JTK: Jurnal Tadris Kimiya 10, 1 (June, 2025): 1-10
Website: http://journal.uinsgd.ac.id/index.php/tadris-kimiya/index
ISSN 2527-9637 **(online) ISSN** 2527-6816 **(print)**

Integrating Plastic Waste Pyrolysis Technology into STEM Education to Improve Students' Environmental Knowledge and Attitude

Euis Nursaadah[1*], Raidatul Fannyda[2], Annida Nurul Shabrina[1], Aceng Ruyani[1]
[1]Magister Study Program in Natural Science Education, Faculty of Teacher Training and Education, Universitas Bengkulu, Bengkulu 38122, Indonesia
[2]Madrasah Aliyah Negeri (MAN) Insan Cendekia, Central Bengkulu, Bengkulu 38381, Indonesia
**E-mail: euis@unib.ac.id*

Received: March 2025; Accepted: May 2025; Published: June 2025

Abstract

The growing concern over plastic waste pollution and its harmful byproducts, such as CO, CO_2, NO_x, and SO_x gases from incineration, necessitates alternative and environmentally responsible waste management strategies. At MAN Insan Cendekia Bengkulu Tengah, a boarding school that manages its own waste, the integration of pyrolysis as a cleaner method for plastic waste treatment offers both practical and educational value. This study aimed to contextualize plastic waste pyrolysis within STEM-based learning to enhance students' environmental knowledge and attitudes through interdisciplinary instruction. A quasi-experimental two-group pre-test–post-test design was employed, involving 32 students divided equally into control and experimental groups. The control group received STEM instruction using a module and video on plastic pyrolysis, while the experimental group engaged in a more immersive approach involving the same materials supplemented with hands-on pyrolysis activities. Results indicated that the experimental group outperformed the control group, with an environmental knowledge normalized gain (N-gain) score of 0.67 (medium), compared to 0.47 (low) in the control group. Additionally, the experimental group achieved higher environmental attitude scores (85) than the control group (76). These findings demonstrate that STEM education incorporating contextual, multimodal, and practical components can significantly enhance students' conceptual understanding and engagement with environmental issues. The study contributes to the growing body of evidence supporting experiential STEM education as an effective approach for fostering environmental awareness and action in secondary education settings.

Keywords: plastics, pyrolysis, STEM, waste

DOI: https://doi.org/10.15575/jtk.v10i1.40753

1. Introduction

STEM-based learning (Science, Technology, Engineering, and Mathematics) is an integrated and practical approach to enhancing students' understanding and skills. This approach encourages students to think critically, creatively, and innovatively in solving real-world problems (Davidi et al., 2021). The need for education relevant to everyday life is becoming increasingly urgent in the ever-evolving modern era. Education is no longer just about understanding theoretical concepts in the classroom but also about how students can apply that knowledge in real-life situations. Therefore, the STEM approach is essential. STEM enables students not only to learn science and technology but also to integrate this knowledge into contexts relevant to the challenges they face in the real world (Mu'minah, 2021).

STEM learning generally utilizes complex real-world problems as instructional content and applies knowledge and practices from multiple disciplines (Mu'minah, 2021). STEM learning integrates technology, engineering, and mathematics content into science education (Khut & Shimizu, 2023). In STEM, science is the objective study of natural phenomena involving observation and measurement. Technology is anything innovative that makes something easier. Technology fulfills human needs and desires to make life more effective and efficient. Engineering consists of applying scientific knowledge to design and build machines, devices, systems, materials, and processes that benefit humanity in an economical, practical, and environmentally friendly way (Rosen, 2012). Meanwhile, Math is the pattern that connects science, technology, and engineering within STEM learning (Suwardi, 2021).

Learning STEM encourages students to develop problem-solving skills in dealing with global issues, such as climate change, renewable energy, and waste management. By connecting learning to real problems, students better understand the real-world impact of science and technology, feeling more engaged and motivated in the learning process (Situmorang, 2016).

Implementing STEM learning provides students with opportunities to engage in engineering or system design processes, such as addressing plastic waste, a real societal issue. Students can tackle this challenge with practical solutions by applying chemical and mathematical knowledge. Research by Arini & Lovisia (2019) demonstrated that using pyrolysis technology in the learning process to address plastic waste has received positive responses from students. Pyrolysis is breaking down long-chain polymer molecules into smaller molecules through thermochemical reactions. This technology can effectively solve plastic waste treatment and energy conversion (Nasrun et al., 2017). By studying the pyrolysis of plastic waste as part of STEM learning, students can better understand how to convert plastic waste into valuable energy and increase their environmental awareness. Integrating STEM within an ecological context can enhance students' knowledge, environmental awareness, and creativity (Farwati et al., 2018).

Plastic waste pyrolysis has been widely carried out in school and community environments. Students who use plastic pyrolysis in environmental science learning respond positively in school environments (Arini & Lovisia, 2019). In the community plastic waste pyrolysis technology has been introduced to the Waste Bank community (Mitan, et al., 2022). Research on STEM learning has also been widely conducted in Indonesia; STEM learning is often carried out through project learning in chemistry subjects to prepare competent human resources to face the 21st century (Sumartati, 2021). In addition, developing STEM-based chemistry teaching materials for basic chemistry learning can improve students' knowledge and learning outcomes (Siregar et al., 2023).

Although pyrolysis and STEM learning have been widely conducted before, no research has integrated plastic waste pyrolysis into STEM-based learning to measure students' environmental knowledge and environmental care attitudes. For researchers, it is necessary to apply STEM to students' learning content directly. Thus, each component of STEM, which includes Science, Technology, Engineering, and Mathematics, is truly created in the learning process.

Based on initial observations at Madrasah Aliyah Negeri Insan Cendekia (MAN IC) Bengkulu Tengah, plastic waste management activities are still handled by the school's cleaning staff and have not been fully optimized. Plastic bottles made from polyethylene terephthalate (PET) take approximately 450 years to decompose. At the same time, incineration is not an effective method for plastic waste disposal due to releasing harmful pollutants, such as exhaust gases (CO, CO_2, NO_x, SO_x) and other particles that are detrimental to the environment (Kusnandar, 2011). Therefore, an alternative and more effective waste management method is needed. By studying hydrocarbons based on plastic waste pyrolysis, students are encouraged to explore in-depth how this technology works and how its application can solve environmental problems.

The knowledge students gain goes beyond theory and is directly connected to practical applications with positive environmental impacts. For example, they will learn how pyrolysis can convert plastic waste into fuel, reducing waste volume and generating reusable energy (Herrera, et al., 2024). Additionally, integrating STEM into learning encourages students to develop a deeper environmental awareness. They will better understand that small actions, such as proper waste management, significantly impact when applied broadly (Asrib & Ibrahim, 2023). This awareness is expected to motivate them to become active agents of change in environmental conservation efforts within the school environment and the wider community. Therefore, this study analyzed students' knowledge and environmental awareness after using STEM learning on the hydrocarbon concept integrated with plastic waste pyrolysis, Unfortunately, there is often a disconnect between students' environmental knowledge and their actual behavior (Sapanova et al., 2023; Sousa et al., 2021).

This study examines the impact of integrating the plastic waste pyrolysis process as a learning context by applying knowledge and practices from various disciplines in STEM chemistry education.

2. Research Method

This research utilized a quantitative approach with a quasi-experimental, two-group pre-test and post-test design. The control group applied chemistry learning using assisted modules and videos, while the experimental group applied STEM learning assisted modules, videos, and hands-on experiences through practical plastic waste pyrolysis activities.

Learning in the experimental group uses modules, videos, and direct pyrolysis practice, while learning in the control group only uses modules and videos. The subjects of this study were students in 12th grade of MAN Insan Cendikia Bengkulu Tengah. The researcher chose MAN IC Bengkulu Tengah students because MAN IC Bengkulu Tengah is a boarding school with a waste management program. Hence, students already have experience managing waste. The researcher selected a sample of 12th grade science students because this class studies Chemistry and has already covered the general concepts of Hydrocarbons.

Data collection techniques for students' knowledge were conducted through tests using pre-test and post-test instruments. At the same time, environmental awareness was measured using a questionnaire technique, with the instrument being an attitude assessment questionnaire. Environmental knowledge is measured using 10 multiple-choice questions. Aspects of knowledge measure: (1) knowledge of polymer types, monomers, and reactions involved; (2) properties of plastic; (3) changes and chemical processes during pyrolysis; (4) concept of plastic waste processing; (5) Innovation in plastic waste processing technology

Environmental awareness was measured using a Likert scale questionnaire (strongly agree-strongly disagree) consisting of 8 questions. The aspect of environmental awareness was measured based on four indicators: (1) appreciation for the environment; (2) concern for the environment; (3) sensitivity to environmental issues; (4) motivation and intention to take action in solving environmental problems.

Both the learning module and the instrument to measure environmental knowledge and environmental awareness were validated by five experts. The results of expert judgment were presented and categorized. The results of expert validation on the module showed a result of 85.33 (valid), and the results of instrument validation showed a result of 81 (valid).

Analysis of the results of students' knowledge is calculated using the N-Gain Furthermore, the N-gain scores are categorized into high, medium, and low categories which can be seen in Table 1.

$$\text{N-gain} = \frac{posttest\ score - pretest\ score}{maximum\ score - pretest\ score}$$

Table 1. Criteria for N-Gain Score

N-Gain	Criteria
0.70 > N-Gain	High
0.30 ≤ N-Gain ≤ 0.70	Medium
N-Gain < 0.30	Low

The N-Gain data was tested for significance using a t-test. The analysis of the self-assessment questionnaire score in Table 2.

Table 2. Scores of Questionnaires

No.	Statement	Score Description
1.	SA (Strongly Agree)	5
2.	A (Agree)	4
3.	U (Undecided)	3
4.	DA (Disagree)	2
5.	SDA (Strongly Disagree)	1

(Wulandari & Radia, 2021)

The study subjects were 32 students from the 12th grade science class at MAN Insan Cendekia Bengkulu Tengah, consisting of 16 students in the control and 16 in the experimental groups. The researcher selected a sample of 12th grade science students because this class studies chemistry and has already covered the general concepts of Hydrocarbons. Therefore, purposive sampling is used in this study.

3. Result and Discussion

3.1. Student's Environmental Knowledge

The study was conducted with a control and an experimental group. The control group implemented chemistry learning-assisted modules and videos. The experimental group applied STEM learning-assisted modules, videos, and hands-on experiences through practical sessions about plastic waste pyrolysis. Table 3 presents the results of the N-gain analysis of students' environmental knowledge scores between the control and experimental groups.

Table 3. N-Gain Score of Environmental Knowledge

Class	N-Gain Score		
	Minimum	Maximum	Mean
Control	0.20	0.83	0.47
Experiment	0.40	1.00	0.67

Table 3 shows that the experimental group's N-Gain score is higher than the control groups. The environmental knowledge of students in the experimental group reached 67%, while that of the control group only reached 47%. This data is supported by the results of the independent sample t-test on homogeneous and normal data, the significance of 0.001 < 0.005 indicates that there is a significant difference between the two groups.

Using videos and modules alone without hands-on activity could not improve students' environmental knowledge. This data aligns with the research results by (Sukarelawan et al., 2024) that hands-on activities must accompany environmental chemistry learning. This finding implies that the chemistry learning focused on plastic waste pyrolysis, which solely relies on instructional media, may not significantly improve students' environmental understanding.

The higher N-Gain score in the experimental group indicates that the applied STEM learning had a more significant positive impact than the control group. The STEM learning in the experimental group was conducted using modules, videos, and direct experience through the practice of plastic waste pyrolysis. Plastic waste processing is not new for students of MAN Insan Cendikia Bengkulu Tengah; this is because the school has a waste processing facility called an incinerator.

Students in the experimental group were divided into four groups to carry out pyrolysis: groups one and two carried out pyrolysis of PET plastic, and groups three and four carried out pyrolysis of metal-coated PET plastic. Two groups that carried out pyrolysis of the same type of plastic were expected to be able to discuss the pyrolysis process and products. Each group consisted of four students who had essential roles in their group. The small number of groups made their work effective and involved in all pyrolysis processes. The limitation of this experiment was that no characterization was carried out on the bio-oil pyrolysis product, so students did not yet know the function and application of the pyrolysis product in terms of application.

This data shows that STEM learning with direct practice can better impact increasing environmental knowledge for students even though the topics studied are not new. This study's findings align with the results of Akleman et al. (2019), who found that students directly involved in plastic waste recycling projects showed a clear sense of social-environmental awareness and responsibility for plastic recycling. The students' pyrolysis practice activities are shown in Figure 1.

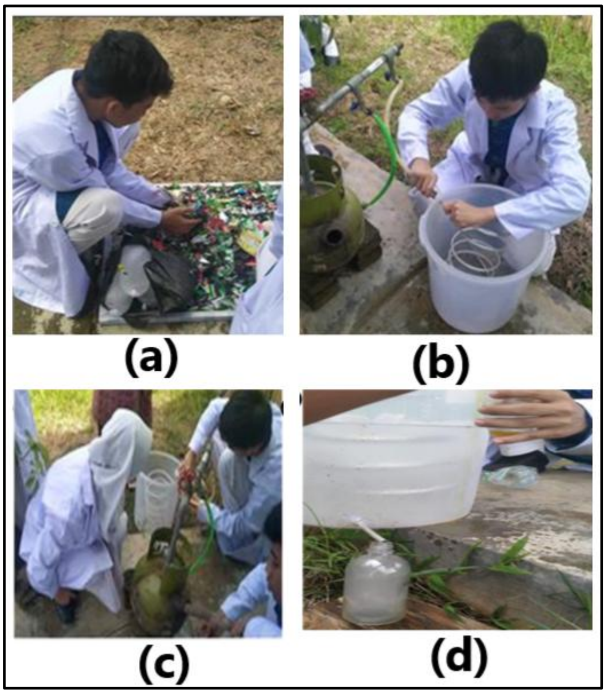

Figure 1. Students Carry Out the Plastic Waste Pyrolysis Practice Activity; (a) Students collect PET Pla stic Waste; (b) Pyrolysis Tool Assembly; (c) Students Pyrolyze Waste using the Pyrolysis Tool; (d) Students Get the First Drop of Oil Produced from Pyrolysis.

The integration of practical activities enables students to actively engage in the learning process, thereby improving their understanding of hydrocarbon concepts. This understanding extends beyond theoretical knowledge to real-life applications. This aligns with the findings of (Sativa, 2023) which indicate that the integration of practical activities enhances student engagement, aids in the practical comprehension of hydrocarbon concepts, bridges the gap between theory and real-life applications, fosters awareness, and leads to comprehensive learning As a result, students can better understand both the processes and their environmental impacts. Learning through practical experience allows students to gain direct insights from real-world scenarios (Arini & Lovisia, 2019).

The application of STEM principles in this relevant and contemporary learning approach motivates students to actively understand and respond to environmental issues (Sari et al., 2023). The combination of module-based media, videos, and hands-on practical experience in the experimental class demonstrates that a learning approach incorporating various media and practical methods is highly effective in enhancing students' understanding. The combination of environmental approaches and audio-visual technology in STEM disciplines can be effective in optimizing the learning process (Álvarez-Castillo et al., 2022). Merriënboer et al. (2005) also said that the cognitive load to achieve complex learning needs to be linked to real-life tasks. Thus, the results show that the learning method followed by students can connect students' initial concepts and ideas with those learned during learning.

The increase in students' environmental knowledge in the experimental group was higher than in the control group. The environmental knowledge consists of ecological knowledge and environmental conditions, such as students' skills in describing types of plastic based on the structure of hydrocarbon compounds and identifying the chemical and physical properties of plastic; knowledge of environmental pollution, which involves detailing the causes of plastic waste pollution and its impacts; knowledge of solving environmental problems, such as through plastic waste pyrolysis technology. These knowledges are the basis for plastic waste pyrolysis and can be improved through hands-on activity.

Experimental group strengthened by conducting direct pyrolysis in addition to using learning modules and videos. There was an increase in scores for both knowledge and environmental awareness in the experimental class because, in that class, students were allowed to build concepts directly through observations that resulted in meaningful learning (Munfaida et al., 2022). Practical activities encourage students to discuss with their group mates, be more active and enthusiastic in learning, and foster curiosity from within students so that students will try to find and analyze. If students succeed in finding the information or knowledge they are looking for, satisfaction will arise from within themselves (Wahyuningtyas et al., 2023).

3.2. Student's Environmental Awareness

Students' environmental awareness was assessed through four indicators. The results between control and experimental groups presented in Figure 2.

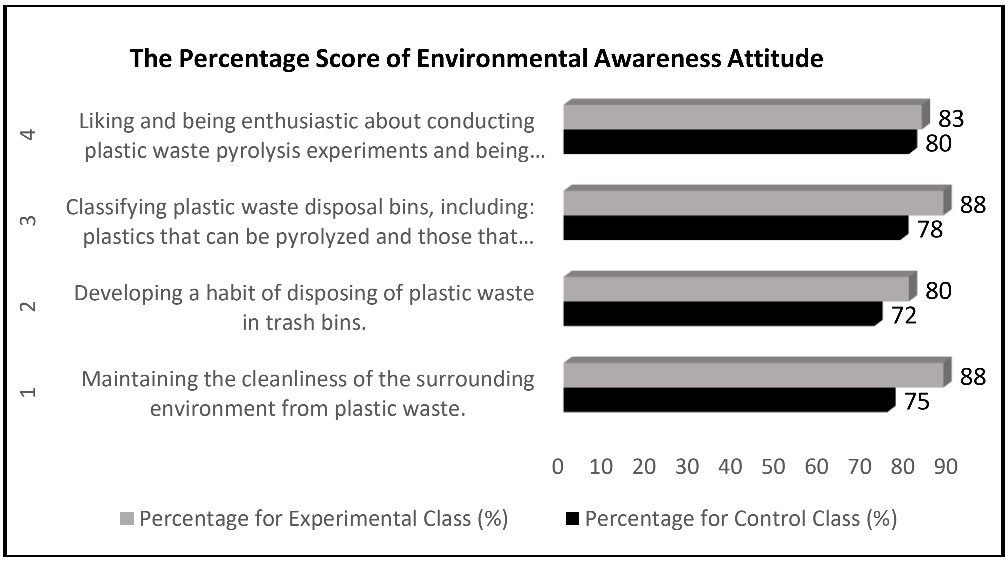

Figure 2. The Percentage Score of Environmental Awareness Attitude

Figure 2 shows that the first indicator, which is the ability to maintain environmental cleanliness and manage plastic waste, is better achieved by students in the experimental group. This indicates that students in the experimental group are more proactive in managing plastic waste and maintaining cleanliness.

The second indicator focuses on the habit of throwing garbage in its place; students in the experimental group showed better habits. These data indicate that learning through direct practice influences students' behavior in managing waste more responsibly, which may be difficult to achieve only through module and video-based learning methods.

The third indicator related to students' concern in grouping plastic waste based on its ease of pyrolysis. Students in the experimental class scored high, indicating their ability to understand and apply relevant methods of grouping plastic waste related to pyrolysis.

The last indicator is students' enthusiasm for conducting plastic waste pyrolysis experiments and their desire to contribute if pyrolysis is implemented permanently in schools. Based on the scores, students in the experimental class were more enthusiastic and motivated to participate in practical activities. These data indicate that STEM-based learning involving direct experience can increase students' interest in sustainable environmental activities (Thompson & Herriges, 2024). This finding aligns with the statement Herrera et al. (2024) that STEM disciplines can increase environmental actions, as indicated by students' skills in finding solutions to solve problems or change their behavior.

Increasing environmental awareness in experimental classes that follow learning using modules, videos, and direct pyrolysis practicums makes implementing their competencies and skills in solving environmental problems easier. Therefore, each practicum activity is expected to improve students' basic, essential, and generic skills (Sarjan & Hakim, 2022). In addition to increasing student knowledge, practical activities can raise environmental awareness (Ardiansyah et al., 2023). The success of using modules, videos, and pyrolysis practicums in increasing environmental awareness is also due to the relationship between each contextual learning component and environmental awareness indicators.

Based on research data, it is known that, in general, students show an attitude of caring for the environment. However, further guidance and supervision are still needed so students consistently actively pay attention to the surrounding environment. In addition, the percentage of higher score achievement in the experimental group shows the effectiveness of applying STEM learning that combines modules, videos, and direct experiments (Proudfoot & Kebritchi, 2017). In the practicum process, students are involved in direct activities that allow them to discover new concepts and develop new understandings. In addition, the practicums focused on real problems and their handling so that learning is centered on applying and transferring knowledge to realistic contexts. Teamwork in practicums can improve collaboration and teamwork using communication skills. These components are presented in the STEM-based module developed in this study.

In general, STEM learning has increased students' enthusiasm in applying the concept of plastic waste pyrolysis, both in the control and experimental groups. Through STEM-based learning media, students gain in-depth knowledge and increase their environmental awareness (Nugroho et al., 2019; Fathurohman et al. 2023). The media used in the learning process in electronic learning media and simple experimental tools have made the learning experience more meaningful and effective in increasing students' environmental knowledge and awareness. This study highlights the importance of integrating theory with direct practice in environmental education to achieve optimal results.

The use of learning modules and videos without direct pyrolysis experiments in the control group prevented students from applying the concept of a holistic environment. Passive learning media such as modules and videos can convey information but are not always sufficient to encourage active engagement and hands-on experience needed for more profound and more impactful learning. Collaboration of audio-visual technology with direct experience in learning will be more easily accepted by students than using technology alone (Alexandre-Franco, et al., 2024).

The results of this study are expected to be one of the efforts in overcoming the problem of plastic waste and providing knowledge and attitudes of environmental care for students ready to be shared with family members or the wider community. The researcher hopes this study can be developed to integrate other STEM-based learning practices to improve student's knowledge and attitudes toward environmental care.

4. Conclusion

STEM education, supported by modules, videos, and hands-on experience, is more effective in improving students' environmental knowledge and attitudes. The experimental group students who took part in the plastic waste pyrolysis practical session gained n-gain 67 in environmental knowledge, while the control group gained N-gain 47, which matched their environmental attitude scores. STEM learning, which includes a variety of media and hands-on methods, has been shown to provide additional benefits, such as deepening students' understanding and increasing their engagement in environmental issues. This approach is essential to achieve more optimal results in environmental education.

References

Akleman, E., Barroso, L., Capraro, M. M., Creasy, T., Fleming, K., He, W., Liang, H., & Williams, A. M. (2019). Recycling plastics: middle school students create solutions during a summer camp. *European Journal of STEM Education*, *4*(1), 1–15. https://doi.org/10.20897/ejsteme/6341

Alexandre-Franco, M. F., Kouider, R., Kassir Al-Karany, R., Cuerda-Correa, E. M., & Al-Kassir, A. (2024). Recent advances in polymer science and fabrication processes for enhanced microfluidic applications: An overview. *Micromachines, 15*(9), 1137. https://doi.org/10.3390/mi15091137

Álvarez-Castillo, E., Felix, M., & Bengoechea, C. (2022). Assessment of a pedagogical model for stem education: combining technology and collaborative tasks. *Afinidad, 80*(598), 8–18. https://doi.org/10.55815/413456

Ardiansyah, B., Ramdani, A., Hakim, A., Makhrus, M., & Yustiqvar, M. (2023). Preliminary study : profile of management of practicum activities science at middle school level to improve higher level thinking skills, science process skills, and scientific attitudes. *Jurnal Penelitian Pendidikan IPA, 9*(10), 9067–9073. https://doi.org/10.29303/jppipa.v9i10.6295

Arini, W., & Lovisia, E. (2019). Respon siswa terhadap media pembelajaran alat pirolisis sampah plastik berbasis lingkungan di smp kabupaten musi rawas. *Journal of Natural Science Teaching*, 2(2), 95–104. https://doi.org/10.21043/thabiea.v2i2.5950

Asrib, A. & Ibrahim, H. (2023). Implementation of environmental education in universities: impact on student knowledge and attitudes. I*n 2nd World Conference on Social and Humanities Research*, pp. 158-165. Atlantis Press. https://doi.org/10.2991/978-2-38476-084-8

Davidi, E. I. N., Sennen, E., & Supardi, K. (2021). Integrasi pendekatan STEM (science, technology, enggeenering and mathematic) untuk peningkatan keterampilan berpikir kritis siswa sekolah dasar. *Jurnal Pendidikan dan Kebudayaan*, *11*(1), 11–22. https://doi.org/10.24246/j.js.2021.v11.i1.p11-22

Farwati, R., Permanasari, A., Firman, H., & Suhery, T. (2018). Integrasi problem based learning dalam stem education berorientasi pada aktualisasi literasi lingkungan dan kreativitas. *Seminar Nasional Pendidikan IPA Tahun 2021*, *1*(1), 198–206. *Retrieved from* https://conference.unsri.ac.id/index.php/semnasipa/article/view/688

Fathurohman, I., Amri, M. F., Septiyanto, A., & Riandi. (2023). Integrating STEM based education for sustainable development (ESD) to promote quality education: a systematic literature review. *Jurnal Penelitian Pendidikan IPA*, 9(11), 1052–1059. https://doi.org/10.29303/jppipa.v9i11.4430

Herrera M. R., Gonzales, K. E., Graham, S. R., Guerrero, M., Robertson, M. L., & Henderson, J. A. (2024). Learning from tomorrow's recyclers: extension of hands-on recycled waste activity. *Journal of Chemical Education, 101*(7), 2899–2902. https://doi.org/10.1021/acs.jchemed.4c00387

Khut, S., & Shimizu, K. (2023). Integrating STEM approach in k-12 science education teaching practice: a systematic literature review. *International Journal of Research in STEM Education, 5*(2), 1–18. https://doi.org/10.33830/ijrse.v5i2.1598

Kusnandar, I. (2011). Pengaruh penambahan mygreenoil dalam premium terhadap emisi gas buang karbon monoksida (CO) pada sepeda motor honda supra x tahun 2004. *UNS-FKIP Jur. Teknik Mesin Jurusan Teknik dan Kejuruan-K.2506034 -2011. Retrieved from* https://digilib.uns.ac.id/dokumen/abstrak/21477/Pengaruh-Penambahan-Mygreenoil-Dalam-Premium-Terhadap-Emisi-Gas-Buang-Karbon-Monoksida-Co-Pada-Sepeda-Motor-Honda-Supra-X-Tahun-2004

Mitan, N. M. M., Sari, M. M., Hastuty, S., GN, R., SF, A., & NA, R. A. (2022). Penerapan teknologi pirolisis dalam pengolahan sampah plastik di bank sampah seni baru, Jakarta Selatan. *Reswara: Jurnal Pengabdian Kepada Masyarakat, 3*(1), 171-178. https://doi.org/10.46576/rjpkm.v3i1.1612

Mu'minah, I. H. (2021). Studi Literatur: pembelajaran abad-21 melalui pendekatan STEAM (science, technology, engineering, art, and mathematics) dalam menyongsong era society 5.0. *Prosiding Seminar Nasional Pendidikan, 3,* 584–594. *Retrieved from* https://prosiding.unma.ac.id/index.php/semnasfkip/article/view/654

Munfaida, S., Mustadi, A., & Kurniawati, W. (2022). The use of practicum-based worksheets can improve conceptual understanding of energy material for science courses. *Jurnal Penelitian Pendidikan IPA. 8*(6), 2859–2863. https://doi.org/10.29303/jppipa.v8i6.2173

Nasrun, N., Kurniawan, E., & Sari, I. (2017). Pengolahan limbah kantong plastik jenis kresek menjadi bahan bakar menggunakan proses pirolisis. *Jurnal Energi Elektrik, 4*(1), 1–5. https://doi.org/10.29103/jee.v4i1.11

Nugroho, O. F., Permanasari, A., & Firman, H. (2019). The movement of stem education in Indonesia: Science teachers' perspectives. *Jurnal Pendidikan IPA Indonesia, 8*(3), 417–425. https://doi.org/10.15294/jpii.v8i3.19252

Proudfoot, D. E., & Kebritchi, M. (2017). Scenario-Based elearning and stem education: a qualitative study exploring the perspectives of educators. International *Journal of Cognitive Research in Science, Engineering and Education, 5*(1), 7–18. https://doi.org/10.5937/IJCRSEE1701007P

Rosen, M. A. (2012). Engineering sustainability: a technical approach to sustainability. *Sustainability, 4*(9), 2270–2292. https://doi.org/10.3390/su4092270

Sapanova, S., Nurbanu, C., & Nuri, B. L. M. D. C. C. D. C. (2023). Kazakhstani high school students' environmental knowledge, attitudes, awareness and concern. *International Research in Geographical and Environmental Education, 33*(2), 139–156. https://doi.org/https://doi.org/10.1080/10382046.2023.2281697

Sari, Y., Qadar, R., & Hakim, A. (2023). Analysis of high school students' conceptual understanding of physics on temperature and heat concepts. *International Journal of STEM Education for Sustainability, 3*(1), 212–224.

https://doi.org/10.53889/ijses.v3i1.92

Sarjan, B. A. M., & Hakim, A. (2022). Science practicum and mini edupark school (MES) as alternatives to improve environmental care attitude in philosophy perspective. *Jurnal Sains dan Teknologi, 5*(2), 17–124. https://doi.org/10.31764/justek.v5i2.11273

Sativa, D. F. (2023). Improving learning outcomes in chemical change topics through practicum activities. *Jurnal Pijar MIPA, 18*(1), 25–29. https://doi.org/10.29303/jpm.v18i1.4558

Siregar, L., & Silaban, S. (2023). Development and implementation of chemistry STEM-based module on buffer solution material in senior high school. *Jurnal Teknologi Pendidikan*, *8*(4), 737–746. https://doi.org/10.33394/jtp.v8i4.8572

Situmorang, R. P. (2016). Analisis potensi lokal untuk mengembangkan bahan ajar biologi di SMA negeri 2 Wonosari. *Jurnal Pendidikan Sains Universitas Muhammadiyah Semarang, 4*(1), 51–57. https://doi.org/10.26714/jps.4.1.2016.51-57

Sousa, S., Correia, E., Leite, J., & Viseu, C. (2021). Environmental knowledge, attitudes and behavior of higher education students: a case study in Portugal. *International Research in Geographical and Environmental Education, 30*(4), 348–365. https://doi.org/10.1080/10382046.2020.1838122

Sukarelawan, M. I., Indratno, T. K., & Ayu, S. M. (2024). *N-Gain vs Stacking*. Yogyakarta: Suryacahya.

Sumartati, L. (2021). Pendekatan STEM dalam pembelajaran kimia 4.0. *Journal of Education, Administration, Training and Religion, 1*(1), 1–8. https://doi.org/10.38075/jen.v1i1.5

Suwardi, S. (2021). Stem (science, technology, engineering, and mathematics) inovasi dalam pembelajaran vokasi era merdeka belajar abad 21. *Jurnal Ilmu Pendidikan dan Psikologi, 1*(1), 40–48. https://doi.org/10.51878/paedagogy.v1i1.337

Thompson, K., & Herriges, M. (2024). Embedding environmentally sustainable practices in learning and teaching : a student perspective. *Open Scholarship of Teaching and Learning, 3*(2), 1–21. *Retrieved from* https://osotl.org/index.php/osotl/article/view/99

Wahyuningtyas, A. D., Dwi, P., Putra, A., Nuha, U., Studi, P., Ipa, P., & Jember, F. U. (2023). The effect of the problem based learning using STEM approach on higher order thinking skills and learning activities in junior high school students. *Jurnal IPA dan Pembelajaran IPA, 7*(2), 166–176. https://doi.org/10.24815/jipi.v7i2.30196

Wulandari, A., & Radia, E. (2021). Pengembangan instrumen penilaian sikap tanggung jawab pembelajaran tematik terpadu kelas V SD. *MIMBAR PGSD Undiksha, 9*(1), 10. https://doi.org/10.23887/jjpgsd.v9i1.32979