Development Of Interactive Website-Based Learning Media Using The PjBL-STEM Laboy-Rush Approach On Thermochemistry Material

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Abstract. The STEM approach has gained prominence in addressing the demands of 21st-century education, particularly in the complex field of thermochemistry, which poses significant challenges for student understanding due to its abstract nature. Traditional inquiry-based methods, relying on PowerPoint presentations, worksheets, and textbooks, often fail to engage students and promote independent learning. This study introduces ThermoSTEM, an innovative website-based learning platform developed through the Project-Based Learning STEM Laboy-Rush (PjBL-STEM Laboy-Rush) model and the ADDIE instructional framework. The development process included comprehensive stages of analysis, design, and development, followed by rigorous construct and empirical validation. Construct validation by a university lecturer and a high school teacher yielded exceptional validity scores—97.5% for the learning matrix, 91.25% for content validation, 94.38% for the module, 91.25% for instructional materials, 97% for the storyboard, and 96% for the website. Empirical validation involving 30 eleventh-grade students from a senior high school in Malang produced a high readability score of 90.18%, indicating ease of comprehension. These findings confirm that ThermoSTEM is pedagogically sound, user-friendly, and effective for enhancing thermochemistry instruction, ultimately fostering increased engagement, critical thinking, and independent learning among students. In alignment with current educational trends, this innovative platform provides a scalable solution that meets the evolving needs of modern STEM education.

1 Introduction

Addressing the Gaps in STEM Media Development. The rapid evolution of 21st-century education has necessitated a paradigm shift from traditional, teacher-centered instruction to student-centered learning environments that cultivate higher-order competencies. Central to this transformation are the so-called “4Cs” of 21st-century skills: creativity, critical thinking, collaboration, and communication. These competencies are widely recognized as essential for preparing learners to navigate the complexities of a volatile, uncertain, complex, and ambiguous (VUCA) world, as emphasized by global frameworks such as the Partnership for 21st Century

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Skills (P21) and the World Economic Forum. Nevertheless, despite widespread acknowledgment of their importance, practical methodologies for embedding, assessing, and validating these skills in digital learning environments remain underdeveloped.

In science education, the integration of Science, Technology, Engineering, and Mathematics (STEM) with Project-Based Learning (PjBL) has emerged as a promising approach for fostering interdisciplinary understanding and authentic problem-solving abilities (Wahyudi et al., 2025). The PjBL-STEM model, particularly when operationalized through the Laboy-Rush five-step syntax—Reflection, Research, Discovery, Application, and Communication—provides a robust framework for designing learning experiences that are both cognitively demanding and contextually relevant (Laboy-Rush, D., 2011). This model is rooted in constructivist learning theory, which emphasizes student agency, inquiry, and the co-construction of knowledge through projects that mirror real-world challenges (Kwon, H., & Lee, Y., 2025).

While there has been a proliferation of digital and web-based learning media, much of the existing research and development has been anchored in generic frameworks such as TPACK (Technological Pedagogical Content Knowledge). While TPACK offers valuable guidance for integrating technology, pedagogy, and content, it often remains at a high level of abstraction and does not provide detailed, actionable design principles that can effectively operationalize 21st-century skills within specific disciplinary contexts (Ghafara et al., 2025). Furthermore, most TPACK-based studies have emphasized the technical feasibility and usability of digital platforms, neglecting the explicit mapping of theoretical models to media features and the systematic integration and validation of the 4Cs (Husna & Asrizal, 2025).

Study Novelty and International Contribution. This study addresses critical gaps in current literature through several key advancements: a. Theoretical Integration: Instead of framing the Laboy-Rush PjBL-STEM model as merely a label, this research operationalizes its five-step syntax as a principal design and analytical framework for both the development and validation of the learning media. Each phase of the ADDIE instructional design model is explicitly mapped to the corresponding steps of the Laboy-Rush model, ensuring that the theoretical framework is embedded throughout the process (Masruri et al., 2024); b. Explicit Operationalization of 21st-Century Skills: This study refrains from general claims by defining, embedding, and validating each of the 4Cs within the media's features, learning activities, and assessment instruments. The design includes collaborative digital spaces, problem-based inquiry tasks, and communication channels aligned with targeted competencies (Saragih et al., 2025); c. Mapping Theory to Media Features: Detailed mapping of the Laboy-Rush model to the developed website's features (ThermoSTEM) will demonstrate substantive instantiation of the theoretical model within the platform's structure, content, and user interactions. This addresses the critique that theoretical models are often cited without substantive; d. Reframing as a Development and Feasibility Study: Acknowledging the limitations of outcome evaluation without robust experimental designs, this study positions itself as a development and feasibility investigation. The focus is on the validity, usability, and perceived effectiveness of the media through expert validation and empirical readability testing rather than claims of demonstrated impact on learning outcomes (Widya et al., 2024); and, e. International Relevance: By situating this research within the broader landscape of STEM education and digital media development and engaging with international literature on project-based STEM education, 21st-century skills, and instructional design, the study presents insights and design principles that can be adapted across contexts and disciplines (Widya, 2025).

Justification for the Laboy-Rush Syntax. The selection of the Laboy-Rush PjBL-STEM model over more generic frameworks like TPACK is both theoretically and practically justified. Although TPACK provides a valuable lens for considering the interconnection of technology, pedagogy, and content, it does not prescribe specific pedagogical sequences or task structures optimized for STEM education (Zhao et al., 2022). In contrast, the Laboy-Rush framework offers a clear operational sequence—Reflection, Research, Discovery, Application, Communication—that aligns with the cognitive and social processes underpinning effective STEM education and project-based learning (Samala et al., 2023). Numerous validations in diverse contexts have established this model's capacity to scaffold inquiry, foster collaboration, and support the iterative development of solutions to authentic problems (Nasser & Alarfaj, 2020).

Moreover, the Laboy-Rush model is particularly amenable to digital media development, as it provides a modular structure that maps directly onto website features, learning activities, and assessment tools. This facilitates the creation of coherent learning pathways, guiding students from initial engagement through problem resolution while mirroring the processes of scientific and engineering practices.

Focus on Thermochemistry and Digital Innovation. Thermochemistry has been selected as the focal content area owing to its interdisciplinary nature and the persistent challenges students face in grasping its abstract concepts. Mastery of thermochemistry requires the integration of scientific principles, mathematical reasoning, technological tools, and engineering design, making it a compelling domain for demonstrating the efficacy of the PjBL-STEM Laboy-Rush approach. The development of the interactive website-based learning media (ThermoSTEM) represents a significant innovation, leveraging digital technology to support flexible, autonomous, and collaborative learning while also providing a platform for authentic assessment of 21st-century skills.

The objectives of this study are to: a. Develop an interactive website-based learning media (ThermoSTEM) for thermochemistry, grounded in the PjBL-STEM Laboy-Rush model and the ADDIE instructional design framework; b. Explicitly embed and operationalize the 4Cs (creativity, critical thinking, collaboration, communication) within the media's features, tasks, and assessments; c. Map each phase of the ADDIE model to the corresponding Laboy-Rush syntax, ensuring theoretical coherence and design integrity; d. Validate the media's content, structure, and usability through expert review and empirical readability testing, focusing on feasibility and user experience; and, e. Clarify the scope and limitations of the validation approach and provide recommendations for future research on implementation and effectiveness.

2 Method

2.1. Research Design: Educational Design Research and ADDIE-Laboy-Rush Integration

This study adopts a development and feasibility research design situated in the tradition of Educational Design Research (EDR). EDR is characterized by the iterative development of solutions to complex educational problems, emphasizing both practical innovation and theoretical advancement. The research follows the ADDIE instructional design model, with each phase explicitly mapped to the corresponding steps of the Laboy-Rush PjBL-STEM syntax, ensuring that the theoretical model not only informs but drives the design and analysis.

2.2. Operationalization of the 4Cs within Media Design

A central innovation of this study is the explicit operationalization of the 4Cs within the design, content, and assessment features of the ThermoSTEM website. This includes defining, embedding, and validating skills as follows: a. Creativity: Fostered through open-ended project tasks and opportunities for students to propose and test novel solutions to thermochemical problems; b. Critical Thinking: Embedded in inquiry-based activities requiring analysis of data and evaluation of evidence, supported by reflection tools; c. Collaboration: Enhanced through digital discussion forums and group project spaces designed for synchronous and asynchronous teamwork; and, d. Communication: Operationalized by structuring opportunities for students to articulate their reasoning and engage in scientific discourse, with corresponding assessment rubrics. The assessment of the 4Cs includes expert validation for alignment of tasks with targeted skills, as well as empirical readability testing.

2.3. ADDIE Phases and Laboy-Rush Model: Detailed Procedures

Analysis Phase (Reflection) are: a. Needs and Front-End Analysis: Questionnaires and interviews with students and teachers were conducted to identify persistent challenges in thermochemistry instruction; b. Learner Analysis: Profiles of students' academic backgrounds and cognitive characteristics informed the design of multimodal content; and, c. Goal Analysis: Learning objectives were aligned with national curriculum standards and mapped to the Laboy-Rush syntax. Design Phase (Research) are: a. Project Deliverables: A comprehensive inventory of instructional materials was created, including teaching modules and assessment instruments; b. Media Specifications: Visual and interactive design elements were tailored to enhance user engagement; and, c. Content Structure: The website was organized into sequential modules, aligned with the Laboy-Rush steps. Development Phase (Discovery) are: a. Storyboard Creation: A detailed storyboard guided the production of media components; and, b. Media Production: Instructional materials were developed and integrated into the website, ensuring pedagogic goals and user experience principles were met. Implementation Phase (Application) is Planned Deployment: Although full-scale implementation was not executed, the media was prepared for both classroom and online learning environments. Evaluation Phase (Communication) are: a. Expert Validation: The media was reviewed by subject matter experts for accuracy and pedagogical relevance; and, b. Empirical Readability Testing: High school students evaluated the website's design for clarity and engagement.

2.4. Instruments and Validity Evidence

Validation instruments included expert review rubrics and readability questionnaires, ensuring content accuracy and media engagement.

2.5. Scope and Limitations of the Validation Approach

The ccope of this study emphasizes the developmental aspects of ThermoSTEM, focusing on expert validation and readability testing without experimental implementation data. The limitationsof the research is restricted by the absence of robust outcome evaluations and a limited sample size for validation, necessitating further studies in diverse educational settings.

2.6 Mapping Laboy-Rush Syntax to Website Features (ThermoSTEM)

A distinctive feature of this study is the explicit mapping of the Laboy-Rush PjBL-STEM syntax to the ThermoSTEM website features, demonstrating a substantive interaction between theoretical models and practical design. Look Table 1. Each phase is supported by digital tools and scaffolds designed to reinforce the targeted competencies.

2.7 Operationalization of 21st-Century Skills in Tasks and Assessments

To operate the21st-Century Skills in Tasks and Assessments, we've done: a. Creativity: Open-ended project prompts and opportunities for students to design digital artifacts; b. Critical Thinking: Inquiry tasks and reflection tools that promote analysis and evaluation; c. Collaboration: Digital platforms that facilitate group work and peer feedback; and, d. Communication: Tools for articulating reasoning and presenting findings, with associated rubrics. Assessment practices include expert validation of task alignment, student self-reports, and empirical testing of engagement metrics.

Table 1. Mapping of the Laboy-Rush PjBL-STEM syntax to the ThermoSTEM website features

Laboy-Rush Step	Website Feature(s)	Operationalization of 4Cs
Reflection	Diagnostic assessments, learning objectives	Critical thinking (self-assessment), communication (goal articulation)
Research	Instructional materials, guided inquiry tasks	Critical thinking (analysis), creativity (exploration), collaboration (group research)
Discovery	Inquiry-based activities, collaborative problem-solving	Creativity (ideation), collaboration (teamwork), critical thinking (synthesis)
Application	Project tasks, real-world problem-solving	Creativity (solution design), critical thinking (application), communication (presentation)
Communication	Discussion forums, peer feedback, presentation tools	Communication (oral/written), collaboration (peer review), critical thinking (argumentation)

2.8 Methodological Fit and Reporting Standards

The research design adheres to best practices in Educational Design Research (EDR), emphasizing iterative development and validation of educational innovations. The integration of the ADDIE model with the Laboy-Rush syntax underscores both process rigor and theoretical coherence. This study is transparent about its limitations, reframing itself as a feasibility investigation without robust outcome evaluations

3 Results and Discussion

3.1 Development Outcomes: Addressing the Need for Interactive, TPACK-Driven Thermochemistry Media

The development of the ThermoSTEM (on Google Sites in THERMOSTEM - Learning Activities) interactive website-based learning media was initiated in response to persistent challenges in thermochemistry instruction at the senior high school level. Survey data from Grade XI students in Malang revealed that a staggering 95% failed to meet the minimum competency threshold (KKM), with the majority perceiving thermochemistry as moderately difficult (45%), difficult (30%), or very difficult (20%). Only 5% reported no difficulty. Teachers corroborated these findings, noting low student engagement and a predominance of teacher-centered, textbook-reliant instruction despite attempts to use inquiry-based strategies and various media (e.g., PowerPoint, worksheets, textbooks). This context underscores the limited efficacy of existing media in fostering student autonomy, engagement, and mastery of abstract thermochemistry concepts.

The novelty of this study lies in the explicit integration of the Technological Pedagogical Content Knowledge (TPACK) framework with the Project-Based Learning (PjBL) STEM (PjBL-STEM) Laboy-Rush model and the R2DAC instructional sequence (Reflection, Research, Discovery, Application, Communication), operationalized within a web-based platform. Unlike prior TPACK-based media development studies, which often focus on generic digital integration or local adaptations, ThermoSTEM was designed to: a. Accommodate diverse learning styles (visual, auditory, kinesthetic) through multimodal content delivery; b. Embed authentic, inquiry-driven, and collaborative learning activities mapped to the 4Cs (critical thinking, creativity, collaboration, communication); and, c. Leverage the affordances of web-based technology

(Google Sites, Padlet, Google Forms) for seamless access, interactivity, and formative assessment.

This approach responds directly to recent international calls for context-sensitive, skill-oriented, and theoretically grounded digital learning innovations. The explicit mapping of TPACK components to media features and the systematic operationalization of the 4Cs distinguish this study from prior work, addressing specific concerns regarding limited novelty and contribution.

3.2 TPACK Integration: Mapping Framework Components to ThermoSTEM Design and Analysis

Explicit Mapping of TPACK Components. Technological Knowledge (TK): ThermoSTEM leverages web-based technologies (Google Sites for platform development, Padlet for collaborative discussion, Google Forms for diagnostic, evaluation, and reflection instruments) to deliver content, facilitate interaction, and support formative assessments. The choice of a web-based platform (over apk applications) was informed by a technology analysis considering device storage constraints and the availability of internet-enabled devices (smartphones, laptops) and classroom infrastructure (projectors, whiteboards).

Pedagogical Knowledge (PK): The instructional design is grounded in the PjBL-STEM Laboy-Rush model and the R2DAC sequence, emphasizing student-centered, inquiry-based, and collaborative learning. The structured learning activities scaffold reflection, research, discovery, application, and communication, aligning with best practices in STEM pedagogy and 21st-century skills development, as highlighted by.

Content Knowledge (CK): The learning objectives, content structure, and assessment instruments align with the 2024/2025 national curriculum for thermochemistry. The platform provides comprehensive coverage of core concepts (energy changes, enthalpy, calorimetry, Hess's Law) with materials including handouts, PowerPoint slides, instructional videos, and dry-lab experiment guides, facilitating effective content delivery.

Table 2. Mapping of TPACK Components to ThermoSTEM Features

TPACK Component	ThermoSTEM Feature(s)	Example(s)
TK	Web platform, Padlet, Google Forms	Interactive discussion, online assessment
PK	PjBL-STEM, R2DAC, collaborative tasks	Inquiry-based projects, reflection prompts
CK	Curriculum-aligned content, handouts, videos	Thermochemistry concepts, problem sets
TPK	Tech-enabled collaboration and feedback	Padlet for peer review, Google Forms for formative assessment
TCK	Multimedia representations, simulations	Videos explaining enthalpy, calorimetry
PCK	Content-specific inquiry, scaffolding	Dry-lab experiments, structured problem-solving
TPACK	Integrated, authentic STEM learning	R2DAC sequence within web-based environment

Intersections and Synthesis are: a. Technological Pedagogical Knowledge (TPK), the integration of Padlet and Google Forms supports collaborative learning and formative assessment, enabling teachers to moderate discussions and provide feedback; b. Technological Content Knowledge (TCK), Multimedia resources (videos, interactive simulations) are utilized to represent abstract thermochemistry concepts in accessible formats, enhancing comprehension; c. Pedagogical Content Knowledge (PCK), the R2DAC sequence and PjBL-STEM model guide the selection of inquiry tasks, problem-solving activities, and collaborative projects that are content-specific and pedagogically sound; and d. Technological Pedagogical Content Knowledge (TPACK), the platform synthesizes technology, pedagogy, and content, facilitating authentic, technology-enhanced, and content-rich learning experiences.

This explicit mapping addresses concerns regarding the superficial use of TPACK, demonstrating how each component is operationalized in both design and analysis. The TPACK framework was used not only to guide media development but also to interpret validation and readability results. High validity and readability scores across content, language, interactivity, and presentation (ranging from 91.25% to 97.5% for validation and 90.18% for readability) reflect the synergistic integration of technology, pedagogy, and content. Qualitative feedback from validators and students confirms the effectiveness of this integration, with suggestions for refinement leading to iterative improvements.

3.3 Operationalization of 21st-Century Skills: Defining and Measuring the 4Cs

Measurement Strategies and Instruments. Diagnostic Assessment use a Google Form-based diagnostic test assesses prerequisite knowledge and readiness for thermochemistry learning. This formative tool identifies conceptual gaps and informs differentiated instruction. Formative Assessments, embedded throughout the learning sequence (e.g., quizzes, problem sets, dry-lab reports) aligned with the 4Cs. For example, open-ended questions encourage critical analysis, while group tasks assess collaboration. Summative Evaluation, conducted via structured Google Forms, with items mapped to specific learning outcomes and 4C indicators. Learning Reflection, A Google Form-based reflection instrument prompts students to self-assess their progress regarding the 4Cs, identify challenges, and set goals for improvement. This metacognitive tool supports self-regulation and provides qualitative data on skill development. Collaborative Discussion Forum, Padlet facilitates peer-to-peer feedback, group problem-solving, and collaborative inquiry. Participation and quality of contributions serve as indicators of collaboration and communication.

Validation and Readability Instruments. Expert validators and student participants completed structured questionnaires assessing content validity, clarity, interactivity, and relevance. These instruments were adapted from established rubrics and validated for reliability.

Table 3. Operationalization and Measurement of the 4Cs in ThermoSTEM

4C Skill	Operational Definition	Measurement Strategy	Instrument/Indicator
Critical Thinking	Analyze, evaluate, synthesize information	Open-ended questions, problem-solving tasks	Formative quizzes, dry-lab reports
Creativity	Generate original ideas, design solutions	Project design, novel representations	Project submissions, creative tasks
Collaboration	Work effectively in teams, share responsibility	Group tasks, peer feedback	Discussion forum analytics, group reports
Communication	Articulate ideas clearly, use scientific language	Written explanations, oral presentations, peer review	Reflection forms, presentation rubrics

This systematic operationalization addresses concerns regarding weak definitions and measurement of 21st-century.

3.4 Validation, Readability, and Empirical Evidence: Aligning Claims with Data

Validation and Readability Results. Expert Validation: a. Learning matrix: 97.5% (content, presentation, STEM integration), 90% (language); b. Learning content: 100% (content), 90% (clarity), 86.67% (interactivity), 93.34% (relevance); average 91.25%; c. Teaching module: 98.75% (content), 90% (language); average 94.38%; d. Instructional materials: 92.85% (content), 90% (language), 92.5% (presentation); average 91.25%; e. Storyboard: 100% (alignment, clarity, consistency, interactivity); average 97%; and, f. Website: 96.67% (content), 94% (language), 97.5% (presentation); overall 96%.

Student Readability Testing: a. Presentation/layout: 90.75%, b. Language: 89.2%, c. Content clarity: 90.6%

Qualitative Feedback: a. Validators recommended specific enhancements (e.g., clearer learning outcomes, improved visuals, enhanced navigation); b. Students praised the platform's design but suggested improvements (e.g., making homepage images clickable, adding more supportive illustrations). All actionable feedback informed iterative revisions, except for achievement instruments, which was beyond the current phase.

Empirical Evidence and Limitations. Empirical Claims, this study presents robust evidence of content validity, usability, and feasibility based on expert and user evaluations. It does not claim experimental evidence of effectiveness in improving 21st-century skills but is rightly framed as a development and feasibility study.

Limitations: a. The study was limited to the development, validation, and readability testing phases; implementation and outcome evaluations were not conducted due to time constraints, b. The absence of a control group, comparative data, or effect size calculations precludes causal claims regarding skill improvement, c. Findings are context-specific (senior high school in Malang) but designed to be scalable and adaptable.

3.5 Positioning Within Recent International Literature (2020–2025)

Novelty and Contribution Beyond Existing TPACK-Based Media Development. Recent systematic reviews highlight the proliferation of TPACK-based media development studies but also spotlight gaps in mapping TPACK components, operationalizing 21st-century skills, and integrating current instructional models. ThermoSTEM addresses these gaps by Gidakovic (2023): a. Explicitly mapping TPACK domains to media features and learning activities, b. Integrating the PjBL-STEM Laboy-Rush and R2DAC models to scaffold inquiry, collaboration, and communication, c. Operationalizing and measuring the 4Cs using validated instruments.

International Benchmarks and Comparable Platforms. ThermoSTEM's design is benchmarked against international platforms such as ChemCollective, PhET, and Gizmos, which emphasize inquiry-based, interactive learning. The PjBL-STEM Laboy-Rush model and the R2DAC instructional sequence are recognized for fostering authentic, interdisciplinary, and skill-oriented STEM learning. By embedding these models within a TPACK-driven, web-based platform, ThermoSTEM advances the state of the art in project-based STEM education.

3.6 Validation and Readability Evidence: Interpretation and Limitations

Interpretation of Validation and Readability Results. The high validity and readability scores across all components confirm that ThermoSTEM meets rigorous standards for accuracy, pedagogical alignment, usability, and learner accessibility. The study's framing as a development and feasibility study properly corresponds with best practices in early-stage educational technology research. It recognizes the absence of large-scale implementation or outcome data.

ThermoSTEM's design prioritizes interactivity through: a. Interactive forums (Padlet) for collaborative inquiry, Formative assessments (Google Forms) for self-paced learning and immediate feedback, and c. Multimodal instructional materials for diverse learning preferences. Student feedback confirms that the platform fosters independence and engagement, consistent with international findings on the value of interactivity in STEM education.

Validation instruments showed high reliability (e.g., Cronbach's alpha > 0.8). The combination of quantitative scores and qualitative feedback provides substantial evidence of validity and reliability, responding to concerns about insufficient reporting. The iterative development process involved expert validation and student readability testing, leading to enhancements in clarity and user experience. Revisions included clearer learning outcomes, better navigation, and improved visuals.

ThermoSTEM is designed for scalability across diverse educational contexts, with potential for content expansion and collaboration. Future research should evaluate classroom impact and long-term effectiveness. ThermoSTEM benchmarks against leading platforms for inquiry-based learning, emphasizing TPACK integration and operationalization of the 4Cs in STEM education. The study is framed as a development and feasibility study without experimental outcome data, acknowledging its context-specific findings and recommending future empirical research.

4 Conclusion

The development of ThermoSTEM, an interactive website-based learning media, signifies the feasibility of integrating the TPACK framework with the PjBL-STEM Laboy-Rush model to tackle challenges in thermochemistry instruction. Validation and readability results confirm that ThermoSTEM is highly valid, accessible, and engaging, operationalizing 21st-century skills through inquiry-driven tasks and collaborative forums. Despite evidence being limited to expert validation and small-scale readability testing, ThermoSTEM stands as a pioneering example of context-sensitive, digital learning innovations. Future research must engage empirical designs to substantiate its educational impact.

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