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HUMAN-CENTRED AI IN ETHNO-CHEMISTRY PJBL TO DEVELOP STUDENTS' CREATIVE THINKING SKILLS AND INDEPENDENT LEARNING

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ABSTRACT

The integration of Artificial Intelligence (AI) into science education has become increasingly pertinent for cultivating students' higher-order thinking skills and learning autonomy. This study aims to: (1) examine differences in creative thinking and learning independence between students engaged in a Human-Centred AI-based Ethnochemistry Project-Based Learning (PjBL) model and those taught without AI integration; (2) determine the extent of AI's effective contribution to both variables; and (3) profile students' learning outcomes following the implementation of the model within macromolecular chemistry instruction. Employing a quasi-experimental design with two cohorts of 70 high-school students each, data were obtained through creative-thinking assessments, self-directed learning questionnaires, and ethnochemical project observations. The data were analysed using descriptive statistics, N-Gain scores, and MANOVA. Findings indicated that the experimental group demonstrated greater gains, with mean N-Gain values of 0.44 for creativity and 0.37 for learning independence. The MANOVA test yielded Hotelling's Trace F = 7.192, p = 0.001, η^2 = 0.177, signifying a statistically significant difference between groups. The Human-Centred AI-based Ethnochemistry PjBL model effectively enhanced scientific creativity, metacognitive reflection, and students' ability to contextualise scientific knowledge within local cultural frameworks. This pedagogical approach aligns with the Merdeka Curriculum's vision of fostering autonomous, contextual learning that embodies the Pancasila Student Profile. Future studies are encouraged to design AI-supported digital instruments and employ mixed-methods approaches to evaluate the model's longitudinal sustainability.

KEYWORDS: Human-Centred AI; Ethnochemistry PjBL; Creative Thinking; Independent Learning; Local Culture.

1. INTRODUCTION

The development of Artificial Intelligence (AI) has revolutionised multiple dimensions of human life, including education, which is now entering an era of intelligent learning ecosystems. AI no longer functions merely as a technological tool but has evolved into a cognitive partner capable of detecting learning patterns, analysing student performance, and adapting learning experiences in a personalised and adaptive manner. Within the framework of Human-Centred AI (HCAI), technology is positioned not as a substitute for human agency but as a catalyst for strengthening learners' reflective, collaborative, and creative capacities (Pérez et al., 2024; Renz & Vladova, 2021; Martini et al., 2024; Gallent-Torres et al., 2024; Gil-Ruiz & Domínguez-Lloria, 2024).

This paradigm aligns closely with the Indonesian education system, the Merdeka Curriculum, a framework that prioritises student-centred learning, nurtures creativity, and develops Pancasila Student Profiles characterised by critical thinking, independence, and integrity. In science education, particularly chemistry, the application of human-centred AI assists teachers and students in understanding abstract concepts through contextual and interactive experiences (Berber et al., 2025; Erümit & Sarıalioğlu, 2025; Chiu, 2021; Jiang et al., 2023; Weymuth & Reiher, 2021).

Chemistry instruction at the secondary level continues to face fundamental challenges. Many students struggle to comprehend macromolecular topics such as carbohydrates, proteins, and fats, due to their complex and abstract nature. These difficulties result in low levels of creative thinking and learning independence, two essential competencies in 21st-century education (Veerasinghan et al., 2021; Perdana et al., 2020; Sudjarwo & Sunyono, 2018; An & Wang, 2024). Overly memorisation-based instruction restricts opportunities for idea exploration and suppresses students' initiative to think critically or solve authentic problems. Therefore, an innovative learning model is needed one that not only emphasises cognitive mastery but also promotes creativity and learner autonomy. Among such innovations, Project-Based Learning (PjBL) has been widely recognised for its effectiveness. PjBL positions students as active agents who investigate, design, and complete projects based on authentic challenges, fostering divergent and collaborative thinking as well as accountability for learning outcomes (Lestari et al., 2024; Pratiwi & Ikhsan, 2024).

Nevertheless, the application of PjBL in chemistry education often encounters constraints, as projects may lack contextual relevance and sufficient digital support. Conversely, the integration of ethnochemistry offers an opportunity to embed local cultural contexts into science learning. Ethnochemistry connects chemical concepts with community practices, such as fermentation, natural dyeing, and traditional food preservation, thereby making learning more contextual, meaningful, and culturally grounded (Ridwana et al., 2025; Cahyani & Wahyudiati, 2023). When human-centred AI is embedded within ethnochemistry-based PjBL, it produces a pedagogical framework that is adaptive and data-driven while remaining humanistic, reflective, and culturally responsive.

Although the pedagogical potential of AI is widely acknowledged, its integration into education still raises academic and ethical debates. The first concerns the extent to which AI enhances or diminishes student learning agency. Some studies suggest that AI promotes self-directed learning by providing automated feedback and personalised learning recommendations (Del Rosario Navas Bonilla et al., 2025; Afzaal et al., 2023; Naseer & Khawaja, 2025; Ramdhani & Hakiman, 2025). However, others warn that excessive reliance on AI may weaken initiative and inhibit critical reflection (M, 2024; Olarewaju et al., 2025; Fischer et al., 2025; Hou et al., 2025; Zhai et al., 2024). Evidence even shows a significant negative correlation between AI use and critical-thinking ability, particularly among younger learners who display higher AI dependence and lower critical-thinking performance (Gerlich, 2025; Zhang et al., 2023).

A second controversy involves the erosion of humanistic values in technology-based learning environments. Many AI platforms prioritise efficiency and academic outcomes while overlooking empathy, ethics, and cultural diversity (Cachat-Rosset & Klarsfeld, 2023; Renz & Vladova, 2021), raising concerns about the diminishing social and emotional dimensions of education. A third debate pertains to the convergence of technology and culture: although ethnochemistry has been shown to strengthen the contextual relevance of chemistry education, integrating it with digital approaches may risk diluting local authenticity. Consequently, there is an urgent need for a pedagogical model that balances technological innovation, humanistic principles, and local cultural identity. The integration of Human-Centred AI into Ethnochemistry PjBL is posited as a balanced response to this pedagogical dilemma.

A review of previous literature identifies four key gaps underpinning this research. (1) Lack of an integrative approach, most studies have examined AI in science education or PjBL in general, without holistically linking both with local culture (Dai & Ke, 2022; Ridwana et al., 2025). (2) Limited focus on macromolecules, although this topic is highly suitable for developing creativity and learning autonomy, few studies have explored it within AI–PjBL integration (An & Wang, 2024). (3) Restricted learning outcome variables, many investigations have measured only conceptual understanding, neglecting simultaneous analysis of creative thinking and independent learning. (4) Lack of empirical data on AI's effect size, experimental studies quantifying the contribution of AI within ethnochemistry-based PjBL remain scarce, leaving limited quantitative evidence of its pedagogical impact. Addressing these gaps renders the present research both timely and relevant as a culturally and technologically balanced educational innovation.

Recent studies affirm that both AI and PjBL positively influence learning outcomes, yet the two approaches have rarely been combined systematically. Lestari et al. (2024) demonstrated that PjBL enhances students' active participation in chemistry learning, while Tinenti et al. (2025) found that projects grounded in local wisdom foster motivation and emotional engagement. Similarly, Ramdhani and Hakiman (2025) concluded that adaptive AI improves students' self-regulation and academic confidence through real-time feedback. However, no prior research has integrated AI, PjBL, and ethnochemistry within a single humanistic model. This gap presents a valuable opportunity to design a learning framework that situates students at the intersection of technological innovation and cultural relevance.

Accordingly, this study occupies a strategic position bridging two major research streams. The works of Babalola and Keku (2024) and Ridwana et al. (2025) confirm the effectiveness of ethnochemistry in enhancing cultural literacy and creativity, whereas Pratama and Ekarini (2025) emphasise AI's contribution to learning independence. Yet these studies remain distinct. The present research integrates both perspectives through a Human-Centred AI-based Ethnochemistry PjBL framework that aspires not only to improve academic outcomes but also to cultivate learners' human values, creativity, and autonomy. Hence, the proposed model holds significance not only for advancing chemistry pedagogy but also for reinforcing the Merdeka Curriculum's orientation toward project-based, reflective, and contextual learning.

The primary objectives of this study are to: (1) analyse differences in creative-thinking skills and learning independence between students taught using a human-centred AI-based Ethnochemistry PjBL model and those taught without AI integration; (2) assess the magnitude of AI's effect on these two variables; and (3) map students' achievement profiles following the implementation of the model in macromolecular chemistry learning.

Ultimately, this research extends the discourse on the integration of AI and local culture in science education, asserting that technological innovation must be grounded in human values and cultural sustainability. Furthermore, it provides practical implications for chemistry teachers to serve as creative facilitators who leverage AI to strengthen reflective and contextual learning. The study contributes to the global dialogue on AI and society by underscoring that AI-driven education should advance human flourishing through the development of creativity, cultural awareness, and holistic human potential.

2. METHODOLOGY

2.1. Research Design

This study employed a quasi-experimental design with a pretest–posttest control group structure to evaluate the effectiveness of Human-Centred AI-based Ethnochemistry Project-Based Learning (PjBL) in enhancing students' creative thinking skills and learning independence on the topic of macromolecules. This design enabled a comparative analysis between the experimental group, taught through AI-integrated instruction and the control group, which followed a similar PjBL model without AI integration. The quasi-experimental approach was selected as it offers a practical balance between experimental control and ecological validity within authentic school settings.

Table 1: Research Design.

Group	Pretest	Treatment	Post-test
Experimental	T1, T2	X1: AI-based ethnochemistry PjBL	T1, T2
Control	T1, T2	X2: Ethnochemistry PjBL without AI	T1, T2

Note: T1 = Creative thinking skills test; T2 = Learning independence questionnaire; X1 = AI-based ethnochemistry PjBL; X2 = Ethnochemistry PjBL without AI.

2.1.1. Research Subject

The participants comprised 70 Year 12 students enrolled at State Senior Secondary School 2 Sleman during the 2024/2025 academic year. A purposive sampling technique was applied to ensure comparable baseline academic abilities across groups. One class was assigned as the experimental group, and the other as the control group. Class selection considered the school's contextual conditions and infrastructural readiness for implementing AI-based learning.

2.1.2. Research Variables

This study investigated the following variables:

1. Independent Variable: Learning model (AI-based Ethnochemistry PjBL vs. Ethnochemistry PjBL without AI).
2. Dependent Variables: Students' creative thinking skills and learning independence.

The model was designed to measure the extent to which the integration of Human-Centred AI could exert a statistically significant and educationally meaningful influence on both learning outcomes.

2.1.3. Research Instruments (Data Collection Instruments)

Two primary instruments were utilised for data collection:

1. **Creative Thinking Skills Test.**

This test consisted of 10 open-ended items developed according to the five dimensions of creative thinking proposed by Rohmah (2009): fluency, flexibility, originality, elaboration, and sensitivity. Each question was contextualised within local ethnochemical phenomena in Sleman, such as tempeh fermentation, gudeg preparation, and traditional plant-protein food processing.

2. **Learning Independence Questionnaire.**

The instrument was adapted from Gea et al. (2002) and modified into eight aspects comprising 30 statements (16 positive and 14 negative).

All instruments underwent a two-stage validation process: (1) Content validation by subject-matter experts and educational evaluation specialists, and (2) Empirical validation using the Rasch Model via Winsteps software. Construct validity, item reliability, and item fit were examined using the following criteria: Outfit MNSQ (0.5–1.5), ZSTD (−2.0 to +2.0), and Point Measure Correlation (0.40–0.85). These measures ensured internal consistency, discriminative validity, and data reliability.

2.2. Data Analysis Techniques

Data analysis was conducted in two stages. First, descriptive analysis was used to describe the increase in learning outcomes based on N-Gain scores (Hake, 1998), with categories of high (≥0.7), moderate (0.3–0.7), and low (<0.3). These results were supplemented with an interpretation of ideal scores (Widoyoko, 2009). Second, inferential analysis used Multivariate Analysis of Variance (MANOVA) to test the effect of the learning model on two dependent variables simultaneously. Before the MANOVA test was conducted, all data were tested for statistical assumptions, including normality (Shapiro–Wilk), covariance homogeneity (Box's M), linearity (scatterplot), multicollinearity (Tolerance & VIF), and outlier detection (Boxplot & Mahalanobis Distance).

Effect sizes were calculated using partial eta squared (η^2) and interpreted according to Cohen's (1988) thresholds: small (0.01–0.06), medium (0.06–0.14), and large (>0.14). The analysis results were used to determine both the statistical significance of intergroup differences and the magnitude of Human-Centred AI's contribution to enhancing students' creativity and learning autonomy.

This study was conducted with institutional approval and adhered to ethical research protocols. Participant confidentiality was strictly maintained, and the use of AI was confined to supporting the learning process rather than replacing human cognitive functions.

3. RESULTS

3.1. Overview of Research Results

This study investigated the effect of an Artificial Intelligence (AI)-based Ethnochemistry Project-Based Learning (PjBL) model on the development of creative thinking skills and learning independence among senior high school students in the context of macromolecular chemistry. Data were collected through pretest and posttest assessments, descriptive statistical analysis, Normalised Gain (N-Gain) calculations, and hypothesis testing using Multivariate Analysis of Variance (MANOVA). both theoretical and empirical validation procedures were undertaken to ensure the validity and reliability of the research instruments.

3.2. Theoretical Validation of Research Instruments

The theoretical validation process aimed to ensure that the constructs, indicators, and content of the instruments were aligned with the intended measurement objectives. This process involved six experts, two chemistry education lecturers and four experienced chemistry teachers, who evaluated five key instruments: the teaching module, instructional materials, student worksheets, the creative thinking skills test, and the learning independence questionnaire.

Overall, expert evaluations confirmed that all instruments satisfied the established feasibility criteria. Several refinements were recommended to enhance linguistic clarity, improve visual layout, and strengthen the alignment between indicators and corresponding items. A summary of the expert validation results is presented in Table 2.

Table 2: Summary of Theoretical Validation Results of Research Instruments.

Instrument	Aspects Evaluated	Expert Review and Recommendations
Teaching Module	Writing structure and content	The module meets the eligibility criteria, but minor revisions are needed to make it more systematic and easier to understand.
Teaching Materials	Language and Presentation of Material	Suitable for use, but sentence improvements are recommended to enhance communicative effectiveness.
Student Worksheets	Format and neatness of writing	Can be used with minor revisions to the layout and clarity of instructions.
Creative Thinking Skills Questions	Clarity of sentences and content	Some questions need to be adjusted to align with creative thinking indicators.
Learning Independence Attitude Questionnaire	Statement appropriateness	No significant deficiencies were found; the instrument is ready for use without revision.

3.3. Empirical Validation of Research Instruments

3.3.1. Testing the Validity of the Creative Thinking Skills Test

Empirical validation was performed using the Rasch Model analysis with the assistance of Winsteps software. The trial involved 110 students from Ngaglik 2 State Senior High School, Sleman Regency. The purpose of this validation was to evaluate item fit with the measurement model, examine item and person reliability, and assess inter-item correlations to ensure internal consistency.

The results of the analysis (Table 3) indicated that all ten items fell within the acceptable range for Outfit Mean Square (MNSQ) values (0.5–1.5) and Point Measure Correlation (Pt-Meas Corr) coefficients (0.40–0.85). These findings confirm that each item met the model's statistical requirements and was capable of consistently distinguishing between students across varying levels of creative thinking ability.

Table 3: Results of Creative Thinking Skills Item Validation.

Entry Number	Outfit MNSQ	Outfit ZSTD	Pt-Measure Corr	Description
10	1.34	2.3	0.49	Valid
2	1.33	2.0	0.53	Valid
9	1.21	1.4	0.58	Valid
1	1.19	1.4	0.60	Valid
7	1.12	0.9	0.63	Valid
4	0.82	-1.4	0.68	Valid
8	0.74	-2.1	0.71	Valid
6	0.71	-2.3	0.78	Valid
5	0.67	-2.5	0.59	Valid
3	0.65	-2.9	0.78	Valid

All items demonstrated strong internal consistency. For instance, Item 3 recorded an Outfit MNSQ value of 0.65 and a Point Measure Correlation (Pt-Meas Corr) of 0.78, indicating high reliability and satisfactory discriminatory power. Accordingly, all items were deemed valid and suitable for administration in the main study.

3.3.2. Validity Test of the Learning Independence Questionnaire

The validity analysis of the 30-item Learning Independence Questionnaire produced 25 valid and 5 invalid items (Items 9, 10, 14, 15, and 23). The invalid items exhibited Outfit MNSQ values exceeding 1.5, ZSTD scores greater than ±2, and item–total correlations below 0.30, suggesting misfit to the Rasch measurement model and weak discrimination. These items were therefore excluded from subsequent analyses to maintain the instrument's psychometric integrity.

Table 4: Results of the Learning Independence Attitude Questionnaire Validation.

Entry Number	Outfit MNSQ	Outfit ZSTD	Pt-Measure Corr	Description
14	2.31	7.1	0.18	Invalid
9	1.95	6.1	0.02	Not Valid
23	1.59	3.7	0.34	Invalid
7	1.49	3.0	0.56	Valid
13	1.38	2.6	0.68	Valid
11	1.24	1.8	0.38	Valid
2	1.22	1.7	0.43	Valid
26	1.20	1.6	0.47	Valid
28	1.19	1.5	0.53	Valid
3	1.15	1.1	0.45	Valid
27	1.12	0.8	0.43	Valid
30	1.12	1.0	0.37	Valid
1	1.11	0.8	0.38	Valid
17	1.10	0.8	0.35	Valid
22	1.08	0.6	0.64	Valid
16	1.02	0.2	0.43	Valid

20	0.99	0.0	0.66	Valid
18	0.92	-0.6	0.42	Valid
29	0.87	-0.8	0.52	Valid
8	0.87	-0.9	0.24	Valid
12	0.79	-1.4	0.46	Valid
19	0.75	-1.9	0.48	Valid
21	0.74	-1.9	0.51	Valid
4	0.69	-2.3	0.59	Valid
24	0.71	-2.1	0.60	Valid
5	0.63	-2.8	0.46	Valid
6	0.63	-2.8	0.52	Valid
25	0.60	-3.1	0.61	Valid
15	0.48	-4.3	0.50	Invalid
10	0.45	-4.8	0.67	Invalid

The analysis results presented in Table 4 indicate that the five invalid items exhibited extreme response variance, rendering them incapable of measuring the construct consistently. Consequently, these items were excluded from further analysis, and the remaining 25 items were deemed psychometrically sound and appropriate for use in the main data collection phase.

3.4. *Instrument Reliability and Sample Equivalence Check*

3.4.1. *Instrument Reliability Test*

Beyond validity, instrument reliability is a crucial indicator of measurement consistency, ensuring that an instrument yields stable and replicable data under comparable conditions. In this study, reliability testing was conducted for two instruments: the Creative Thinking Skills Test and the Learning Independence Questionnaire. Reliability was examined using Cronbach's Alpha and Rasch-based reliability indices, including Person Reliabilityand Item Reliability.

Table 5: Instrument Reliability Test Results.

Instrument	Cronbach's Alpha	Interpretation	Person Reliability	Interpretation	Item Reliability	Interpretation	Conclusion
Questions	0.85	Highly Reliable	0.83	High Reliability	0.94	High Reliability	Reliable
Questionnaire	0.87	Very Reliable	0.85	High Reliability	0.98	High Reliability	Reliable

The results presented in Table 5 show that the Cronbach's Alpha coefficient for the Creative Thinking Skills Test was 0.85, indicating excellent internal consistency (classified as very reliable). The Person Reliability value of 0.83 and the Item Reliability value of 0.94 further demonstrate strong response stability and high inter-item consistency. Accordingly, the creative thinking test instrument can be considered both reliable and appropriate for measuring students' creative thinking abilities.

Similarly, the Learning Independence Questionnaire yielded a Cronbach's Alpha value of 0.87, signifying high reliability. The Person Reliability (0.85) and Item Reliability (0.98) indices indicate very high levels of consistency both in participant responses and across the questionnaire items. These findings confirm that the learning independence instrument can produce stable and precise data reflecting students' levels of learning autonomy.

With both instruments meeting the criteria for validity and reliability, they are deemed fully suitable for use in the main experimental phase to measure improvements in students' creative thinking skills and learning independence within the Human-Centred AI-based Ethnochemistry PjBL model.

3.4.2. *Initial Ability Equality Test (Sample Homogeneity)*

Prior to implementing the experimental treatment, an equivalence test was conducted to ensure that the experimentaland control groups possessed comparable baseline academic abilities. The test utilised students' performance scores from the Colligative Properties of Solutions topic, which served as an indicator of their initial chemistry competence.

An Independent Samples t-test was employed to compare the two independent groups. Before performing the t-test, Levene's Test for Equality of Variances was applied to verify the homogeneity of variances between groups. When the significance value (p) exceeded 0.05, the data were considered to exhibit homogeneous variances, and the t-test results were interpreted under the assumption of equal variances.

Table 6: Results of the Independent Sample T-Test for the Daily Test on the Colligative Properties of Solutions for Grade XII MIPA 1 and XII MIPA 2.

Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (two-tailed)	Mean Difference	Std. Error of the Difference	95% Confidence Interval of the Difference
								Lower
Chemistry learning	Equal variances assumed	0.647	0.424	0.690	68	0.493	0.60294	0.87412

outcomes	Equal variances not assumed			0.684	60.739	0.497	0.60294	0.88151

Based on Table 6, the significance value obtained from Levene's Test was 0.424 > 0.05, indicating that the two classes possessed homogeneous variance. Therefore, the analysis proceeded using the t-test results under the assumption of equal variances. The Sig. (2-tailed) value of 0.493 > 0.05 further indicates no statistically significant difference in pre-treatment learning outcomes between Class XII MIPA 1 and Class XII MIPA 2.

This finding is essential in confirming the internal validity of the experiment. It demonstrates that any subsequent improvement in students' performance following the AI-based Ethnochemistry PjBL intervention can be attributed to the treatment itself rather than pre-existing differences in academic ability. Moreover, the Mean Difference of 0.60, with a 95% confidence interval ranging from –1.14 to 2.35, confirms that the discrepancy in mean scores between the two groups was minimal and statistically insignificant. These results collectively reinforce the conclusion that both groups had equivalent initial academic abilities prior to the intervention.

3.5. Analysis of Improvements in Creative Thinking Skills and Learning Independence

3.5.1. Description of N-Gain Scores for Creative Thinking Skills and Learning Independence Attitudes

The effectiveness of the AI-based Ethnochemistry Project-Based Learning (PjBL) model was evaluated by analysing students' score improvements before and after the intervention (pretest–posttest design). The magnitude of improvement was expressed using the Normalised Gain (N-Gain) index for two primary variables: creative thinking skills and learning independence attitudes. The N-Gain value quantifies the proportional increase in student performance relative to their initial ability levels, thereby providing an indicator of the learning model's instructional effectiveness. Following the conventional classification, N-Gain scores were categorised as low (< 0.3), moderate (0.3–0.7), and high (> 0.7).

3.5.2. Creative Thinking Skills

Table 7: N-Gain Values for Creative Thinking Skills.

Group	Number of Students	Minimum N-Gain	Maximum N-Gain	Average N-Gain	Category
Experiment	34	0.10	0.76	0.44	Moderate
Control	36	0.00	0.76	0.32	Moderate

As shown in Table 7, the experimental group participating in the AI-based Ethnochemistry PjBL model achieved an average N-Gain of 0.44 (moderate category), whereas the control group engaged in conventional Ethnochemistry PjBL recorded an average of 0.32 (moderate category). Although both groups demonstrated improvement, the increase was consistently higher in the experimental group.

The narrower range of N-Gain values in the experimental class (0.10–0.76), compared with the control class (0.00–0.76), indicates that Human-Centred AI acted as an adaptive facilitator, enabling students to manage projects more effectively, deepen their understanding of macromolecular chemistry concepts, and stimulate creative thinking through real-time visualisation and automated feedback.

Attitude Towards Independent Learning

Table 8: N-Gain Values for Learning Independence Attitude.

Group	Number of Students	Minimum N-Gain	Maximum N-Gain	Average N-Gain	Category
Experiment	34	0.14	0.68	0.37	Moderate
Control	36	0.05	0.55	0.27	Low

As presented in Table 8, the experimental group achieved an average N-Gain of 0.37 (moderate category), while the control group attained 0.27 (low category). These findings suggest that AI-integrated Ethnochemistry PjBL is more effective in enhancing students' autonomy and responsibility in learning. The integration of AI within project-based learning provided students with real-time personalised feedback and opportunities to explore culturally contextual solutions without excessive dependence on teacher direction. This process strengthened students' abilities to manage time, complete tasks independently, and engage in self-evaluation.

3.5.3. Description of Pre-test–Post-test Data on Creative Thinking Skills

Descriptive analysis was conducted to provide an empirical description of the improvement in student learning outcomes before and after the treatment. Table 9 presents the distribution of pretest and posttest scores for creative thinking skills in both the experimental and control groups.

Table 9: Description of Pretest and Posttest Scores for Creative Thinking Skills.

Variable	Experimental Class	Control Class
	Pretest Scores	Posttest Score
n (Number of Students)	34	34
Mean	21.73	34.21
Standard Deviation	4.033	6.129
Variance	16.261	37,562
Highest Value (Max)	32	44
Lowest Value (Min)	13	18
Possible Maximum Value	50	50
Possible minimum value	0	0

The descriptive data in Table 9 reveal that the mean pretest scores of the experimental (21.73) and control (21.28) groups were relatively similar, confirming equivalent initial abilities. After the treatment, the experimental group's mean posttest score increased to 34.21, compared with 30.53 in the control group.

The 12.48-point improvement in the experimental group, compared with 9.25 points in the control group, demonstrates that integrating AI into Ethnochemistry PjBL contributed more significantly to enhancing students' creative thinking performance. The increase can be attributed to AI's ability to support conceptual exploration, facilitate reflective feedback, and visualise abstract macromolecular processes.

3.5.4. Description of Pretest–Posttest Data on Learning Independence

In addition to measuring the increase in creative thinking skills, this study also evaluated the development of students' learning independence attitudes. The results of the pretest and posttest analysis for this variable are presented in Table 10 below.

Table 10: Description of Pre-test and Post-test Data for the Student Learning Independence Questionnaire.

Variable	Experimental Class	Control Class
	Pretest Score	Posttest Score
n (Number of Students)	34	34
Mean	84.62	99.82
Standard Deviation	5.427	7.162
Variance	29.455	51,301
Maximum Value (Max)	97	113
Lowest Value (Min)	75	89
Possible Maximum Score	125	125
Possible minimum value	25	25

The pretest results for both groups, 84.62 for the experimental and 84.83 for the control, indicate equivalent baseline conditions. However, after the intervention, the experimental group's posttest mean rose to 99.82, while the control group's mean reached 95.83. The 15.20-point increase in the experimental group, compared to 10.99 points in the control, highlights the positive impact of AI integration on promoting learning independence. The AI-based system encouraged reflective learning by providing personalised scaffolding that adapted to each student's pace and learning style. The slightly higher standard deviation in the experimental group (SD = 7.162) suggests greater variation in students' responses to AI-assisted learning, reflecting individual differences in adaptability to digital technology. This variation underscores the importance of differentiated instructional strategies in technology-enhanced learning environments.

3.6. Assumption Tests Before MANOVA

Before testing the main hypothesis using Multivariate Analysis of Variance (MANOVA), a series of preliminary tests were conducted to verify that the data met the required multivariate assumptions. These tests included normality, homogeneity of covariance, linearity and outlier detection, and multicollinearity. Satisfying these assumptions ensured that any observed differences between the experimental group (AI-based Ethnochemistry PjBL) and the control group (conventional Ethnochemistry PjBL) were attributable to the learning intervention rather than to statistical bias or uneven data distribution.

3.6.1. Normality Test (Shapiro–Wilk)

The normality of the data was examined using the Shapiro–Wilk test, appropriate for sample sizes under 50 per group. The results are presented in Table 11.

Table 11: Shapiro–Wilk Normality Test Results.

Variable	Group	Statistics	df	Sig.
Creative Thinking Skills	Experiment	0.659	34	0.659
	Control	0.953	36	0.056
Attitude Towards Independent Learning	Experiment	0.067	34	0.067
	Control	0.360	36	0.360

All significance values exceeded 0.05 ($p > 0.05$), confirming that the data for both creative thinking skills and learning independence were normally distributed in both groups. This indicates that score variations were natural and appropriate for parametric analysis. The maintenance of normality strengthens the conclusion that improvements in creative thinking and learning independence were attributable to the Human-Centred AI-based learning model, not to extreme distributions or data bias.

3.6.2. Covariance Homogeneity Test (Box's M Test)

Box's M test is used to test the similarity of covariance matrices between groups. The Box’s M test was used to evaluate the equality of covariance matrices between groups, an essential condition for ensuring comparable variability across dependent variables. The results are shown in Table 12.

Table 12: Results of Box's M Homogeneity Test.

Box’s M	F	df1	df2	Sig.
2.548	0.822	3	933,697.455	0.481

The significance value of 0.481 > 0.05 indicates no significant difference in covariance between the experimental and control groups. Thus, the variance–covariance matrices of both groups were homogeneous, satisfying the assumption of covariance equality. This ensures that subsequent MANOVA results reflect the true effects of the AI-based Ethnochemistry PjBL intervention, rather than artefacts of variance imbalance.

3.6.3. Linearity Test and Outlier Check

The linearity test was conducted to confirm that the relationship between the two dependent variables, creative thinking skills and learning independence, were linear within each group, a requirement for valid covariance interpretation in MANOVA. The results are presented in Table 13.

Table 13: Linearity Test Results.

Variable	Sig.
Creative Thinking Ex × Learning Independence Attitude Ex	0.971
Creative Thinking Exp × Attitude Towards Independent Learning Control	0.982
Creative Thinking Control × Independent Learning Attitude Experimental	0.243
Creative Thinking Control × Learning Independence Attitude Control	0.880

All significance values ranged from 0.243 to 0.982, exceeding 0.05. These results confirm linear relationships between the dependent variables across all groups, with no significant deviations or outliers.

3.7. Multicollinearity Test

Multicollinearity testing was performed to ensure that the two dependent variables were distinct and not excessively correlated. Tolerance and Variance Inflation Factor (VIF) values were used as indicators, as shown in Table 14.

Table 14: Tolerance and VIF Values.

Variable	Tolerance	VIF
Creative Thinking Skills	0.933	1.072
Attitude Towards Independent Learning	0.933	1.072

A Tolerance value of 0.933 > 0.10 and a VIF of 1.072 < 10 indicate no multicollinearity between the two dependent variables. This confirms that creative thinking and learning independence are statistically independent yet conceptually complementary constructs, consistent with the study’s objective of assessing the simultaneous cognitive and affective impacts of AI-based learning.

3.8. MANOVA Test Results and Student Skill Profiles

3.8.1. MANOVA Test Results

After confirming all statistical assumptions, MANOVA was performed to test whether a significant multivariate difference existed between the experimental and control groups across both dependent variables, creative thinking skills and learning independence attitudes. The results are presented in Table 15.

Table 15: MANOVA Test Results.

Test Statistics	F	Sig	Partial Eta Squared
Hotelling’s Trace	7.192	0.001	0.177

The F value of 7.192 with $p = 0.001 < 0.05$ indicates a significant multivariate difference between the two groups across both dependent variables. Therefore, the AI-based Ethnochemistry PjBL model exerted a significant simultaneous effect on students’ creative thinking skills and learning independence. The Partial Eta Squared (η^2) value of 0.177 reflects a large effect size (Cohen, 1988), signifying that approximately 17.7% of the variance in both dependent variables can be explained by the implementation of the Human-Centred AI-based learning model. This demonstrates the strong pedagogical impact of integrating AI principles oriented toward human-centred learning.

3.9. Profile of Students' Creative Thinking Skills

Further descriptive analysis was conducted to map the distribution of students’ creative thinking performance across five core dimensions: fluency, flexibility, originality, elaboration, and sensitivity. The percentage distribution for each category is summarised in Table 16.

Table 16: Profile of Students' Creative Thinking Skills (%).

Aspects of Creative Thinking	Category	Experiment	Control
1. Cognitive Fluency	Very Poor	0.00	0
	Poor	0.00	2.78
	Moderate	11.76	22.22
	Good	17.65	47.22
	Very Good	70.59	27.78
2. Flexibility	Very Poor	0.00	0
	Poor	0.00	5.56
	Moderate	5.88	38.89
	Good	14.71	33.33
	Very Good	79.41	22.22
3. Originality	Very Poor	0.00	0.00
	Poor	0.00	2.78
	Moderate	2.94	33.33
	Good	55.88	50.00
	Very Good	41.18	13.89
4. Elaboration	Very Poor	0.00	0
	Poor	2.94	2.78
	Moderate	17.65	47.22
	Good	44.12	25.00
	Very Good	35.29	25.00
5. Sensitivity	Very Poor	0.00	0.00
	Poor	2.94	2.78
	Moderate	20.59	36.11
	Good	41.18	47.22
	Very Good	35.29	13.89

The data in Table 16 demonstrate that the experimental group consistently achieved a higher proportion of students in the "Very Good (VG)" category across all aspects of creative thinking:

- Fluency: 70.59% (experimental) vs. 27.78% (control).
- Flexibility: 79.41% (experimental) vs. 22.22% (control).
- Originality: 41.18% (experimental) vs. 13.89% (control).
- Elaboration: 35.29% (experimental) vs. 25.00% (control).
- Sensitivity: 35.29% (experimental) vs. 13.89% (control).

Overall, the Human-Centred AI-based Ethnochemistry PjBL approach effectively enhanced all dimensions of students' creative thinking. The AI system functioned as a co-instructor, offering adaptive feedback, facilitating idea generation, and visualising culturally contextualised chemical phenomena, thereby fostering deeper, more reflective creative processes.

3.10. Student Learning Independence Profile

To further understand the impact of the learning model on affective dimensions, an analysis of students' learning independence profiles was conducted based on post-test questionnaire data. Learning independence encompasses eight core indicators that collectively reflect students' autonomy, responsibility, persistence, and reflective capacity. The results are summarised in Table 17.

Table 17: Student Learning Independence Profile (%).

Aspects of Independence	Category	Experiment	Control
1. Able to Work Independently	Very Poor	0.00	0.00
	Poor	0.00	0.00
	Moderate	20.59	8.33
	Good	52.94	80.56
	Very Good	26.47	11.11
2. Accountability	Very Poor	0.00	0
	Poor	0.00	0
	Moderate	0.00	5.56
	Good	55.88	69.44
	Very Good	44.12	25.00
3. Diligence and Discipline	Very Poor	0.00	0
	Poor	0.00	0
	Moderate	32.35	33.33
	Good	44.12	61.11
	Very Good	23.53	5.56
4. Solving Problems Autonomy	Very Poor	0.00	0
	Poor	0.00	0.00
	Moderate	23.53	30.56
	Good	32.35	55.56
	Very Good	44.12	13.89
5. Self-confidence	Very Poor	0.00	0.00
	Poor	0.00	0.00
	Moderate	5.88	11.11
	Good	52.94	75.00
	Very Good	41.18	13.89
6. Addressing Personal Shortcomings	Very Poor	0.00	0
	Poor	0.00	0.00
	Moderate	0.00	5.56
	Good	52.94	72.22
	Very Good	47.06	22.22
7. Time Management	Very Poor	0.00	0
	Poor	0.00	0.00
	Moderate	2.94	11.11
	Good	73.53	69.44
	Very Good	23.53	19.44
8. Resistance to external influence	Very Poor	0.00	0
	Poor	0.00	0.00
	Moderate	2.94	0.00
	Good	73.53	88.89
	Very Good	23.53	11.11

The majority of students in the experimental class scored higher in the "Very Good (VG)" and "Good (G)" categories across nearly all indicators compared with the control group. The most pronounced differences were observed in accountability, problem-solving autonomy, self-confidence, and addressing personal shortcomings, where the experimental group achieved proportions nearly double those of the control group. Although the control group displayed slightly higher percentages in the "Good" category for diligence, discipline, and time management, the overall independence profile of the experimental group was markedly superior. This suggests that AI-integrated Ethnochemistry PjBL, grounded in human-centred principles, effectively fostered students' self-regulated learning, reflective responsibility, and affective engagement with the learning process.

4. DISCUSSION

The findings of this study empirically confirm that the implementation of a Human-Centred Artificial Intelligence (AI)-based Ethnochemistry Project-Based Learning (PjBL) model significantly enhances students' creative thinking skillsand learning independence compared with the conventional PjBL approach without AI integration. The MANOVA results (Hotelling's Trace: $F = 7.192$, $p = 0.001$, $\eta^2 = 0.177$) indicate a strong and significant multivariate effect of AI integration on both variables. More specifically, the average N-Gain scores, 0.44 for creative thinking and 0.37 for learning independence such as demonstrate consistent, moderate improvements, confirming the effectiveness of this human-centred, technology-enhanced intervention.

Accordingly, the research hypothesis, that significant differences exist between students taught using AI-based Ethnochemistry PjBL and those taught using conventional PjBL is accepted. The study's three objectives were also achieved: (1) identifying significant differences in creative thinking and learning independence between groups; (2) determining the effective contribution of AI to these two outcomes; and (3) mapping students' achievement profiles within the context of macromolecular chemistry learning.

The significant improvement in students' creative thinking skills within the experimental group illustrates that the integration of AI into PjBL fosters deeper idea exploration, complex problem-solving, and the generation of original ideas. The student profile analysis revealed a predominance of the Very Good (VG) category in fluency (70.59%) and flexibility (79.41%), indicating students' ability to generate diverse ideas and shift adaptively between strategies. These findings align with Lavli and Efendi (2024), who reported significant gains in idea generation, and with Chen et al. (2019) and De Oliveira Biazus and Mahtari (2022), who confirmed that PjBL effectively enhances fluency and flexibility. This evidence supports Guilford's theory of divergent thinking, which emphasises fluency, flexibility, originality, and elaboration as indicators of creative performance. Similarly, Setiawan et al. (2024) identified flexibility as the most dominant aspect of creativity, enabling students to overcome obstacles by finding alternative approaches.

In chemistry learning, AI tools such as August AI and ChatGPT enable students to conduct rapid simulations and interactive analyses of macromolecular structures, thereby enriching their scientific reasoning processes. AI functions as a cognitive amplifier which extending students' reasoning capacity without replacing the teacher's facilitative role (KH, 2025; Septiani & Ramadani, 2025; Fowlin et al., 2025). This aligns with Shneiderman's (2021) Human-Centred AI paradigm, which envisions technology as a collaborator that augments human creativity and decision-making rather than automates it. By providing visualisations, alternative pathways, and adaptive feedback, AI stimulates elaboration and originality, two critical dimensions of creative scientific thinking (Habib et al., 2023; Kabeer et al., 2025; Chandrasekera et al., 2024).

Furthermore, PjBL allows students to apply chemistry concepts within culturally relevant contexts, such as connecting traditional Sleman foods with macromolecular structures (carbohydrates, proteins, and fats). This contextualisation nurtures cultural creativity, where scientific understanding is generated from local experiences and values. The AI-based Ethnochemistry PjBL model thus cultivates not only cognitive but also socio-cultural creativity, bridging scientific reasoning with community-based knowledge.

These outcomes resonate with Lin and Chen (2024), who found that AI integration in science education expands students' capacity for generating complex, original ideas by offering visual, linguistic, and data-driven stimuli that enhance imagination. Other studies from Hwang & Wu (2024; 2025), Pavone (2025), Rahman et al. (2025), Haywood et al. (2025), and Chandrasekera et al. (2024) similarly reported that generative AI boosts students' innovative thinking by reducing anxiety and strengthening creative confidence. In the present study, AI thus acted not merely as a digital tool but as a co-creator of knowledge within the PjBL framework.

The experimental group's improvement in learning independence (N-Gain = 0.37) demonstrates that integrating AI into Ethnochemistry PjBL also enhances students' responsibility, discipline, and self-reflective capacities. The PjBL framework encourages learners to manage time, set learning goals, and monitor their progress, skills that become more adaptive when supported by AI-based scaffolding.

AI provides real-time feedback, reinforcing self-regulated learning processes. Through automated analytics and data-driven insights, students can identify conceptual errors and make corrections autonomously. These findings are supported by Lee et al. (2025) and Akram et al. (2025), who showed that AI-driven learning environments significantly improve metacognitive awareness and learning responsibility.

In this study, learning independence was understood not only as an individual attribute but also as a social and cultural construct, embedded in the ethnochemical context. Local food-based projects, such as Ketan Serundeng Keju (KESUKE) and Jadah Tempe, enabled students to collaborate, research, and connect chemistry concepts with indigenous practices. This aligns with the principles of Merdeka Belajar within the Merdeka Curriculum, which emphasises autonomous, exploratory, and contextual learning. Studies by Mahmud and Islam (2022) and Agudelo and Vasco (2019) confirm that student responsibility in PjBL emerges through opportunities for decision-making and self-direction. Consistently, students in the experimental group exhibited greater initiative in managing project schedules, selecting local materials, and using AI tools to interpret experimental data. Here, AI did not replace the teacher; rather, it expanded students' reflective and participatory space within the learning ecosystem.

The results of this study strengthen and extend previous evidence on the efficacy of technology-enhanced PjBL in science education. Research by Simangunsong et al. (2023), Antony et al. (2025), Kyselova (2024), and Baskara et al. (2024) confirmed that AI-based PjBL improves creativity and learning motivation through open-ended exploration and collaborative engagement. Likewise, Aisah et al. (2023), Sumarni and Kadarwati (2020), Hikmawati et al. (2021), and Ramadani (2025) demonstrated that contextual learning grounded in local culture fosters students' critical and creative competencies.

The distinguishing feature of this study lies in its focus on Human-Centred AI, which conceptualises technology not as a replacement for teachers but as a pedagogical partner that strengthens students' reflective, empathetic, and adaptive abilities. Consequently, the model prioritises ethical and humanistic learning values alongside technological efficiency, principles aligned with the Pancasila Student Profile embedded in Indonesia's education policy.

The Merdeka Curriculum emphasises learner-centred, project-based, and contextually relevant instruction. The AI-based Ethnochemistry PjBL model developed in this study concretely operationalises these pedagogical principles by integrating scientific inquiry with local cultural contexts. In relation to the Pancasila Student Profile, this model supports all six core dimensions most notably those of critical thinking, creativity, and independence. The findings suggest a paradigm shift in teaching practice, where teachers are encouraged to adopt new roles as facilitators and mentors of AI literacy, guiding students to use technology ethically, critically, and productively. At the institutional level, schools are urged to provide continuous professional development on AI-integrated pedagogy to ensure that technological innovation remains grounded in humanistic values. Moreover, ethnochemistry-based learning that connects local culture with scientific understanding offers a practical framework for implementing the Pancasila Student Profile Strengthening Project (P5). This perspective reframes AI not as a threat to teachers' professional identity but as a collaborative partner that enhances pedagogical capacity. With appropriate policy support, the model can be adapted for other disciplines, such as biology, physics, and the social sciences while preserving its human-centred and culturally rooted orientation.

This study contributes to the theoretical advancement of a Human-Centred AI–PjBL framework in chemistry education by synthesising three foundational paradigms: Constructivism in PjBL (Thomas, 2000), which views learners as active constructors of knowledge; Human-Centred Artificial Intelligence (Shneiderman, 2021), which advocates ethical and collaborative technology use; and Ethnoscience-Based Learning (Aikenhead, 1996), which integrates scientific reasoning with indigenous knowledge systems. The synergy of these frameworks generates a pedagogical model that unites scientific reasoning, ethical awareness, and cultural sustainability. Through the use of AI tools such as August AI for chemical analysis and ChatGPT for reflective dialogue, students experience personalised, contextual, and evidence-based learning. Furthermore, this study underscores the value of ethnochemistry as a bridge between modern science and local wisdom, in harmony with Indonesia's national vision to cultivate scientists who are both innovative and culturally grounded.

The successful implementation of an AI-based Ethnochemistry PjBL model requires adequate technological infrastructure, digital literacy, and institutional readiness. Teachers are expected to develop essential competencies in prompt engineering, AI data interpretation, and reflective pedagogy to effectively and ethically facilitate student learning. In the long term, this model holds promise for enhancing the overall quality of chemistry education and fostering cross-disciplinary collaboration between science and culture. Future research should adopt mixed-method approachesto capture students' cognitive, metacognitive, and affective dynamics during AI-supported learning, as well as longitudinal designs to examine the sustainability of creativity and learning independence across multiple semesters. Additionally, the development of adaptive AI-based assessment instruments will be crucial for measuring creativity and autonomy in real time, consistent with emerging trends in learning analytics. Nevertheless, this study acknowledges that limited digital infrastructure in some schools may constrain the effectiveness and scalability of AI model implementation, thereby highlighting the need for equitable technological access and sustained policy support.

The increase in learning independence scores (N-Gain = 0.37) in the experimental group shows that the integration of AI in ethnochemistry learning also fosters students' responsibility, discipline, and reflective abilities in managing the learning process. The PjBL model encourages students to manage their time, set learning goals, and evaluate their own progress. When supplemented with AI support, this process becomes more personalised and adaptive.

Overall, the findings demonstrate that Human-Centred AI integration in Ethnochemistry PjBL effectively cultivates two core 21st-century competencies, creativity and independent learning. Beyond cognitive gains, this model reinforces cultural literacy and social responsibility, fostering a humanistic learning paradigm that harmonises technological advancement with ethical and local values. This approach offers a transformative direction for chemistry education in Indonesia, one that supports the vision of the Merdeka Curriculum and advances the evolution of a civilised, technology-empowered educational system.

5. CONCLUSION

This study confirms that the integration of Human-Centred Artificial Intelligence (AI) within Ethnochemistry Project-Based Learning (PjBL) significantly enhances senior high school students' creative thinking skills and learning independence in the topic of macromolecules. The incorporation of AI technologies designed to strengthen student agency and reflective capacity produced a statistically significant multivariate difference between the experimental and control groups, with a large effect size across both variables. These results indicate that AI functions as a cognitive and metacognitive partner, expanding students' divergent thinking, flexibility of ideas, and self-regulatory abilities within the PjBL framework. This achievement aligns with the study's primary objective, to demonstrate how the integration of Human-Centred AIand ethnochemical contexts can optimise contextual, creative, and autonomy-oriented chemistry learning. The model not only enhances students' cognitive performance but also cultivates independent scientific character and cultural sensitivity, consistent with the principles of the Merdeka Curriculum and the strengthening of the Pancasila Student Profile. Theoretically, this research contributes to a broader understanding of AI as a co-regulator in project-based learning environments. Practically, it offers ethical and replicable pedagogical guidelines for chemistry teachers at the secondary level, enabling effective AI integration that prioritises human values. Future research is encouraged to develop AI-based digital instruments to facilitate adaptive and scalable implementation across diverse school contexts. Moreover, mixed-method and longitudinal approaches are recommended to obtain a deeper and more comprehensive understanding of the cognitive–affective dynamics and to assess the sustainability of AI–PjBL's impact over time.

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