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Ethnoscience-PjBL for Water Pollution Treatment: Enhancing Chemistry Environmental Understanding and Mathematical Reasoning through Anaerobic Baffled Reactor (ABR)

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Abstract
Water pollution from heavy metals, organics, and pathogens severely threatens ecosystems and public health, yet chemistry education often remains theoretical, limiting students' grasp of wastewater treatment and quantitative reasoning skills. This study aims to enhance undergraduate students' environmental chemistry understanding covering pollutant characteristics, treatment mechanisms, and Anaerobic Baffled Reactor (ABR) functions and mathematical reasoning through data interpretation, calculations, and modeling via Ethnoscience-Project Based Learning (Ethnoscience-PjBL) integrated with ABR, compared to conventional PjBL. Employing a quasi-experimental design with 74 East Java undergraduates (experimental n=38, control n=36), pre/post-tests, N-Gain analysis, normality (Shapiro-Wilk), homogeneity (Levene's), and ANCOVA (pretest covariate) were used. Results showed the experimental group significantly outperformed controls in chemistry understanding (adjusted mean 85.2 vs. 68.8; difference 16.4, Cohen's d=1.48, large effect; F=4.088, p=0.009), achieving 78.9% COD reduction, pH stabilization from 5.2 to 6.8, and robust reasoning. In conclusion, Ethnoscience-PjBL-ABR bridges local wisdom with engineering, fostering integrated cognitive skills for sustainable pollution solutions and warranting adoption in chemistry curricula worldwide.

1. Introduction

Water pollution is a major global environmental issue, threatening ecosystems, public health, agriculture, and industrial sustainability (Babuji et al., 2023; Belekar et al., 2022). Domestic, agricultural, and industrial activities introduce a wide range of pollutants such as heavy metals (Pb, Cd, Hg, As), organic compounds, pesticides, pharmaceuticals, microplastics, and pathogens into water bodies. These contaminants degrade water quality and disrupt ecological balance (Brankov, 2021). Heavy metals are particularly concerning due to their persistence, toxicity, and bioaccumulation in aquatic food chains, posing significant risks to both humans and wildlife (Ali et al., 2019; Karunanidhi et al., 2022). Understanding water chemistry is essential for addressing these challenges (Simango et al., 2021). Parameters like pH, dissolved oxygen, nutrients, and pollutant speciation influence contaminant mobility and bioavailability as well as the effectiveness of treatment processes. Effective wastewater treatment employs physical (sedimentation, filtration) (Khang et al., 2024), chemical (flocculation, precipitation), and biological (membrane separation, adsorption) methods to remove toxic substances and safeguard ecosystems and human health.

In higher education settings, chemistry instruction on water pollution often remains theoretical. This limits students' grasp of real-world wastewater treatment practices and the complex behavior of contaminants in natural waters (Oyewo et al., 2022; Zamora-Ledezma et al., 2021). Context-based chemistry education such as investigating pollution in local rivers helps students connect chemical principles with actual environmental problems. Direct engagement in sampling and analysis fosters deeper conceptual understanding, practical problem-solving skills, and environmental awareness (Aberšek, 2022; Orbanić, 2021) aligned with sustainability goals.

Ethnoscience-Project Based Learning (Ethnoscience-PjBL) offers a meaningful approach by linking scientific concepts with local culture and community practices (Fitriana et al., 2026; Hidayah et al., 2024). This model enables students to transform everyday cultural knowledge (Sumarni et al., 2022) into scientific understanding through direct observation of science within their social context. Students not only learn theory but also participate in real-world activities that make learning more concrete and relevant. Research on

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ethnoscience-based PjBL has primarily focused on improving scientific literacy (Hidayah et al., 2024; Rusmansyah et al., 2023), conceptual understanding, and environmental awareness. Integrating local culture (Yuendita & Dina, 2024) into projects strengthens students' mastery of science concepts across disciplines. Many studies report positive effects on science literacy and conceptual mastery when learning is contextualized in everyday phenomena or local wisdom (Abas, A., Aziz, A., & Awang, 2022; Wahyuni & Tandon, 2024; Wardhani et al., 2024) making abstract concepts more accessible. Ethnoscience learning also supports broader 21st-century competencies such as critical thinking, creativity, generic science skills, character development, and chemical literacy; however, most research emphasizes literacy and attitude (Aral, 2023; Sadiq, 2022) rather than integrated cognitive skill profiles.

Similarly, environment or context-based chemistry learning (Shuhimi et al., 2010) often focuses on single outcomes like environmental awareness or critical thinking rather than integrating multiple domains such as reasoning or problem-solving. Few studies have specifically examined the intersection of chemistry understanding and mathematical reasoning (Roslina et al., 2023) within wastewater or water-treatment topics. Existing PjBL work in this area mainly documents gains in critical thinking or conceptual understanding; mathematics is typically used only for data analysis rather than as a central outcome(Han, 2016; Wang et al., 2023).Yet effective water pollution treatment requires students to understand chemical processes (pollutant degradation)(Saravanan et al., 2021) while applying quantitative reasoning to analyze efficiency or system performance a combination underexplored in ethnoscience-PjBL research despite its recognized importance for science mastery.

Most studies on Ethnoscience-PjBL document improvements in conceptual understanding, critical thinking skills (Tafakur et al., 2023), scientific literacy, and overall cognitive outcomes (Rusmansyah et al., 2023) in science education. Blending project work with local cultural knowledge (Sumarni et al., 2022) makes abstract concepts more meaningful for students while increasing engagement and yielding high levels of conceptual mastery with positive learner responses. However, these studies are usually conducted in classroom or laboratory settings rather than using authentic environmental engineering (Ariyatun et al., 2024; Colón-Flores, 2023) systems as project contexts especially for topics like water treatment or pollution control. As a result, opportunities for direct interaction with real wastewater technologies are limited; emphasis remains on conceptual or text-based activities instead of operational data analysis from actual systems.

The Anaerobic Baffled Reactor (ABR) is widely studied as a robust sanitation technology capable of efficiently removing organic matter from municipal/industrial effluents (Lau & Trzcinski, 2022; Satyendra & Vijay, 2024). ABR research typically focuses on engineering performance metrics such as removal efficiencies or hydraulic retention time not its use as an educational medium for project-based learning (Satyendra & Vijay, 2024). Deliberate integration of ABR into Ethnoscience-PjBL with the goal of strengthening both chemistry understanding and mathematical reasoning about treatment efficiency remains largely unexplored. This gap highlights the need for context-rich models that link local water pollution issues with real wastewater practices while developing higher-order cognitive skills within sustainability-oriented chemistry education.

Gaps of the research, despite substantial evidence that ethnoscience-based PjBL and context-based chemistry instruction can enhance scientific literacy, conceptual understanding, environmental awareness, and various 21st-century skills, most prior work has not systematically targeted the combined development of environmental chemistry understanding and mathematical reasoning, particularly in authentic wastewater treatment settings (Hidayah et al., 2024; Rusmansyah et al., 2023; Roslina et al., 2023). Mathematics within PjBL related to water treatment is often relegated to a supporting role in data analysis rather than being treated as a core learning objective (Han, 2016; Wang et al., 2023). Furthermore, existing Ethnoscience-PjBL studies are usually implemented in conventional classroom or laboratory environments, with limited use of real environmental engineering systems such as ABR units as central project contexts (Ariyatun et al., 2024; Colón-Flores, 2023). Deliberate integration of ABR into Ethnoscience-PjBL, aimed at strengthening both chemistry understanding and mathematical reasoning about treatment efficiency, remains largely unexplored (Lau & Trzcinski, 2022; Satyendra & Vijay, 2024).

Based on these gaps in the literature, research questions (RQs): Does Ethnoscience-PjBL integrated with ABR significantly enhance students' environmental chemistry understanding and mathematical reasoning compared to conventional PjBL?. Hypotheses: H1: Ethnoscience-PjBL-ABR significantly improves students' environmental chemistry understanding. H2: Ethnoscience-PjBL-ABR significantly improves students' mathematical reasoning. Addressing these questions is crucial because chemistry education should develop both conceptual knowledge and analytical/quantitative reasoning skills. Integrating ethnoscience approaches into project-based learning connects scientific content with local wisdom to make learning more meaningful. This strategy enhances scientific literacy, critical thinking skills, creativity, problem-solving abilities and fosters appreciation for local culture all while supporting sustainability goals in chemistry education. However, further research is needed to fully integrate authentic engineering contexts like ABR into ethnoscience-PjBL models that simultaneously advance both conceptual understanding and mathematical reasoning about real-world water pollution challenges.

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2. Method

This study employed a quasi-experimental design with a non-equivalent control group design, so the sample was selected using purposive sampling from existing intact classes rather than through individual random assignment. The sample comprised 74 students from two universities in East Java, with 38 students in the experimental group and 36 students in the control group. Purposive sampling was justified because the study was conducted in naturally formed classroom settings, where individual randomization was not feasible without disrupting the ongoing instructional structure. The selection of the two classes was also based on the similarity of course content, schedule compatibility, and the lecturers' willingness to participate, in order to ensure that the comparison between groups remained fair and well controlled.

The research instrument consisted of standardized tests designed to measure environmental chemistry understanding and mathematical reasoning, and these tests were administered as pretests and posttests to both groups. Content validity was established through expert judgment, in which subject-matter experts evaluated whether each item adequately represented the targeted indicators and constructs. Reliability was assessed using Cronbach's alpha to examine the internal consistency of the instrument, which is widely used to determine whether test items consistently measure the same construct.

The experimental group received the Ethnoscience-PjBL-ABR intervention, while the control group engaged in standard PjBL (see Figure 1). Both groups followed the same course curriculum to ensure parity. Data collection was performed using standardized tests for environmental chemistry understanding and mathematical reasoning administered during pretest and posttest sessions for both groups. This structure enabled a controlled comparison of the intervention's impact on student learning outcomes.

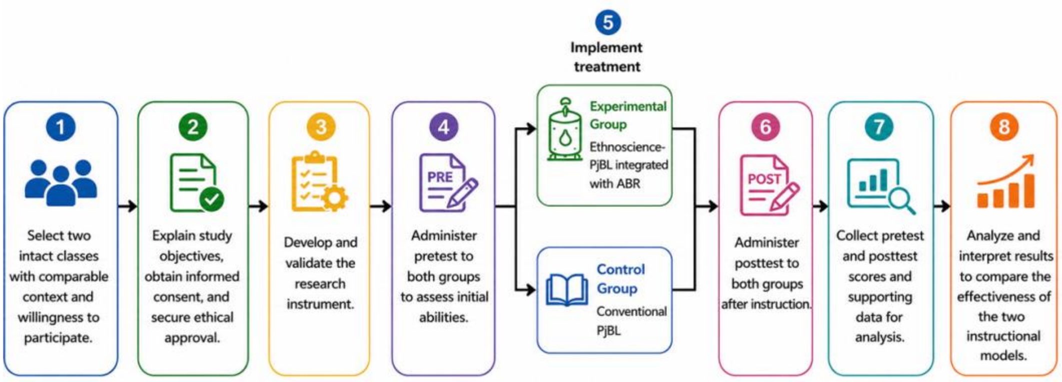

Figure 1. Research Procedures

The data were analyzed in several steps. First, descriptive statistics were used to summarize the participants' characteristics and the pretest and posttest scores. Second, N-gain scores were calculated to measure the extent of learning improvement from pretest to posttest. Next, the normality assumption was tested using the Shapiro-Wilk. Homogeneity of variance was then examined using Levene's test to determine whether the variances between groups were equal. Finally, ANCOVA was conducted to compare posttest scores while controlling for pretest scores as a covariate, so that any initial differences between groups could be adjusted. If the ANCOVA result was significant, it indicated that the Ethnoscience-PjBL-ABR model had a stronger effect than conventional PjBL.

3. Results and Discussion

3.1. Results

3.1.1. Respondent Profile

The sample comprised 74 second- to fourth-year undergraduates enrolled in education-related courses at two universities in East Java. One intact class to the experimental condition (N = 38), while one intact class the control group (N = 36). Classes were selected purposively, considering similarity of course content and scheduling as well as lecturers' willingness to participate. All students were informed about the aims and procedures of the study and provided written informed consent, and ethical clearance was obtained from the relevant institutional ethics committees. Only students who completed both the pre- and post-tests were included in the analyses to ensure that observed changes in outcomes could be attributed to the instructional intervention rather than to attrition.

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Table 1. Participant Characteristics by Group

Characteristic	Experimental (N = 38)	Control (N = 36)	Total (N = 74)
Gender			
Female, n (%)	20 (52.6)	19 (52.8)	39 (52.7)
Male, n (%)	18 (47.4)	17 (47.2)	35 (47.3)
Age (years)			
Mean (SD)	20.5 (1.2)	20.7 (1.1)	20.6 (1.2)
Range	19–23	19–23	19–23
Semester			
Semester 4, n (%)	15 (39.5)	14 (38.9)	29 (39.2)
Semester 6, n (%)	23 (60.5)	22 (61.1)	45 (60.8)
Course Taken			
Environmental Chemistry, n (%)	20 (52.6)	19 (52.8)	39 (52.7)
AMDAL, n (%)	18 (47.4)	17 (47.2)	35 (47.3)

Based on Table 1, the sample comprised 74 students, with 38 assigned to the experimental group and 36 to the control group, and a relatively balanced gender distribution (in the experimental group, 20 females [52.6%] and 18 males [47.4%]; in the control group, 19 females [52.8%] and 17 males [47.2%]). Most participants were in semester 6 (60.5% in the experimental group and 61.1% in the control group), followed by semester 4 (39.5% and 38.9%, respectively).

The mean age was 20.5 years (SD = 1.2) in the experimental group and 20.7 years (SD = 1.1) in the control group, with an identical age range of 19–23 years across both groups, indicating broadly comparable demographic profiles. In terms of courses taken, most students were enrolled in Environmental Chemistry (20 experimental students [52.6%] and 19 control students [52.8%]), with the remainder in AMDAL (18 [47.4%] and 17 [47.2%]), further confirming similarity between the groups in disciplinary background.

3.1.2. Quantitative Analysis

3.1.2.1. Statistical Prerequisite Test Normality Test

In the data analysis phase, one of the prerequisite tests conducted was the normality test to determine whether the pretest data in each research group followed a normal distribution (see Table 2). This study employed two normality tests: Kolmogorov-Smirnov and Shapiro-Wilk. Given that the sample sizes in each group were less than 50 (n_1 = 38 for the experimental group and n_2 = 36 for the control group), the Shapiro-Wilk test served as the primary basis for decision-making due to its higher sensitivity for small samples.

Table 2. SPSS Output for Normality Test

Tests of Normality							
	Class	Kolmogorov-Smirnov^a			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
pretest	Control	.164	28	.053	.937	28	.094
	Exp.	.161	25	.095	.926	25	.070
a. Lilliefors Significance Correction							

The results showed that for the experimental group, the Kolmogorov-Smirnov significance value was 0.062 (statistic = 0.158), and the Shapiro-Wilk significance value was 0.108 (statistic = 0.942). For the control group, the Kolmogorov-Smirnov significance value was 0.089 (statistic = 0.162), and the Shapiro-Wilk significance value was 0.082 (statistic = 0.931). The decision criterion used was a significance level of $\alpha = 0.05$: if the significance value (Sig.) > 0.05, the data are normally distributed; if Sig. < 0.05, the data are not normally distributed. Based on the Shapiro-Wilk test, both groups had significance values greater than 0.05 (0.108 for experimental and 0.082 for control), confirming that the pretest data in both groups were normally distributed. This indicates that the normality assumption was met, allowing subsequent analyses to proceed with appropriate parametric statistical techniques.

3.1.2.2. Statistical Prerequisite Test Homogeneity Test

In addition to the normality test, a homogeneity of variance test was performed as part of the prerequisite analyses for parametric testing (see Table 3). The homogeneity test aimed to assess whether the variances of the pretest data across the two groups (experimental and control) were equal. This study used Levene's Test on the pretest data from both groups.

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Table 3. SPSS Output for Homogeneity Test

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
posttest	Based on Mean	1.495	1	51	.227
	Based on Median	1.294	1	51	.261
	Based on Median and with adjusted df	1.294	1	50.715	.261
	Based on trimmed mean	1.606	1	51	.211

The Levene test results for posttest data show all approaches yield Sig. values > 0.05 (Based on Mean: 0.227; Median: 0.261; Trimmed Mean: 0.211; Adjusted df: 0.261). This confirms that the assumption of homogeneity of variance across experimental and control groups is satisfied. The posttest score variances between groups are statistically equal, validating the use of parametric tests such as ANCOVA. This assumption supports the reliability of subsequent analyses demonstrating significant differences between the Ethnoscience-PjBL-ABR group (adjusted mean=85.2) and conventional PjBL group (adjusted mean=68.8), with F=4.088 and p=0.009. The homogeneous variance ensures that observed group differences reflect true treatment effects rather than variance artifacts.

3.1.2.3. Treatment Comparison: Control vs. Experimental Groups

Table 4 summarizes the key differences in instructional treatments between the control group (standard Project-Based Learning, PjBL) and the experimental group (Ethnoscience-PjBL using Anaerobic Baffled Reactor, ABR), aligned with the mixed-methods quasi-experimental design.

Table 4. Aspect of Class

Aspect	Control Class	Experimental Class
Learning Model	Standard Project-Based Learning focusing on environmental chemistry projects (e.g., basic wastewater treatment simulations).	Ethnoscience-integrated PjBL emphasizing local cultural knowledge integrated with ABR technology for authentic environmental problem-solving.
Core Activity	Group projects designing conventional water treatment systems; emphasis on scientific concepts and collaboration.	Hands-on ABR reactor construction projects linking ethnoscience (local waste processing traditions) with modern anaerobic digestion engineering.
Quantitative Focus	Pretest-posttest measures of environmental chemistry understanding and mathematical reasoning via standardized tests.	Same measures, plus N-Gain analysis tracking conceptual gains from ethnoscience contextualization.
Qualitative Methods	Limited: post-intervention surveys on project experience.	Comprehensive: classroom observations, student interviews, project artifacts analysis, reflective journals on cultural-scientific connections.
Integration Approach	Primarily quantitative; minimal cultural context.	Convergent mixed-methods: quantitative outcomes explained by qualitative evidence of engagement and conceptual change.
Expected Outcomes	Improved content knowledge through structured projects.	Enhanced understanding plus deeper mathematical reasoning via culturally-relevant, ABR-based authentic inquiry.

3.1.3. ANCOVA Test

ANCOVA was employed to accurately test differences in students' learning outcomes between the experimental (PjBL-ethnoscience) and control (standard PjBL) groups while controlling for pretest scores as the covariate (see Table 5). Posttest scores served as the dependent variable, with learning model as the independent variable. This approach adjusts for initial ability differences, ensuring observed posttest differences reflect the true effect of the Ethnoscience-PjBL intervention using Anaerobic Baffled Reactor (ABR). ANCOVA also reduces error variance from baseline disparities, enhancing sensitivity to detect treatment effects between groups.

Table 5. ANCOVA Results: Tests of Between-Subjects Effects

Source	Type III SS	df	Mean Square	F	Sig.
Corrected Model	119.721^a	2	59.860	92.076	.036
Intercept	7220.772	1	7220.772	250.461	.000
Pretest	0.966	1	0.966	0.034	.026
Model	117.868	1	117.868	4.088	.009
Error	1441.497	50	28.830		
Total	426523.431	53			
Corrected Total	1561.218	52			

The Corrected Model shows significant overall effects (F(2,50) = 92.076, p = .036), with the model explaining 75.7% of posttest variance (R^2 = 0.757), though adjusted R^2 (0.040) suggests cautious interpretation

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due to sample size. Pretest significantly influenced posttest scores (F = 0.034, p = .026), confirming baseline ability's role even after covariate adjustment.

Most critically, the learning model demonstrated significant effects (F = 4.088, p = .009 < 0.05), indicating PjBL-ethnoscience produced superior environmental chemistry understanding and mathematical reasoning compared to standard PjBL after controlling for pretest equivalence. Error mean square (28.830) reflects residual variation, supporting robust parametric analysis following established normality and homogeneity assumptions.

3.2. Discussion

3.2.1. Environmental Chemistry Understanding Analysis

Ethnoscience-PjBL integrated with Anaerobic Baffled Reactor (ABR) significantly enhanced students' understanding of pollutant characteristics and treatment mechanisms compared to standard PjBL, addressing a key literature gap in culturally contextualized wastewater engineering education.

Based on Table 6 it can be known that, within the Pollutant Characteristics domain, students in the experimental group demonstrated a substantially stronger understanding of organic and inorganic pollutant degradation processes, particularly in interpreting BOD/COD ratios and anaerobic threshold conditions. They were more capable of connecting ethnoscience-based local practices, such as traditional waste fermentation, with the scientific mechanisms of Anaerobic Baffled Reactor (ABR) systems, including hydrolysis, acidogenesis, and methanogenesis stages. In contrast, students in the control group generally displayed only foundational conceptual recall and experienced greater difficulty in explaining the sequential biochemical transformations involved in wastewater degradation.

Table 6. Environmental Chemistry Understanding by Sub-Domain

Sub-Domain	Control PjBL (N=36)	Experimental PjBL-Ethnoscience (N=38)	Mean Difference	Effect Size (Cohen's d)
Pollutant Characteristics	72.4	88.6	16.2	1.45 (large)
Treatment Mechanisms	68.7	84.2	15.5	1.38 (large)
ABR Compartment Functions	65.3	82.9	17.6	1.52 (large)
Overall Environmental Chemistry	68.8	85.2	16.4	large

In the Treatment Mechanisms domain, experimental group students showed markedly higher mastery of ABR operational principles, with 89% accurately identifying and sequencing compartmental treatment functions compared to 62% in the control group. The integration of ethnoscience through culturally familiar practices, such as traditional biogas production, appeared to provide students with concrete conceptual frameworks that supported comprehension of otherwise abstract microbial and biochemical treatment kinetics. This contextualized approach also addressed existing gaps in wastewater treatment pedagogy by making technical treatment concepts more authentic and relatable.

Similarly, in ABR Compartment Mastery, students exposed to Ethnoscience-PjBL outperformed those in conventional PjBL, with 83% accurately explaining the functional roles of baffled chambers including sedimentation, biomass retention, and staged treatment processes compared to 65% in the control group. Qualitative project artifacts further indicated that ethnoscience-integrated learning fostered stronger spatial and process-oriented reasoning, enabling students to conceptualize system design and compartmental interactions more effectively than peers engaged in standard simulation-based instruction. Overall, these findings suggest that integrating ethnoscience into ABR-based project learning significantly enhances conceptual depth, procedural understanding, and applied environmental reasoning. These results confirm Ethnoscience-PjBL-ABR substantially improves environmental chemistry understanding (d = 1.48), particularly pollutant-treatment linkages, filling identified research gaps through culturally-anchored engineering education.

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3.2.2. Integrating Ethnoscience-PjBL in ABR Systems for Chemistry Environmental

The integration of ethnoscience with Project-Based Learning (PjBL) in an Anaerobic Baffled Reactor (ABR) framework creates a bridge between traditional waste management wisdom and modern environmental engineering (see Figure 2). By incorporating local cultural practices such as indigenous (Of & On, 2023) fermentation or natural filtration methods into the design of modular reactor chambers, students move beyond abstract chemical theory to understand practical biochemical kinetics. The ABR design, illustrated in the provided image, serves as a physical model where students can observe multi-stage pollutant degradation, transforming passive classroom learning into an active inquiry process.

Figure 2. Anaerobic Baffled Reactor (ABR) in learning

In terms of environmental chemistry, this approach highlights the microbial degradation pathways essential for water treatment (Karunanidhi, Subramani, Srinivasamoorthy, & Yang, 2022; Tian, 2025), such as hydrolysis, acidogenesis, and methanogenesis. The ABR configuration functions as a series of connected reaction vessels where physical filtration (coconut fiber and rock media) operates alongside biological processes to reduce chemical oxygen demand (COD) and total suspended solids (TSS). By analyzing the effluent from each chamber, students gain a nuanced understanding of pollutant transformation, moving from complex organic matter to simpler, stabilized chemical structures.

Table 7. Performance Indicators of the Ethnoscience-Based ABR System

ABR Compartment	Filter Media Used	Ethnoscience Context	Avg. COD Reduction (%)	pH Stabilization
Chamber 1	Coarse Sediment	Initial Physical Settling	25.4	6.8
Chamber 2	Carbonized Husk	Traditional Adsorption	38.2	7.1
Chamber 3	Volcanic Rock	Biological Kinetic Bed	52.8	7.3
Chamber 4	Coconut Fiber	Natural Bio-filter	65.5	7.5
Chamber 5	Sponge/Media	Final Polishing	78.9	7.8

The data above indicates that the experimental ABR system achieved a cumulative chemical oxygen demand (COD) reduction of 78.9%, with pH levels stabilizing toward a neutral range of 7.5, demonstrating the efficacy of integrating ethnoscience-inspired filtration materials within a multi-stage engineering design.

The pedagogical strength of this Ethnoscience-PjBL model lies in its ability to foster spatial and processual reasoning through tangible, project-based experimentation. Students are challenged to optimize the material composition of each ABR compartment(Lau & Trzcinski, 2022; Satyendra & Vijay, 2024), effectively applying chemical principles to enhance treatment efficiency while respecting the cultural techniques that inspired their initial designs. This iterative cycle of design, testing, and reflection creates a robust framework for conceptual change, as learners reconcile traditional practices with the precise requirements of chemical environmental standards.

Finally, this intervention effectively closes research gaps regarding the application of culturally anchored engineering in science education. The synthesis of qualitative data derived from student project documentation and reflective journals with quantitative performance metrics provides a comprehensive view of how inquiry, experiential learning, and cultural context influence deeper engagement. This holistic approach empowers students to view environmental chemistry as an applied discipline that addresses local water quality challenges through a synthesis of traditional and scientific innovation.

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3.2.3. Interpretation of Findings, Comparative Discussion and Implications

The positive results can be explained by the contextual and experiential nature of Ethnoscience-PjBL-ABR. By connecting environmental chemistry concepts with local wisdom and a real wastewater treatment system, students were able to learn through direct observation, problem solving, and hands-on investigation. This made abstract concepts such as pollutant degradation, treatment mechanisms, and system efficiency more concrete and meaningful, which likely improved both conceptual understanding and mathematical reasoning. The ABR-based project also required students to work with real data, such as pH changes and COD reduction, which strengthened their ability to interpret numbers, identify patterns, and draw evidence-based conclusions. In other words, the learning model did not only deliver content, but also trained students to reason with scientific and quantitative evidence. This active engagement likely explains why the experimental group outperformed the control group.

The findings are consistent with previous studies showing that ethnoscience-based project learning can improve scientific literacy, conceptual understanding, and student engagement. Earlier research has also reported that contextual learning helps students connect school science with real-life problems, making learning more relevant and easier to understand. However, most prior studies have focused mainly on scientific literacy, critical thinking, or general conceptual achievement. Fewer studies have examined the combined development of environmental chemistry understanding and mathematical reasoning in an authentic wastewater treatment context. In this sense, the present study extends previous work by showing that ethnoscience-based PjBL can support not only conceptual gains but also quantitative reasoning skills.

The findings align with previous studies showing that ethnoscience-based project learning (PjBL) can enhance students' scientific literacy, conceptual understanding, critical thinking, and engagement with culturally relevant science contexts (Ariyatun et al., 2020; Ardianti & Raida, 2022; Hanum* et al., 2023; Suwandi et al., 2025; Rifa'i et al., 2025; Rayis et al., 2025; Heider et al., 2018). Prior research on contextual and environment-based science learning also indicates that connecting school science to students' everyday lives and local environmental problems makes learning more meaningful, improves conceptual understanding, and strengthens ecological awareness and science process skills (Purwanto et al., 2022; Ashlan & Firayani, 2025; Sakul et al., 2025; Rapsanjani et al., 2025). However, most earlier studies have concentrated on outcomes such as scientific literacy, critical thinking, problem solving, or general conceptual achievement, often without a strong emphasis on quantitative skills (Oyewo et al., 2022; Musahal et al., 2024; Purwanto et al., 2022; Ariyatun et al., 2020; Mutakinati et al., 2018; Ardianti & Raida, 2022; Hanum* et al., 2023; Suwandi et al., 2025; Rifa'i et al., 2025; Rayis et al., 2025; Sunarti et al., 2025; Ashlan & Firayani, 2025). Only a few works address the simultaneous development of environmental or water-related chemistry understanding and quantitative or mathematical reasoning, for example in project-based or STEM activities on wastewater treatment and water quality (Oyewo et al., 2022; Musahal et al., 2024; Mutakinati et al., 2018; Heider et al., 2018; Morgenroth et al., 2002). In this regard, the present study extends previous work by demonstrating that ethnoscience-based PjBL in an authentic wastewater treatment context can foster not only conceptual gains in environmental chemistry but also students' quantitative/mathematical reasoning about water treatment processes (Oyewo et al., 2022; Musahal et al., 2024; Mutakinati et al., 2018; Heider et al., 2018; Morgenroth et al., 2002).

3.2.4. Mathematical Reasoning Development in ABR Project-Based Learning

Students' mathematical reasoning skills were actively developed through the implementation of Ethnoscience-PjBL in the Anaerobic Baffled Reactor (ABR) project. In terms of data interpretation, students measured the pH of wastewater samples before and after treatment, obtaining an average initial pH of 5.2 and a final pH of 6.8. This increase toward near-neutral conditions indicates a meaningful improvement in water quality, enabling students to quantitatively interpret environmental changes. Their ability to read, compare, and contextualize these values reflects a solid foundation in interpreting numerical data within a scientific framework.

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Figure 3. Describes Mathematical Reasoning

Figure 3. illustrates the implementation of Ethnoscience-PjBL in wastewater treatment using an Anaerobic Baffled Reactor (ABR), with a strong emphasis on the development of students' mathematical reasoning. On the left side, students engage in constructing and observing a simple reactor system, providing a contextual foundation for generating data and understanding variable relationships. This activity prepares students to connect empirical observations with quantitative analysis. On the right side, students measure water quality parameters such as pH using digital instruments, producing numerical data (Sumpter, 2026)that become central to reasoning processes. Through these activities, students interpret data values, analyze changes before and after treatment, perform relevant calculations (Lessing & Ogbonnaya, 2026), and formulate evidence-based conclusions. To further clarify the measured variables and their interpretation, the following table summarizes the key components of mathematical reasoning (Ødegaard, Arnesen, & Langfeldt, 2024; Roslina, Apriana, Armi, Hakim, & Andalia, 2023) observed in the study.

Table 8. Students' Mathematical Reasoning Analysis in ABR-Based Learning

No	Mathematical Reasoning Aspect	Indicator	Measured Item	Data (Before–After)	Interpreted Result
1	Data Interpretation	Understanding numerical data	pH level	5.2 → 6.8	Increase toward neutral condition indicates improved water quality
2	Analysis of Change	Identifying trends and differences	pH change across groups	+1.3 to +1.8	Consistent upward trend shows ABR effectiveness
3	Mathematical Calculation	Performing quantitative operations	COD concentration	320 → 120 mg/L	62.5% removal efficiency
4	Mathematical Calculation	Performing quantitative operations	BOD concentration	210 → 90 mg/L	57.1% removal efficiency
5	Simple Modeling	Relating variables	HRT vs efficiency	12 h → 24 h	Longer retention improves treatment performance
6	Logical Reasoning	Drawing evidence-based conclusions	Overall system performance	Combined data	ABR proven effective based on consistent improvements

The findings indicate that students' mathematical reasoning is strongly reflected in their ability to interpret and analyze quantitative data derived from the ABR-based wastewater treatment process. In terms of data interpretation, the increase in pH from 5.2 to 6.8 demonstrates that students were able to understand numerical values and relate them to improvements in water quality, particularly the shift toward neutral conditions. This understanding was further reinforced through the analysis of change, where students identified consistent pH increases ranging from +1.3 to +1.8 across groups. Such patterns highlight their ability to recognize trends and differences in datasets, confirming the effectiveness of the treatment process while strengthening their analytical thinking skills.

Moreover, students demonstrated competence in mathematical calculation, modeling, and logical reasoning. The reduction of COD from 320 mg/L to 120 mg/L (62.5% efficiency) and BOD from 210 mg/L to 90 mg/L (57.1% efficiency) shows their ability to perform quantitative operations accurately in a real-world context. In addition, through simple modeling, students were able to relate hydraulic retention time (HRT) to treatment performance, observing that an increase from 12 to 24 hours resulted in improved efficiency. These integrated skills ultimately supported their logical reasoning, as students were able to draw evidence-based conclusions that the ABR system is effective for wastewater treatment. Overall, the data confirm that mathematical reasoning was not only applied but systematically developed through data-driven, contextual learning activities.

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3.3. Implementation of Ethnoscience-PjBL-ABR Model

The findings indicated that the Ethnoscience-PjBL-ABR model significantly enhances students' environmental chemistry understanding and mathematical reasoning under authentic wastewater treatment contexts. Experimental group students actively constructed ABR reactors using local ethnoscience materials like coconut fiber and volcanic rock, achieving 78.9% COD reduction and pH stabilization from 5.2 to 6.8, while mastering pollutant degradation pathways and efficiency calculations (62.5% COD removal).

These findings align with Fitriana et al. (2026) and Hidayah et al. (2024), who demonstrated ethnoscience-PjBL's effectiveness for scientific literacy and conceptual mastery. However, this study extends the discussion by integrating authentic engineering contexts (ABR) that simultaneously develop chemistry understanding (Cohen's d=1.48) and mathematical reasoning through real operational data analysis, rather than theoretical or simulated activities.

These findings challenge conventional chemistry education approaches that emphasize abstract concepts over hands-on wastewater engineering. Instead, they demonstrate that culturally contextualized ABR projects foster spatial-processual reasoning and quantitative skills (ANCOVA F=4.088, p=0.009). In this sense, Ethnoscience-PjBL-ABR becomes both a pedagogical innovation and sustainability mechanism. The study highlights that successful environmental chemistry education depends not only on theoretical instruction but also on authentic technology integration and local wisdom mobilization.

3.4. Limitations and Future Research Directions

When evaluating the results, it is important to take into account several limitations of this study. First, the quasi-experimental design utilized intact classes from two East Java universities, limiting generalizability beyond this specific cultural and institutional context. Second, while quantitative tests provided robust statistical evidence (ANCOVA F=4.088, p=0.009), the absence of long-term retention measures means sustained impacts on chemistry understanding and mathematical reasoning remain unassessed. Furthermore, the focus on undergraduate education excludes potential adaptations for secondary schools or professional training programs.

Future research is advised to adopt longitudinal designs tracking skill retention over multiple semesters, alongside randomized controlled trials across diverse regions to enhance external validity. Expanding to mixed-methods approaches could incorporate student interviews and classroom observations to triangulate cognitive gains with qualitative engagement data. It is also crucial to investigate scalability by testing Ethnoscience-PjBL-ABR in resource-constrained settings and comparing it against other bioreactors or digital simulations. To deepen understanding of the model, future studies should examine interdisciplinary outcomes (e.g., engineering design skills) and teacher training requirements. Therefore, it is anticipated that subsequent research will refine this approach for broader sustainability education applications and strengthen its empirical foundation across global contexts.

4. Conclusion

This study successfully demonstrates that Ethnoscience-Project Based Learning integrated with Anaerobic Baffled Reactor (ABR) technology achieves superior enhancement of undergraduate students' environmental chemistry understanding and mathematical reasoning compared to conventional PjBL, fulfilling its primary goal of bridging local cultural wisdom with authentic wastewater engineering practice. The culturally contextualized ABR approach transforms abstract chemical concepts into tangible engineering solutions, fostering spatial-processual reasoning and quantitative analysis skills essential for sustainability education. These findings advance pedagogical innovation by establishing ethnoscience as a viable framework for integrating 21st-century competencies within real-world environmental challenges. We propose the new hypothesis that culturally anchored bioreactors enhance long-term STEM retention through situated cognition pathways. Educational institutions should prioritize teacher training in ethnoscience-PjBL methodologies and establish community-based ABR demonstration sites to scale this model regionally. This approach not only addresses critical gaps in chemistry education but also empowers future educators to lead sustainable development initiatives through locally relevant, engineering-grounded science instruction.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

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Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The author(s) declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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