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ENHANCING TEACHERS' PEDAGOGICAL QUALITY THROUGH STEAM–HERITAGE LEARNING: THE DALIUM PROJECT-BASED LEARNING SYNTAX FOR PORTFOLIO-BASED ASSESSMENT OF SCIENCE COLLABORATION, CIVIC ENGAGEMENT, AND PUBLIC COMMUNICATION

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ABSTRACT

The limited integration of cultural heritage into STEAM education in Indonesia, Malaysia, and Brunei Darussalam has shifted learning practices toward modernization-oriented approaches while weakening students' cultural identity and civic awareness. Although ASEAN countries possess rich Malay cultural heritage as a distinctive national identity, its preservation in education remains largely confined to arts, performances, and museums rather than being meaningfully integrated into classroom learning. This study aims to develop and empirically validate Dalium Project Learning, a culturally integrated Science, Technology, Engineering, Arts, and Mathematics (STEAM) instructional model designed to strengthen teachers' pedagogical quality through portfolio-based assessment and heritage-oriented project learning. The study employed a Research and Development approach based on the Analysis, Design, Development, Implementation, and Evaluation framework, involving 48 in-service teachers from Indonesia and Malaysia selected through purposive sampling, supported by qualitative interview data from Brunei Darussalam. Data were analyzed using K-Means Cluster analysis and Two-Way ANOVA with a 2 × 3 factorial design. The findings revealed significant effects of STEAM–Heritage Learning on science collaboration, civic engagement, and public communication, with the highest improvement observed in science collaboration. The study concludes that Dalium Project Learning effectively integrates cultural heritage, collaborative inquiry, and portfolio-based assessment to strengthen pedagogical quality, communication skills, and socially responsive learning environments. The novelty of this study lies in positioning culture as artistic preservation and as a transformative pedagogical foundation that strengthen ASEAN cultural identity amidst the challenges of globalization.

Keywords: heritage; portfolio-based assessment; pedagogical; cross-national study

INTRODUCTION

In the context of Industry 5.0 and Sustainable Development Goal 4 (SDG 4), education is increasingly expected to develop learners who are cognitively competent, creative, collaborative, culturally responsive, and socially responsible (Medema et al., 2014; Greenier, 2020) Educational systems must prepare students to address social, environmental, and technological challenges through interdisciplinary thinking and human-centered competencies (Astawa et al., 2017; Ortiz-Revilla et al., 2021). Science, Technology, Engineering, Arts, and Mathematics (STEAM) education has gained attention for its capacity to foster creativity, innovation, problem-solving, and twenty-first-century skills through authentic learning experiences (Bautista, 2021; Queiruga-Dios

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et al., 2021; Heung et al., 2025). However, effective STEAM implementation remains highly dependent on teachers' pedagogical quality. Many teachers continue to face difficulties in designing interdisciplinary learning, integrating disciplines, and assessing complex learning outcomes.

These challenges are associated with limited pedagogical readiness, insufficient interdisciplinary competence, and difficulties implementing authentic assessment practices (Duçi, 2021; Ortiz-Revilla et al., 2021; Romero-ariza et al., 2021; Wang et al., 2026). Consequently, teachers' pedagogical quality remains a critical factor affecting STEAM effectiveness and sustainability. Addressing this challenge requires a strong pedagogical foundation. Constructivist theory emphasizes knowledge construction through authentic inquiry (Jiang et al., 2017), while Gagné's cognitive theory supports systematic learning and knowledge transfer (Rapchak, 2017; Dagogo et al., 2019). Social learning and behaviorist theories reinforce collaboration, feedback, and observable outcomes (Lubis & Lubis, 2020; Lubi s et al., 2020a), providing a foundation for science collaboration, civic engagement, public communication, and portfolio-based assessment (Fulmer et al., 2019; Lubis, 2019).

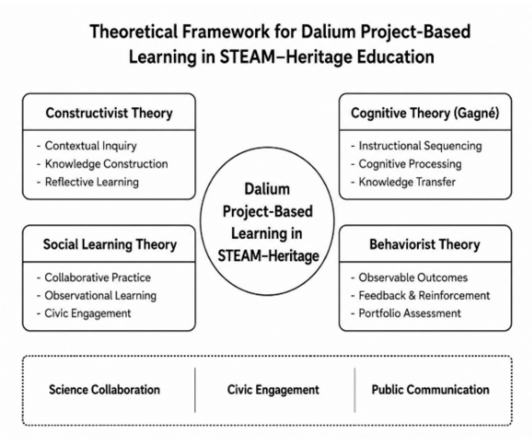

Figure 1. Theoretical Framework

Another important challenge is the limited integration of cultural heritage into STEAM learning. Although STEAM promotes contextual and interdisciplinary learning, its implementation often remains technocentric and disconnected from students' cultural identities (Bautista, 2021). Previous studies have highlighted the importance of arts integration, contextualized learning, and culturally responsive pedagogy in enhancing engagement, creativity, and participation ((Graham & Graham, 2021; López-banet et al., 2021; Queiruga-Dios et al., 2021; Belbase et al., 2022). Nevertheless, culture is often treated as supplementary content rather than as a pedagogical mechanism that shapes learning and competency development. This issue is particularly evident in North Sumatra (Indonesia), Melaka (Malaysia), and Brunei Darussalam, which share a common Malay cultural heritage. Despite these cultural resources, educational practices continue to prioritize scientific and technological competencies while underutilizing culture as an educational asset.

Consequently, many classroom projects replicate globalized models, limiting opportunities to develop cultural identity, civic responsibility, and community engagement (Kim, 2020; Sarti & Bangun, 2021; Stainbank, 2022). Evidence from North Sumatra indicates that 41.5% of teachers still struggle to implement culture-based project learning, while only 45% demonstrate sufficient understanding of STEAM pedagogy. Similar challenges have been reported in Malaysian schools, where project-based learning remains weakly connected to local cultural identity. These findings suggest that cultural sustainability remains marginal within contemporary STEAM practices despite its potential to strengthen contextual learning and human-centered competency development.

A further limitation concerns the assessment of learning outcomes in project-based STEAM education. Portfolio assessment has been widely recommended because it captures authentic learning processes, creativity, collaboration, reflection, and problem-solving skills. However, it is often implemented inconsistently and primarily focuses on final products rather than monitoring students' progress throughout the learning process (Sagastizabal-sáez et al., 2026). Effective portfolio assessment should provide evidence of learning growth, collaboration, communication, and competency development over time (van Duzor, 2012; Barra et al., 2014; Tlili et al., 2019). In practice, teachers frequently encounter difficulties in managing multidimensional assessment criteria, resulting in fragmented and subjective assessment systems. Consequently, assessment practices often fail to provide evidence of science collaboration, civic engagement, public communication, and culturally responsive competencies. These limitations reduce the capacity of portfolio assessment to evaluate the competencies required for Industry 5.0 and SDG-oriented education.

The rapid digitalization of education has strengthened technological competencies while reducing attention to cultural sustainability, civic engagement, and meaningful social participation (Bohloko et al., 2019; Polly et al., 2022; Mehmet Başaran & Erdal Bay, 2023). Although previous studies have demonstrated that STEAM education enhances creativity, collaboration, problem-solving, and environmental awareness (Hoch et al., 2020; Sumarni et al., 2023; Heung et al., 2025), its implementation remains constrained by three critical limitations. First, learning outcomes are typically examined in isolation, with limited attention to the simultaneous development of science collaboration, civic engagement, and public communication. Second, culture is commonly treated as contextual enrichment rather than a pedagogical driver that shapes learning processes and competency development (Barra et al., 2014; Light & Seravalli, 2019; Bautista, 2021; Anderson & Kyzar, 2022). Third, portfolio assessment remains predominantly product-oriented and insufficiently integrated into continuous competency evaluation. Consequently, existing STEAM frameworks have not systematically integrated cultural heritage, project-based learning, and authentic assessment into a coherent model that address the human-centered competencies required for SDG 4 and Industry 5.0 (Leaman & Flanagan, 2013; Saragih et al., 2019; Ito & Takeuchi, 2022; Ja'far et al., 2023).

Building upon the identified gaps, this study proposes the Dalium Project Learning Model, a STEAM–Heritage framework that positions North Sumatra cultural heritage as a core pedagogical driver rather than merely contextual content. Grounded in constructivist, cognitive, social learning, and behaviorist perspectives (Dagogo et al., 2019; Lubis & Lubis, 2019; Wang et al., 2019; Bautista, 2021; Sagastizabal-sáez et al., 2026), the model integrates a structured 16-step project-based learning syntax with continuous portfolio assessment to strengthen science collaboration, civic engagement, public communication, and Industry 5.0 competencies.

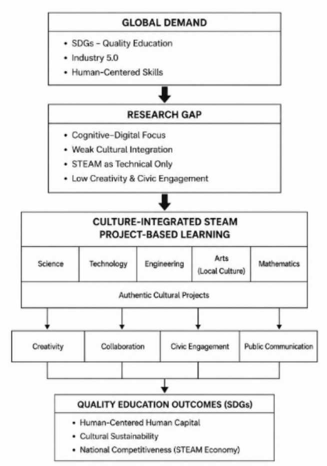

Figure 2. Quality Education Outcomes

Building upon the limitations of previous studies and the identified research gaps, Figure 3 illustrates the novelty of the Dalium Project Learning Model.

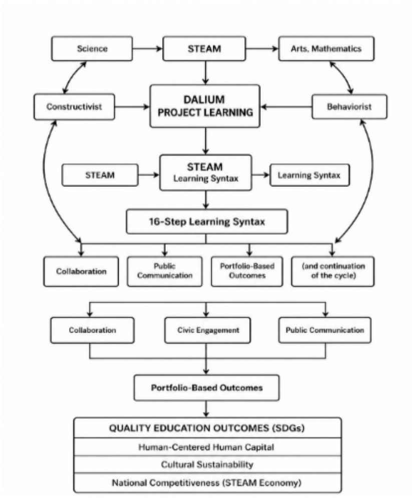

Figure 3. Novelty of Research

Despite the growing body of STEAM education research over the past five years, important gaps remain. Existing studies have mainly emphasized creativity, technological integration, and interdisciplinary learning, while cultural heritage has generally been treated as contextual enrichment rather than as a pedagogical driver (Queiruga-Dios et al., 2021; Sumarni et al., 2023; Heung et al., 2025). Moreover, portfolio assessment largely focuses on final products and rarely supports continuous competency development (Tlili et al., 2019; MacLeod & van der Veen, 2020; Enriched & Skills, 2025; Sagastizabal-sáez et al., 2026; Wang et al., 2026) . Therefore, this study positions itself as an extension of previous research and addresses these gaps by proposing the Dalium Project Learning Model, which integrates North Sumatra cultural heritage, a structured 16-step project-based learning syntax, and continuous portfolio assessment. This integration constitutes the scientific novelty of the study by providing a culturally responsive STEAM framework that simultaneously strengthens science collaboration, civic engagement, and public communication.

Based on the identified research gaps, this study addresses three fundamental questions. First, how can a culture-integrated STEAM learning model grounded in North Sumatra cultural heritage aligned with SDG 4 and Industry 5.0 principles be developed for science education? Second, to what extent is the proposed Dalium Project Learning Model valid, practical, and effective for implementation in science learning contexts? Third, how does the Dalium Project Learning Model improve students' science collaboration, civic engagement, and public communication competencies through a structured 16-step project-based learning syntax supported by continuous portfolio assessment? Addressing these questions is expected to provide empirical evidence for developing a culturally responsive, human-centered, and sustainable STEAM learning framework.

METHODS

This study employed a Research and Development (R&D) design based on the ADDIE model, followed by a quasi-experimental nonequivalent control group design to evaluate the effectiveness of the proposed model as proposed by (Rusdi, 2018, Rusdi, 2020). The ADDIE model was selected because it provides a systematic and iterative framework for developing instructional products grounded in empirical validation. The present study modified the traditional ADDIE cycle by integrating cross-national cluster analysis before hypothesis testing to identify pedagogical typologies between Indonesian and Malaysian teachers. This modification aligns with data-driven instructional development principles and strengthens construct validation in multicultural contexts.

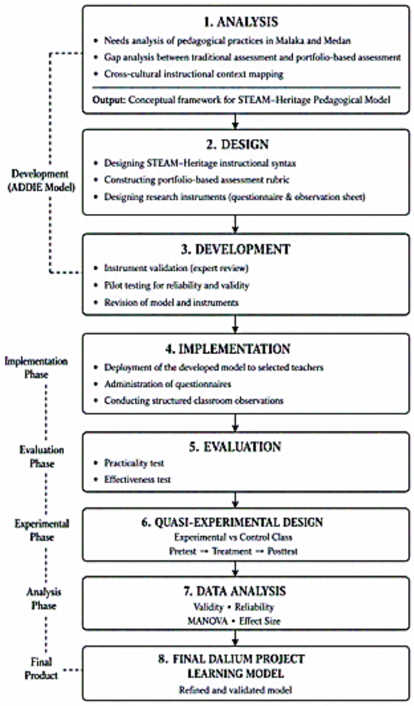

Figure 4. Research Flowchart Based on the ADDIE Model

This study involved 48 in-service teachers from two comparable urban educational contexts in Southeast Asia: Malacca, Malaysia (n = 24) and Medan, Indonesia (n = 24). Participants were selected through purposive sampling based on their experience in science teaching and curriculum implementation. The balanced cross-national composition ensured equal representation from both countries, thereby strengthening comparative statistical analysis within the 2 × 3 factorial design.

The sample size was considered adequate because this research aims to develop, validate, and evaluate the Dalium Project Learning Model rather than to generalize findings to a broader population. Research and development studies emphasize iterative product development, validation, and field testing to assess the practicality and effectiveness of educational innovations. Similarly, the ADDIE model recommends formative evaluation and implementation stages involving representative users to obtain feedback for model refinement and validation (Rusdi, 2018;

Branch, 2021). Therefore, the participation of 48 teachers was considered sufficient to provide meaningful evidence regarding the validity, practicality, and effectiveness of the proposed culture-integrated STEAM learning model. Participant recruitment was limited to schools that met the study criteria and agreed to participate, making purposive sampling the most appropriate approach for achieving the research objectives.

The inclusion criteria were deliberately established to align with both the theoretical framework and the objectives of the study (Creswell & Plano Clark, 2023). Teachers with a minimum of five years of teaching experience were selected because they possess sufficient pedagogical expertise and classroom experience to evaluate the implementation of a culture-integrated STEAM model. The age range of 25–40 years was chosen to ensure participants were actively engaged in contemporary curriculum practices and educational innovation. In addition, all participants held a Bachelor of Education degree, ensuring a comparable level of professional preparation and pedagogical knowledge. These criteria align with the constructivist, cognitive, social learning, and behaviorist foundations of the Dalium Project Learning Model, which require teachers capable of facilitating inquiry-based learning, collaboration, authentic assessment, and competency development. Furthermore, because the study aims to develop, validate, and evaluate the practicality and effectiveness of the proposed model, participants were selected to provide informed and contextually relevant feedback on its implementation in science education settings.

Table 1. Participant Characteristics and Sampling Criteria Across Countries

Variable	Malaka, Malaysia (n = 24)	Medan, Indonesia (n = 24)	Total (N = 48)	Inclusion Criteria	Equivalence Status
Sample Size	24	24	48	—	Balanced (50%–50%)
Teaching Experience	≥ 5 years	≥ 5 years	≥ 5 years	Minimum 5 years	Equivalent
Age Range	25–40 years	25–40 years	25–40 years	25–40 years	Equivalent
Educational Qualification	Bachelor of Education	Bachelor of Education	Bachelor of Education	Bachelor of Education	Equivalent

The minimum teaching experience criterion ensured that participants had passed beyond the early-career adaptation phase and demonstrated stable pedagogical practices. The selected age range represented early-to-mid career teachers, who are typically more adaptive to instructional innovation and pedagogical reform. Requiring a Bachelor's degree in Education ensured baseline pedagogical training consistency across participants. The balanced cross-national design enhanced internal validity by reducing demographic variance while permitting comparative pedagogical pattern identification. By maintaining equivalence in professional characteristics across countries, differences identified through K-Means clustering and subsequent ANOVA could be more confidently attributed to pedagogical quality typologies rather than demographic disparities.

Data Analysis Techniques using SPSS IBM Statistics 27 for Windows, the following:

Table 2. Data Analysis Procedures Using SPSS IBM 27

Analysis Step	Statistical Method	Purpose	Procedure	Output / Interpretation
Step 1	K-Means Cluster Analysis	Classify teachers into homogeneous pedagogical typologies and Identify patterns of STEAM–Heritage pedagogical quality, Determine cluster grouping (High, Moderate, Low)	1. Standardizing all variables using Z-score transformation 2. Determining optimal number of clusters (k = 3) 3. Running iterative centroid recalculation until convergence 4. Interpreting cluster centroids and profile characteristics	Three pedagogical clusters: High, Moderate, Low; Data-driven teacher classification; Cluster membership used as categorical independent variable in ANOVA

Analytical Rationale		Ensures objective, multivariate grouping before inferential testing	Reduces subjectivity in pedagogical categorization	Strengthens internal validity of factorial design
Step 2	Two-Way ANOVA (2 × 3 Factorial Design)	Examine the effect of country and pedagogical cluster on portfolio-based assessment outcomes	Factor A (Country): Indonesia and Malaysia; Factor B (Pedagogical Cluster): High, Moderate, and Low. Dependent Variables: Science Collaboration, Civic Engagement, and Public Communication	Tests: - Main effect of Country - Main effect of Cluster - Interaction effect (Country × Cluster)
Assumption Testing	Normality & Homogeneity Testing	Ensure statistical robustness of ANOVA	Normality: Kolmogorov–Smirnov Test; Homogeneity of variance: Levene's Test and Independence of observations	Confirms the validity of the parametric analysis
Post-Hoc Analysis	Tukey HSD Test	Identify specific group differences if the interaction is significant	Pairwise comparison between cluster groups	Detailed interpretation of group mean differences, The research instrument consisted of 20 statement items. Construct validity was assessed using Confirmatory Factor Analysis (CFA), with all items demonstrating factor loadings greater than 0.50, thereby meeting the criteria for construct validity. Instrument reliability was analyzed using Cronbach's Alpha, yielding a coefficient of 0.86, which indicates a high level of reliability. Therefore, the instrument was considered valid and reliable for measuring teachers' pedagogical quality in the implementation of STEAM education

RESULTS AND DISCUSSION

The research findings were analyzed using two statistical approaches: K-Means Cluster analysis and Two-Way ANOVA (2×3). The first stage of analysis employed K-Means Cluster to identify patterns of teachers' pedagogical quality based on three indicators: instructional readiness, cultural awareness and integration, and learning tools preparedness. By setting k = 3, the 48 teachers (24 from Indonesia and 24 from Malaysia, representing primary and secondary schools) were grouped into three distinct clusters representing high, moderate, and developing levels of pedagogical quality.

These findings support the view that pedagogical quality is context-dependent and influenced by institutional culture, curriculum implementation, and leadership practices. The Malaysian context reflects a curriculum-driven approach in which teachers prioritize compliance with educational directives, whereas the Indonesian context demonstrates a stronger orientation toward project-based learning innovation. The significant interaction between country and educational level confirms that pedagogical quality develops differently across educational environments. Therefore, efforts to improve pedagogical quality should extend beyond adopting STEAM principles to incorporate local cultural values, systematic assessment procedures, and professional development programs that strengthen teachers' capacity to design and evaluate innovative learning experiences.

As shown in Table 3, the Two-Way ANOVA results indicate significant differences in teachers' pedagogical quality based on country and educational level, as well as a significant interaction between these two factors.

Table 3. Tests of Between-Subjects Effects (Two-Way ANOVA General Linear Model)
Dependent Variable: Teachers' Pedagogical Quality Score

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	428.517	5	85.703	18.462	.000
Country	96.284	1	96.284	20.748	.000
Educational Level	184.316	2	92.158	19.859	.000
Country × Educational Level	61.442	2	30.721	6.621	.003
Error	195.017	42	4.643		
Total	7698.000	48			
Corrected Total	623.534	47			

Table 3. The two-way ANOVA demonstrated that the proposed model significantly influences pedagogical quality. Although the main effects of Country ($F(1, 42) = 20.748$, $p < .001$) and Educational Level ($F(2, 42) = 19.859$, $p < .001$), as well as their interaction ($F(2, 42) = 6.621$, $p = .003$), were statistically significant, the effect size analysis provides a clearer understanding of their practical importance. The partial eta squared (η^2p) values indicated large effect sizes for Country ($\eta^2p = .331$), Educational Level ($\eta^2p = .486$), and the interaction between Country and Educational Level ($\eta^2p = .240$). Furthermore, the overall model explained a substantial proportion of the variance in pedagogical quality ($\eta^2p = .687$), indicating a very large effect. These findings suggest that pedagogical quality is not only significantly influenced by country and educational level but that these factors also exert a meaningful and substantial educational impact. In particular, educational level accounted for nearly half of the explained variance, indicating that differences in pedagogical quality are strongly associated with competency development across educational levels. The significant interaction effect further demonstrates that the influence of educational level differs between countries, emphasizing the importance of considering national educational contexts when designing and implementing STEAM pedagogy.

These differences may be associated with variations in curriculum implementation and instructional orientation. Interview findings with the principal of Tun Tjiah School, Melaka, revealed that Malaysian teachers frequently implement learning activities consistent with STEAM principles, although many do not explicitly recognize their practices as STEAM-based instruction. Their teaching approaches emphasize problem-solving, innovation, project work, and competencies required for future employment. In contrast, interviews with the principals of SMA Swasta Al-Washliyah and Yayasan Eria in Indonesia indicated that classroom instruction remains more strongly oriented toward conceptual understanding and the explanation of theoretical knowledge. While both educational systems aim to improve student competencies, Malaysian schools place greater emphasis on practical application and workforce readiness, whereas Indonesian schools remain prioritizing mastery of disciplinary concepts.

These contextual differences may help explain the significant country effect, $F(1, 42) = 20.748$, $p < .001$, and the significant interaction effect between country and educational level, F(2, 42) = 6.621, p = .003. The findings suggest that teachers' pedagogical quality is influenced by educational level and curriculum enactment, instructional traditions, and socio-cultural expectations within each educational system.

The clustering results revealed that most teachers were categorized within the Moderate cluster, followed by the High cluster, while a smaller proportion fell into the Developing cluster. Teachers in the High cluster demonstrated strong readiness in preparing STEAM–Heritage lesson designs, integrating local cultural contexts into classroom practices, and developing structured portfolio-based assessment tools. In contrast, teachers in the Developing cluster showed relatively lower scores, particularly in systematic lesson planning and preparing assessment instruments.

Table 4. Distribution of Pedagogical Quality Clusters

Cluster	Number of Teachers (N)	Percentage (%)	Pedagogical Quality Level
Cluster 1	18	37.5%	High Quality
Cluster 2	20	41.7%	Moderate Quality
Cluster 3	10	20.8%	Developing Quality
Total	48	100%	—

Table 4: The K-Means Cluster classified the 48 participating teachers into three distinct pedagogical quality profiles. Cluster 2 (Moderate Quality) represented the largest proportion, comprising 20 teachers (41.7%), indicating that most participants had established fundamental pedagogical competencies but still required further development to consistently implement high-quality STEAM instruction.

Cluster 1 (High Quality) included 18 teachers (37.5%), suggesting that more than one-third of the participants demonstrated advanced pedagogical practices characterized by effective interdisciplinary integration, authentic assessment, and student-centered learning. In contrast, Cluster 3 (Developing Quality) consisted of 10 teachers (20.8%), indicating that approximately one-fifth of the teachers remain developing essential pedagogical competencies and would benefit from targeted professional development. These findings demonstrate a meaningful variation in pedagogical quality across teachers, with nearly two-thirds (62.5%) remaining in the moderate and developing categories. This distribution highlights the continuing need for systematic interventions to strengthen STEAM pedagogical competencies, particularly for teachers who have not yet achieved high-quality instructional practices.

The predominance of teachers in the Moderate Quality cluster (41.7%) may be explained by several interconnected factors. Interview findings with the principal of SK Malim Tun Tjiah, Malacca, revealed that STEAM training remains limited, particularly in equipping teachers with structured instructional models, learning syntax, and systematic evaluation procedures. The principal acknowledged that many teachers focus primarily on fulfilling curriculum requirements and recommendations from the Malacca Education Department rather than implementing clearly structured pedagogical frameworks. Consequently, teachers often conduct learning activities that already embody STEAM principles without explicitly recognizing them as STEAM-based instruction.

For example, a waffle-making project integrates Science through the exploration of ingredient properties and chemical reactions, Mathematics through measurement and proportion, Technology and Engineering through the use of cooking equipment, and Art through product design and presentation. However, such activities are generally perceived as routine classroom practices rather than structured STEAM learning experiences. In addition, an assessment culture has not yet been fully developed, as teachers tend to prioritize instructional implementation over systematic evaluation of learning outcomes. Furthermore, cultural integration remains an uncommon practice, with teachers often emphasizing current educational trends and policy directives while paying less attention to incorporating local heritage, community values, and national identity into classroom learning. These conditions may explain why most teachers demonstrate adequate pedagogical competence but remain within the Moderate Quality cluster rather than progressing to the High Quality cluster. Subsequently, further statistical analysis was conducted as follows:

Table 5. Final Cluster Centers (Mean Scores)

Indicators	Cluster 1 (High)	Cluster 2 (Moderate)	Cluster 3 (Developing)
Instructional Readiness	4.61	3.74	2.81
Cultural Awareness and Integration	4.53	3.69	2.65
Learning Tools Preparedness	4.58	3.71	2.77

Table 5: The K-Means analysis was conducted on 48 teachers (24 from Indonesia and 24 from Malaysia) by setting k = 3 clusters to classify pedagogical quality into high, moderate, and low categories. The variables analyzed included:

(a) Instructional Readiness (teachers' preparedness in developing lesson plans/modules, designing STEAM–Heritage learning activities, and implementing portfolio-based assessments);

(b) Cultural Awareness & Integration (teachers' ability to recognize, understand, and integrate local cultural values into the learning process);

(c) Learning Tools Preparedness (the completeness and quality of instructional materials, portfolio rubrics, learning media, and evaluation instruments).

The final cluster centers reveal clear differences in pedagogical quality across the three teacher profiles. Teachers in Cluster 1 (High Quality) achieved the highest mean scores for Instructional Readiness (M = 4.61), Cultural Awareness and Integration (M = 4.53), and Learning Tools Preparedness (M = 4.58), indicating strong competence in designing STEAM–Heritage learning, integrating local cultural values into instruction, and preparing comprehensive learning resources and portfolio-based assessments. In contrast, teachers in Cluster 2 (Moderate Quality) demonstrated intermediate performance across all indicators (M = 3.69–3.74), suggesting that although they possessed adequate pedagogical competencies, they further required professional development to implement STEAM consistently and effectively. Teachers in Cluster 3 (Developing Quality) obtained the lowest mean scores (M = 2.65–2.81), reflecting limited readiness to integrate cultural heritage, develop instructional materials, and implement authentic assessment practices. The consistent separation of mean scores across all three indicators confirms that instructional readiness, cultural integration, and learning tools preparedness effectively distinguish teachers' pedagogical quality levels. These findings suggest that cultural integration and instructional preparedness are key dimensions for differentiating STEAM pedagogical quality and should be prioritized in future teacher professional development programs.

The presence of teachers in the Developing Quality cluster may be attributed to differences in access to professional development, school policies, and institutional support. As shown in Table 5, this cluster obtained the lowest scores across pedagogical indicators, particularly in instructional readiness, cultural awareness and integration, and learning tools development, indicating challenges in designing and implementing structured STEAM-based learning. Interview findings revealed that some teachers had limited opportunities to participate in STEAM-related training, particularly training focused on instructional syntax, authentic assessment, and project-based learning. Consequently, teachers often relied on routine classroom practices and curriculum directives rather than evidence-based pedagogical frameworks. Furthermore, variations in school policies and institutional support, including access to teaching resources, mentoring, collaborative planning opportunities, and leadership encouragement, may influence teachers' capacity to innovate and integrate cultural contexts into learning. These findings suggest that strengthening professional development, supportive school policies, and institutional capacity-building initiatives is essential to help teachers progress from the Developing Quality cluster toward higher levels of pedagogical quality.

These findings are further substantiated and visually represented by the curve presented below:

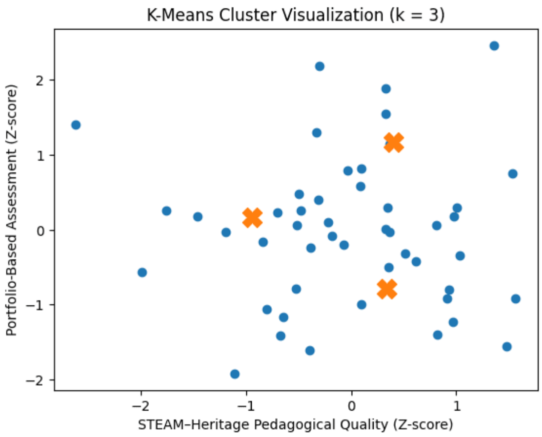

Figure 5. Curve K-Means Cluster

Figure 5 presents the K-Means cluster visualization of 48 teachers based on standardized scores (Z-scores) for STEAM–Heritage Pedagogical Quality (x-axis) and Portfolio-Based Assessment (y-axis). The three orange markers represent the centroids of the identified clusters, illustrating the average position of each pedagogical quality profile. Teachers located around the upper centroid demonstrated consistently higher performance in both pedagogical quality and portfolio-based assessment, representing the High-Quality cluster. The centroid located near the middle-left indicates the Moderate-Quality cluster, characterized by adequate pedagogical competence but less consistent implementation across the assessed dimensions. Meanwhile, the lower centroid represents the Developing-Quality cluster, reflecting teachers with comparatively lower readiness in instructional planning, cultural integration, and authentic assessment practices.

The visual separation among the three cluster centroids demonstrates that the K-Means algorithm successfully differentiated teachers into distinct pedagogical quality profiles. The relatively small overlap between clusters indicates that STEAM–Heritage Pedagogical Quality and Portfolio-Based Assessment effectively discriminate among different levels of teacher competence. These findings strengthen the statistical results presented in Tables 4 and 5, confirming that teachers exhibit heterogeneous pedagogical characteristics rather than a single homogeneous profile. Consequently, the identified clusters provide an empirical basis for designing differentiated professional development programs, enabling educational institutions to tailor capacity-building strategies according to teachers' specific pedagogical needs rather than implementing uniform training.

This clustering stage provided a data-driven categorical variable (Pedagogical Cluster) that was subsequently used as an independent factor in the 2 × 3 factorial ANOVA. By deriving cluster membership empirically, the study minimizes subjective classification bias and enhances the internal validity of inferential testing.

All three parametric assumptions required for Two-Way ANOVA were fulfilled:

Table 5. Summary Three Parametric

Assumption	Test Used	Result	Status
Normality	Kolmogorov–Smirnov	p > .05	Met
Homogeneity	Levene's Test	p > .05	Met
Independence	Research Design	Independent sampling	Met

Prior to hypothesis testing, the assumptions underlying the application of the two-way Analysis of Variance (ANOVA) were systematically evaluated to ensure the robustness and validity of the statistical inferences. As presented in Table 5 and Figure 6, the Kolmogorov–Smirnov test yielded a non-significant result ($p > .05$), indicating that the distribution of pedagogical quality scores did not significantly deviate from normality. This finding confirms that the normality assumption was satisfied, supporting the application of parametric statistical procedures.

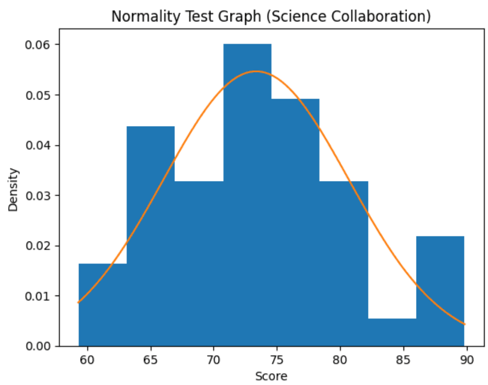

Figure 6. Normality Test Graph

The assumption of homogeneity of variance was subsequently examined using Levene's Test, which also produced a non-significant result ($p > .05$). This outcome demonstrates that the variance of pedagogical quality scores was statistically equivalent across countries and educational levels, indicating that the observed group differences were not attributable to unequal variance. Furthermore, the assumption of independence of observations was ensured through the research design, with participants selected through independent sampling procedures and each teacher contributing only one independent observation to the dataset.

Collectively, these findings confirm that all prerequisite assumptions for conducting the two-way ANOVA were fully satisfied. Consequently, the statistical analyses performed in this study provide unbiased parameter estimates and reliable significance testing, strengthening the validity of the conclusions regarding the effects of country, educational level, and their interaction on teachers' pedagogical quality. Therefore, the data met the necessary conditions to proceed with the 2 × 3 factorial ANOVA analysis.

Thus, the first-stage analysis confirms that strengthening instructional readiness, cultural integration, and assessment preparedness forms the foundational dimension of enhancing teachers' pedagogical quality, providing the basis for further analysis using the 2×3 ANOVA.

Table 6. General Linear Model (GLM) 2×3 Results

Source of Variation	df	F-value	Sig. (p)	Interpretation
Country (Indonesia vs. Malaysia)	1	5.87	.019	Significant difference between countries
Competency Domains (3 Domains)	2	18.42	.000	Significant differences among domains
Country × Competency Domains	2	4.96	.011	Significant interaction effect
STEAM–Heritage Learning (Model Effect)	1	32.75	.000	Strong and significant overall effect

The two-way ANOVA revealed significant differences across all sources of variation. As shown in Table 6, a significant main effect of Country was observed ($F(1) = 5.87$, $p = .019$), indicating that teachers from Indonesia and Malaysia differed in their pedagogical quality. Similarly, Competency Domains demonstrated a highly significant effect ($F(2) = 18.42$, $p < .001$), suggesting that teachers' performance varied substantially across the three pedagogical competency domains. The larger F-value for competency domains indicates that domain-specific competencies contributed more to the observed variation than country differences, emphasizing the importance of strengthening specific pedagogical competencies in STEAM–Heritage education.

Furthermore, the significant Country × Competency Domains interaction ($F(2) = 4.96$, $p = .011$) indicates that the influence of competency domains differed between Indonesia and Malaysia, reflecting the role of educational context on teachers' pedagogical performance. More importantly, the STEAM–Heritage Learning Model demonstrated a strong overall effect ($F(1) = 32.75$, $p < .001$), providing empirical evidence that the proposed model effectively enhanced teachers' pedagogical quality. These findings suggest that integrating cultural heritage, structured project-based learning, and authentic portfolio assessment within a STEAM framework offers a robust pedagogical approach for strengthening teacher competencies and supporting human-centered education aligned with Industry 5.0 and Sustainable Development Goal 4.

Subsequently, further statistical analysis was conducted as follows:

Table 7. Post Hoc Comparison of Competency Domains

Competency Domain	Mean Score (Adjusted)	F-value	Sig. (p)	Rank
Science Collaboration	88.60	21.34	.000	1
Public Communication	84.25	16.12	.000	2
Civic Engagement	81.40	12.57	.001	3

Table 7 shows the significant differences across the three competency domains. Science Collaboration achieved the highest adjusted mean score ($M = 88.60$, $F = 21.34$, $p < .001$), indicating that the STEAM–Heritage Learning Model was most effective in strengthening teachers' ability to collaborate in scientific inquiry and interdisciplinary problem-solving. This was followed by Public Communication ($M = 84.25$, $F = 16.12$, $p < .001$), suggesting substantial improvement in teachers' capacity to communicate scientific ideas and project outcomes effectively. Civic Engagement recorded the lowest, yet still significant, adjusted mean score ($M = 81.40$, $F = 12.57$, $p = .001$), demonstrating that although the model enhanced teachers' participation in culturally responsive and community-oriented learning, this competency requires further reinforcement. Collectively, these findings indicate that the STEAM–Heritage Learning Model exerts a differentiated impact across competency domains, with the strongest contribution on science collaboration while consistently enhancing public communication and civic engagement.

The findings indicate that Science Collaboration achieved the highest mean score (M = 88.60), followed by Public Communication (M = 84.25), while Civic Engagement obtained the lowest mean score (M = 81.40). The dominance of Science Collaboration can be attributed to the nature of the Dalium Project Learning model, which emphasizes collaborative scientific inquiry throughout almost every stage of the learning process. Students work in teams to identify problems, conduct observations, collect and analyze data, generate hypotheses, and develop project solutions. These activities require continuous interaction, teamwork, and shared responsibility, making scientific collaboration the most frequently practiced competency during project implementation.

Public Communication ranked second because students were given several opportunities to present project ideas, discuss findings, and communicate outcomes to peers and community members. The Dalium Project Learning syntax includes project presentations, group discussions, and public dissemination activities that strengthen students' communication skills. However, communication activities are generally conducted at specific stages of the project rather than continuously throughout the entire learning process, which may explain why Public Communication scores were lower than Science Collaboration.

In contrast, Civic Engagement received the lowest score among the three competency domains. Although students were encouraged to identify community issues and develop solutions relevant to local contexts, their active participation in broader community decision-making and long-term social action was relatively limited. Most project activities focused on classroom-based collaboration and product development rather than sustained engagement with community stakeholders. Furthermore, both Indonesian and Malaysian schools tended to prioritize academic achievement, project completion, and curriculum requirements over civic-oriented activities. Consequently, opportunities for students to develop a strong sense of civic responsibility and community involvement were less frequent than those for scientific collaboration and communication.

These findings align with the design of Dalium Project Learning, where collaborative scientific investigation serves as the foundation of project implementation, communication functions as a supporting mechanism for sharing knowledge, and civic engagement emerges as a broader outcome that requires stronger connections between schools, communities, and local stakeholders. Therefore, future implementation of the model should provide more structured opportunities for students to participate in community-based projects, collaborate with local organizations, and engage in authentic social problem-solving to strengthen the civic engagement dimension.

Importantly, the enhancement of Portfolio-Based Assessment competencies reflects a substantial improvement in Teachers' Pedagogical Quality. Teachers demonstrated stronger instructional sequencing, culturally responsive classroom management, reflective assessment practices, and structured feedback mechanisms aligned with constructivist, cognitive, social learning, and behaviorist principles.

This pedagogical strengthening provides the empirical foundation for developing a validated instructional product in the form of the Dalium Project Learning Syntax. The resulting syntax systematically integrates (1) cultural problem identification, (2) collaborative inquiry design, (3) STEAM–Heritage project implementation, (4) portfolio-based reflection and assessment, (5) civic engagement presentation, and (6) public scientific communication. Therefore, the study confirms the effectiveness of the model and generates a practical, research-based learning syntax that enhances teachers' pedagogical quality while fostering value-driven and character-oriented educational practices across primary and secondary education contexts.

The findings demonstrate that Dalium Project Learning contributes to the advancement of STEAM education by addressing several limitations identified in previous studies. Existing STEAM and project-based learning research has generally focused on improving cognitive achievement, creativity, problem-solving skills, or technical competencies, while providing limited guidance on how teachers can systematically integrate assessment, cultural heritage, civic engagement, and communication skills within a single instructional framework (Lage Gómez, & Ros Magán, 2021; Queiruga-Dios et al., 2021; Mehmet Başaran & Erdal Bay, 2023). In many cases, project activities are evaluated primarily based on final products, making it difficult for teachers to monitor students' competency development throughout the learning process. The present study addresses this gap by implementing a structured 16-step instructional syntax that explicitly connects learning activities, competency development, and portfolio-based assessment. As a result, teachers can monitor students' progress continuously while facilitating meaningful learning experiences that connect scientific inquiry with authentic social and cultural contexts.

Another important contribution of this study lies in its assessment framework. Previous studies have emphasized the effectiveness of project-based learning. However, assessment procedures are often insufficiently described or limited to summative evaluations conducted at the end of learning activities. Consequently, important aspects of students' cognitive, social, and communicative development may remain undocumented (Canals & Al-Rawashdeh, 2019; Chen & Yang, 2019; El-Attar, 2019; Kruger et al., 2019; Lubis & Lubis, 2019; Ritawati, 2019; Lubis., et al., 2020b; Mehmet Başaran & Erdal Bay, 2023). Dalium Project Learning addresses this limitation by embedding assessment-by-process throughout each instructional stage, allowing teachers to collect evidence of learning continuously through portfolios. The integration of the Dalium AN-Portfolio platform further strengthens this process by providing a digital environment where project outputs, reflections, and learning progress can be documented systematically (Figure 7). This feature offers a practical solution for teachers seeking to implement authentic and evidence-based assessment practices while maintaining academic integrity through AI-assisted plagiarism detection.

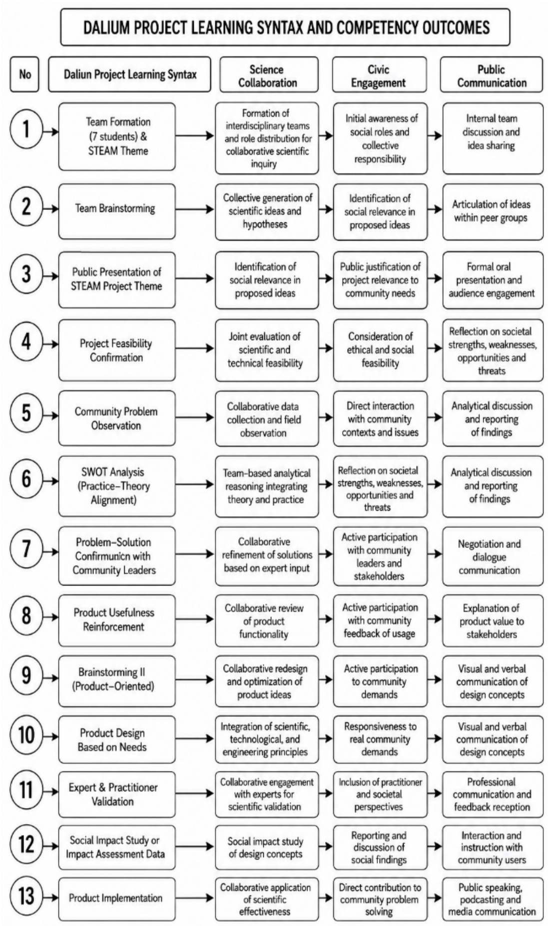

Figure 7. Development of the Instructional Syntax Using the New Learning Model Named Dalium Project Learning

The findings also highlight the significance of cultural heritage integration, an aspect that remains underrepresented in much of the existing STEAM literature. Previous research has demonstrated the value of contextual and culturally responsive learning. However, culture is often treated as a supplementary element rather than a central component of instructional design (Romero-ariza et al., 2021; E Mehmet Başaran & Erdal Bay, 2023; nriched & Skills, 2025;Sagastizabal-sáez et al., 2026). In contrast, Dalium Project Learning places North Sumatran cultural heritage as the foundation of project activities, learning resources, and problem-solving contexts. This approach is supported by constructivist theory, which emphasizes that meaningful learning emerges when students connect new knowledge with their lived experiences and sociocultural environments (Lubis et al., 2023; Yazid et al., 2025). Furthermore, the findings suggest that integrating cultural heritage into STEAM learning strengthens students' scientific understanding and promotes cultural awareness, identity formation, and social responsibility. Such outcomes are particularly relevant for multicultural societies such as Indonesia, Malaysia, and Brunei Darussalam, where cultural preservation and educational innovation should be developed simultaneously (Graham & Graham, 2021; Pada, Chanunan, 2025).

Compared with previous studies, the strength of Dalium Project Learning lies in its ability to integrate multiple educational dimensions within a single pedagogical framework. The model combines structured project implementation, continuous portfolio-based assessment, collaborative inquiry, civic engagement, public communication, digital learning support, and cultural heritage integration. This holistic approach extends beyond the development of technical competencies by fostering communication skills, teamwork, ethical values, and community awareness, which are increasingly important in the context of Industry 5.0 and sustainable development (Nahum et al., 2010; Nahum et al., 2010; Holmes & Hwang, 2016; Jiang et al., 2017; Zhan & So, 2017; Fathonah et al., 2018; Bohloko et al., 2019; Sabuncu, 2022). Nevertheless, this study was conducted within a specific cultural and educational context, and the long-term effects of the model on intercultural competence, environmental literacy, digital adaptability, and character development require further investigation. Future studies should therefore examine the implementation of Dalium Project Learning across diverse educational settings and compare its effectiveness with other international STEAM models to strengthen its generalizability and practical applicability (Mutlu-Bayraktar et al., 2020; Enriched & Skills, 2025; Nguyen & Thai, 2025; Pineda et al., 2025).

CONCLUSION

The findings demonstrate that Dalium Project Learning positively contributes to teachers' pedagogical quality by integrating STEAM, cultural heritage, collaborative inquiry, and portfolio-based assessment. The study confirms that effective pedagogy extends beyond content mastery to include teachers' ability to design meaningful learning experiences, facilitate collaboration, integrate local cultural contexts, and implement systematic assessment practices. The structured 16-step instructional syntax supports the development of science collaboration, civic engagement, and public communication while providing authentic learning experiences connected to real-world issues. Furthermore, integrating North Sumatran cultural heritage enhances the relevance of STEAM learning and promotes cultural awareness, social responsibility, and sustainable educational development aligned with the Industry 5.0 principle. Despite these contributions, the study was conducted within a specific educational context involving a limited number of participants from Indonesia and Malaysia, which may restrict the generalizability of the findings. In addition, the research primarily focused on teachers' pedagogical quality and did not comprehensively examine the long-term effects of Dalium Project Learning on students' academic achievement, intercultural competence, environmental awareness, digital literacy, and character development. Future research should therefore investigate the implementation of the model across broader educational settings and diverse cultural contexts, including comparative studies involving other ASEAN countries. Moreover, future studies are recommended to develop an integrated web-based Dalium System that facilitates the transformation of culturally responsive STEAM learning across both schools and higher education institutions. The proposed platform can utilize cultural heritage sites and local wisdom resources as living laboratories, enabling learners to engage in authentic, interdisciplinary, and community-based learning experiences. Such development would extend the impact of Dalium Project Learning beyond classroom practice by creating a scalable digital ecosystem that supports collaboration, portfolio assessment, heritage preservation, and sustainable STEAM education, while strengthening the connection between education, culture, and societal needs in the Industry 5.0 era.

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