indartono, “The effect of rotor aspect ratio, stages, and twist angle on Savonius wind turbine performance in low wind speeds environment,” Results in Engineering, vol. 25, Art. no. 104041, 2025, doi: 10.1016/j.rineng.2025.104041.
[5] A. G. Chitura, P. Mukumba, and N. Lethole, “Enhancing the performance of Savonius wind turbines: A review of advances using multiple parameters,” Energies, vol. 17, no. 15, Art. no. 3708, 2024, doi: 10.3390/en17153708.
[6] F. Ghafoorian, S. R. Mirmotahari, and H. Wan, “Numerical study on aerodynamic performance improvement and efficiency enhancement of the Savonius vertical axis wind turbine with semi directional airfoil guide vane,” Ocean Engineering, vol. 307, Art. no. 118186, 2024, doi: 10.1016/j.oceaneng.2024.118186.
[7] X. H. Wang, J. S. Y. Foo, A. Fazlizan, W. T. Chong, and K. H. Wong, “Effects of endplate designs on the performance of Savonius vertical axis wind turbine,” Energy, vol. 310, Art. no. 133205, 2024, doi: 10.1016/j.energy.2024.133205.
[8] A. D. Le, P. N. T. Thu, V. H. Doan, H. T. Tran, M. D. Banh, and V. T. Truong, “Enhancement of aerodynamic performance of Savonius wind turbine with airfoil-shaped blade for the urban application,” Energy Conversion and Management, vol. 310, Art. no. 118469, 2024, doi: 10.1016/j.enconman.2024.118469.
[9] A. D. Le, V. H. Doan, P. N. T. Thu, H. T. Tran, V. A. Truong, M. D. Van, D. D. Nguyen, and M. D. Banh, “Performance assessment of Savonius wind turbine: Impact of the cylindrical deflectors with natural shapes,” Ocean Engineering, vol. 315, Art. no. 119900, 2025, doi: 10.1016/j.oceaneng.2024.119900.
[10] S. Chegini, M. Asadbeigi, F. Ghafoorian, and M. Mehrpooya, “An investigation into the self-starting of Darrieus-Savonius hybrid wind turbine and performance enhancement through innovative deflectors: A CFD approach,” Ocean Engineering, vol. 287, Art. no. 115910, 2023, doi: 10.1016/j.oceaneng.2023.115910.
[11] A. Ayadi, N. Rabeh, J. Marzougui, R. Ennetta, and Z. Driss, “Investigation of the blade tip geometry for improved performance of a Savonius rotor,” Results in Engineering, vol. 27, Art. no. 106745, 2025, doi: 10.1016/j.rineng.2025.106745.
[12] M. Seify Davari, H. Seifi Davari, and E. L. Ntantis, “A comprehensive review on Savonius vertical-axis wind turbines: Design advances and efficiency enhancement,” Energy Conversion and Management: X, vol. 30, Art. no. 101830, 2026, doi: 10.1016/j.ecmx.2026.101830.
[13] A. Fazylova, K. Alipbayev, A. Aden, F. Oraz, T. Iliev, and I. Stoyanov, “A comparative review of vertical axis wind turbine designs: Savonius rotor vs. Darrieus rotor,” Inventions, vol. 10, no. 6, Art. no. 95, 2025, doi: 10.3390/inventions10060095.

[14] F. W. Ginting, H. Sakdiah, R. Unaida, Syafrizal, and Fakhrah, "Implementing the STEM approach in high school: Challenges and opportunities in renewable energy learning," Electronic Journal of Education, Social Economics and Technology, vol. 6, no. 2, pp. 1–9, 2025, doi: 10.33122/ejeset.v6i2.1309.
[15] V. Saputri, Y. S. Kusumah, T. Turmudi, and A. Jupri, "Designing a STEM-RME-based mathematics e-module to enhance high school students' numeracy," Journal of Engineering Science and Technology, Special Issue on ISCoE2024, vol. 20, no. 3, pp. 177–184, 2025.
[16] M. Syukri, F. Haya, S. Maghfirah, F. Herliana, M. S. Rasul, and H. Pratama, "STEM-based engineering design process models in physics learning: Systematic literature review," European Journal of STEM Education, vol. 11, no. 1, Art. no. 4, 2026, doi: 10.20897/ejsteme/17784.
[17] F. M. Syamra and A. Suryadi, "Comparing project-based learning and integrated STEM approach in enhancing scientific creativity in renewable energy education," Pedagogical Research, vol. 10, no. 3, Art. no. em0244, 2025, doi: 10.29333/pr/16751.
[18] L. A. Putri, I. Kaniawati, A. Permanasari, and D. Rochintaniawati, "Science, Technology, Engineering, and Mathematics (STEM) project-based learning to enhance students' multiliteracy on renewable energy: A comparative study between urban and rural schools," Jurnal Penelitian Pendidikan IPA, vol. 12, no. 4, pp. 755–762, 2026, doi: 10.29303/jppipa.v12i4.14679.
[19] Jamaludin, J. R. Batlolona, and C. S. A. Barus, "Promoting STEM-creative skills in high school students: Renewable energy in island regions," Unram Journal of Community Service, vol. 6, no. 3, pp. 647–657, 2025, doi: 10.29303/ujcs.v6i3.1173.
[20] I. W. Sukarjita and L. F. Tae, "The application of discovery learning model with STEM approach to improve critical thinking skills and collaboration skills of students at public senior high school (SMA Negeri 3 Kupang)," Jurnal Penelitian Pendidikan IPA, vol. 11, no. 5, pp. 664–676, 2025, doi: 10.29303/jppipa.v11i5.10495.
[21] I. Setiasih, N. Winarno, E. C. Prima, F. Qamila, R. A. Firdaus, and N. J. Ahmad, "Fostering students' critical thinking through STEM project-based learning: Designing earthquake-resistant buildings," STEM Education, vol. 6, no. 2, pp. 284–306, 2026, doi: 10.3934/steme.2026012.
[22] E. Winaryati, Y. Wardat, A. Setiawan, Z. H. Iksan, R. A. A. Rauf, W. I. Kusumaningrum, and L. Nurdiana, "Developing 21st century skills through STEM-based lesson study and project-based approaches in chemistry learning," Educational Process: International Journal, vol. 19, Art. no. e2025534, 2025, doi: 10.22521/edupij.2025.19.534.
[23] D. Linda and R. Arianingrum, "A systematic literature review: How the implementation of STEM enhances critical thinking skills in chemistry education?," Indonesian Journal of Educational Research and Review, vol. 8, no. 1, pp. 190–209, 2025, doi: 10.23887/ijerr.v8i1.84793.
[24] Indrasti and Paidi, "Development of STEM-integrated project-based learning to improve critical thinking skills of senior high school students on environmental change material," Jurnal Biologi-Inovasi Pendidikan, vol. 7, no. 3, pp. 456–465, 2025, doi: 10.20527/bino.v7i3.23218.
[25] I. K. Arisujarnata, I. W. Redhana, and I. N. Tika, "Meta-analysis of the effect of STEM-integrated learning models on students' scientific literacy in science education in Indonesia," Jurnal Penelitian Pendidikan IPA, vol. 11, no. 11, pp. 98–106, 2025, doi: 10.29303/jppipa.v11i11.12109.