



Developing a challenge-based corrosion e-book to enhance vocational students' concept understanding and creative thinking skills

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ABSTRACT

This study aimed to develop a challenge-based corrosion e-book with a chassis coating context using the Four Steps Teaching Material Development (4STMD) method and to evaluate its effectiveness in enhancing vocational students' concept understanding and creative thinking skills. A design and development research approach was employed, comprising design, development, and evaluation phases. The e-book was developed through the 4STMD stages of selection, structuring, characterization, and didactic reduction, yielding ten concept labels on corrosion and redox reactions contextualized within automotive chassis maintenance. The product was validated by expert reviewers and tested with 20 grade-XI students of a Light Vehicle Engineering program at a vocational school in Bandung, Indonesia. Expert evaluation indicated that the e-book was highly feasible across content, language, presentation, and graphic criteria. Student comprehensibility reached an average of 92%. A one-group pretest–posttest design with the Wilcoxon signed-rank test revealed statistically significant improvements ($\alpha = 0.05$) in both concept understanding and creative thinking skills, the latter measured through Torrance's indicators of fluency, flexibility, originality, and elaboration. A Spearman correlation of $r = .985$ confirmed a very strong positive relationship between the two outcomes. These findings demonstrate that integrating challenge-based learning with the 4STMD method in a vocationally relevant e-book effectively supports higher-order thinking in chemistry education for vocational students.

Keywords: challenge-based learning, concept understanding, corrosion, creative thinking, 4STMD

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INTRODUCTION

Chemistry instruction in Vocational High Schools (Sekolah Menengah Kejuruan, SMK) faces a persistent challenge: the teaching materials available to students are overwhelmingly designed for general senior high school curricula and bear little connection to the vocational competencies students are expected to master (Haryani et al., 2021; Wiyarsi et al., 2020; Inandang et al., 2025). In the Automotive Light Vehicle Engineering (Teknik Kendaraan Ringan Otomotif, TKRO) program, for instance, the integrated science subject (Projek IPAS) covers only introductory topics such as classification of matter and energy transformations, without addressing chemical phenomena directly relevant to automotive practice (Deva et al., 2025). Consequently, students struggle to perceive the utility of chemistry for their professional field, and teachers lack discipline-specific resources that bridge chemical theory and vocational application (Harjono et al., 2022; Wibowo et al., 2021).

Corrosion of vehicle chassis represents one such point of intersection between chemistry and automotive engineering. Chassis frames, typically fabricated from carbon steel, are susceptible to electrochemical degradation when protective coatings are compromised (Kolosova et al., 2024; Istiyono et al., 2018). Understanding the redox reactions that underlie corrosion—including oxidation-number assignment, electron-transfer mechanisms, galvanic cell formation, and cathodic protection using sacrificial anodes—is prerequisite knowledge for chassis maintenance (Fauziyah, 2021; Qatrunada et al., 2023). Yet research consistently reports that students find redox concepts difficult because of their abstract, multi-representational nature (Brandriet & Bretz, 2014; Chiang et al., 2014). When instruction remains confined to decontextualized theory, students tend to memorize rules rather than construct meaningful understanding (Kolomuc & Calik, 2012; Damayanti et al., 2026).

Challenge-Based Learning (CBL) offers a pedagogical framework well suited to this problem. CBL engages students with authentic, real-world challenges that require them to mobilize prior knowledge, investigate new concepts, and propose evidence-based solutions (Apple Inc., 2010; Toheri et al., 2020). By anchoring learning in tangible problems—such as how to protect a chassis from corrosion without conventional painting—CBL motivates inquiry and fosters both conceptual depth and creative problem-solving (Ardiansyah et al., 2021; Matilainen et al., 2021). The three-phase structure of CBL (Engage, Investigate, Act) provides a scaffolded pathway through which students can progressively develop higher-order thinking skills within a meaningful vocational context (Sutaphan & Yuenyong, 2023).

Developing high-quality teaching materials for such contextualized learning requires a systematic method (Ruyadi et al., 2026; Iskandar et al., 2026; Juliana et al., 2024; Kodrat, 2021). The Four Steps Teaching Material Development (4STMD) model, introduced by Anwar (1995, 2023), provides a rigorous four-stage framework: selection of curriculum-aligned content from validated sources, structuring of concepts into maps and multi-level representations, characterization of text difficulty through student testing, and didactic reduction of difficult passages to improve comprehensibility. The 4STMD method is particularly advantageous for vocational chemistry materials because it ensures scientific accuracy while systematically calibrating the cognitive demand of each text to the target learners' level (Anwar, 2023).

An electronic book (e-book) was chosen as the delivery format because SMK students, as digital natives, engage more readily with technology-mediated resources than with conventional printed textbooks (Makdis, 2020). E-books can incorporate multimedia elements—images, animations, hyperlinks—that help visualize abstract chemical processes at macroscopic, submicroscopic, and symbolic levels, thereby supporting the multiple-representation approach advocated in chemistry education (Francisca et al., 2022).

Two learning outcomes are central to this study. Concept understanding, operationalized through Bloom's revised taxonomy (Anderson & Krathwohl, 2001), reflects students' ability to explain, apply, and analyze corrosion-related concepts. Creative thinking skills, assessed through Torrance's framework, encompass fluency, flexibility, originality, and elaboration—capacities essential for generating innovative solutions in vocational practice (Suardana et al., 2024). Prior research suggests that concept understanding and creative thinking are mutually reinforcing: mastery of fundamental concepts provides the knowledge base from which creative problem-solving can emerge (Gurteen, 1998; Siahaan et al., 2021).

Despite the recognized need for contextualized chemistry materials in vocational education, no prior study has specifically developed a challenge-based e-book on corrosion with a chassis coating context using the 4STMD method. This study addresses that gap. The research questions guiding this investigation are: (1) What are the characteristics of a corrosion e-book with a chassis coating context developed through the 4STMD method? (2) To what extent is the e-book feasible and comprehensible? (3) Does the implementation of the e-book within a CBL framework significantly improve students' concept understanding and creative thinking skills? (4) What is the relationship between concept understanding and creative thinking skills after the intervention?

METHOD

This study employed design and development research (DDR), specifically the product-and-tool research type described by Richey and Klein (2014). The research proceeded through three phases: (1) design, involving needs analysis and product planning; (2) development, in which the e-book was constructed using the 4STMD method; and (3) evaluation, encompassing expert validation, comprehensibility testing, and classroom implementation. For the implementation phase, a one-group pretest–posttest design was adopted to assess the e-book’s effect on concept understanding and creative thinking skills.

The study was conducted at a public vocational high school in Bandung, Indonesia, within the TKRO program. Participants in the evaluation phase included three SMK teachers (chemistry and vocational subject experts) who served as validators, and 20 grade-XI students who participated in both the comprehensibility test and the pretest–posttest implementation. Convenience sampling was applied, utilizing an intact class without altering the regular learning schedule.

The instruments comprised three categories. Development instruments consisted of expert review sheets applied at each 4STMD stage to ensure the accuracy of content selection, concept structuring, and context integration. Product evaluation instruments included feasibility checklists based on the standards of the Indonesian Centre for Educational Books (Pusat Perbukuan), covering content, language, presentation, design and graphics, legality, and morality, supplemented by additional checklists for contextual relevance and creative thinking orientation. Comprehensibility instruments required students to read each text segment in the e-book and identify its main idea; texts for which fewer than 50% of students correctly identified the main idea were classified as difficult (Anwar, 2023). For the implementation phase, a validated and reliable test instrument measured concept understanding (multiple-choice and short-answer items aligned with Bloom’s revised taxonomy) and creative thinking skills (open-ended items targeting Torrance’s indicators of fluency, flexibility, originality, and elaboration).

The e-book development procedure followed the four 4STMD stages, as illustrated in Figure 1. In Selection, chemistry content was aligned with the Merdeka Curriculum learning outcomes for the TKRO program, yielding ten concept labels spanning redox reactions, oxidation-number determination, corrosion mechanisms, factors accelerating corrosion, protective coating principles, cathodic protection, the electrochemical series, and the comparative merits of protection methods. Substantive context (chassis coating applications) and pedagogical context (values and skills development) were identified for each label. In Structuring, the concept labels were organized into a concept map, a macro structure determining the sequence of presentation, and three levels of chemical representation (macroscopic, submicroscopic, and symbolic). In Characterization, 20 students read each of the 60 text segments and identified main ideas; one text (Text 16, concerning the electrochemical mechanism of iron corrosion) was classified as difficult (45% main-idea accuracy). In Didactic Reduction, Text 16 was simplified through sentence reformulation and the addition of an explanatory diagram illustrating the galvanic cell process on a corroding iron surface. The resulting e-book was then subjected to expert feasibility review and a second round of student comprehensibility testing.

For classroom implementation, a teaching module integrating CBL with the developed e-book was prepared. The lesson sequence began with a pretest, followed by three CBL phases. In the Engage phase, students were presented with the essential question: “Can a chassis be coated without painting?” In the Investigate phase, students formulated guiding questions, explored the e-book as their primary learning resource, and collaboratively answered these questions. In the Act phase, students conducted a simplified laboratory challenge (Nano Challenge) involving corrosion observation and protection simulation, then completed a student worksheet (LKPD) designed to exercise creative thinking indicators. The lesson concluded with a posttest using the same instrument as the pretest.

Development-stage data from expert reviews were analyzed descriptively to inform iterative refinement of the e-book. Feasibility data were analyzed using percentage-based categorization against Pusat Perbukuan standards. Comprehensibility data were computed as the

mean percentage of students correctly identifying main ideas across all texts. Because the sample was selected non-randomly, pretest–posttest differences in concept understanding and creative thinking were analyzed using the Wilcoxon signed-rank test at $\alpha = 0.05$. The relationship between the two outcome variables was examined using Spearman’s rank-order correlation coefficient.

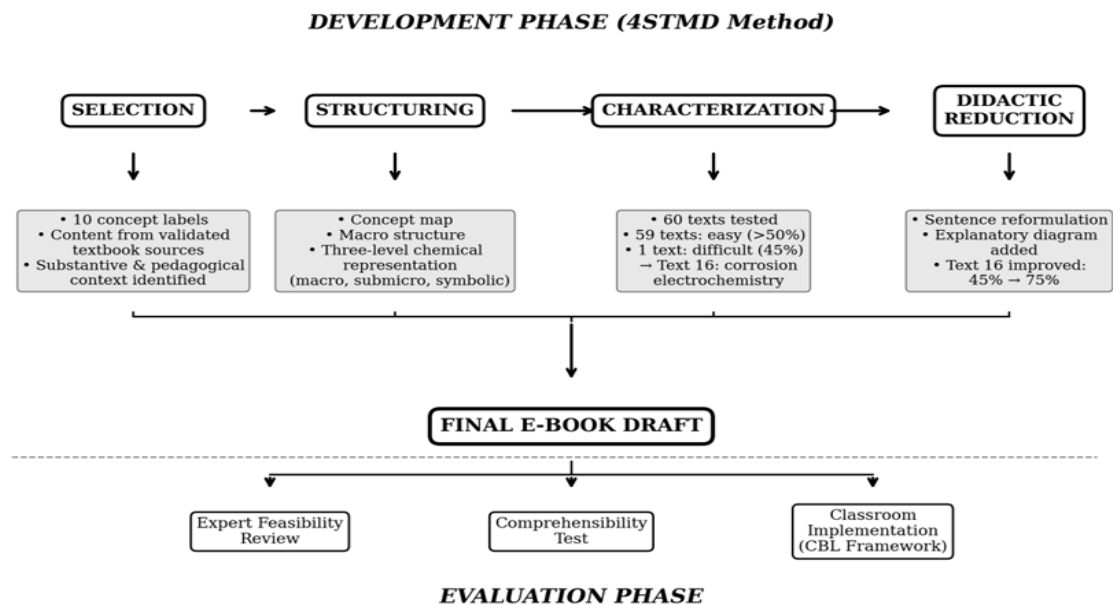


Figure 1. The 4STMD-Based E-Book Development and Evaluation Process

FINDINGS AND DISCUSSION

Findings

E-book characteristics

The Selection stage produced ten concept labels aligned with the Merdeka Curriculum learning outcomes for the TKRO program: (1) oxidation and reduction reactions, (2) oxidation-number determination, (3) the chemical process of iron rusting (corrosion), (4) factors accelerating corrosion, (5) the function of protective coatings, (6) the principle of physical barriers preventing contact with oxygen and moisture, (7) cathodic protection, (8) the use of a more reactive sacrificial anode to protect iron, (9) the electrochemical series (Volta series) as a reactivity reference, and (10) advantages and limitations of cathodic protection. For each label, substantive context linking the chemical concept to chassis coating practice and pedagogical context promoting creative thinking were identified and reviewed by the supervising academic experts.

In the Structuring stage, a concept map depicting the hierarchical and relational organization of the ten labels was constructed, followed by a macro structure determining the logical sequence of content presentation. Three levels of chemical representation—macroscopic (observable corrosion phenomena on chassis surfaces), submicroscopic (electron transfer and ion formation at the atomic level), and symbolic (half-reaction equations and cell potentials)—were developed for each concept to facilitate comprehensive understanding.

In the Characterization stage, 20 students read the 60 text segments of the draft e-book and identified main ideas. Fifty-nine texts were classified as easy (main-idea accuracy > 50%), whereas one text (Text 16) was classified as difficult (45% accuracy). Text 16 addressed the electrochemical mechanism of iron corrosion, involving simultaneous anode and cathode half-reactions and cell-potential calculations—a passage whose abstract and quantitative nature posed comprehension barriers. In the Didactic Reduction stage, Text 16 was simplified by reformulating complex sentences and inserting an annotated diagram of a galvanic cell forming on a water droplet on an iron surface (adapted from Whitten, 2014). This visualization made the

simultaneous oxidation of iron at the anode and reduction of oxygen at the cathode more concrete and traceable for students (see Figure 1 for stage outputs).

E-book feasibility and comprehensibility

Three SMK teachers evaluated the e-book against Pusat Perbukuan standards. As shown in Figure 2, the legality and morality aspect and the design and graphics aspect each received a 100% feasibility rating, indicating full compliance with ethical and visual-quality standards. The content aspect was rated at 93.3%, the language aspect at 83.3%, and the presentation aspect at 83.3%. All five aspects exceeded the feasibility threshold and fell within the “highly feasible” category. Minor recommendations concerned consistency of technical terminology and the sequencing of certain explanatory passages, which were subsequently addressed in the final revision.

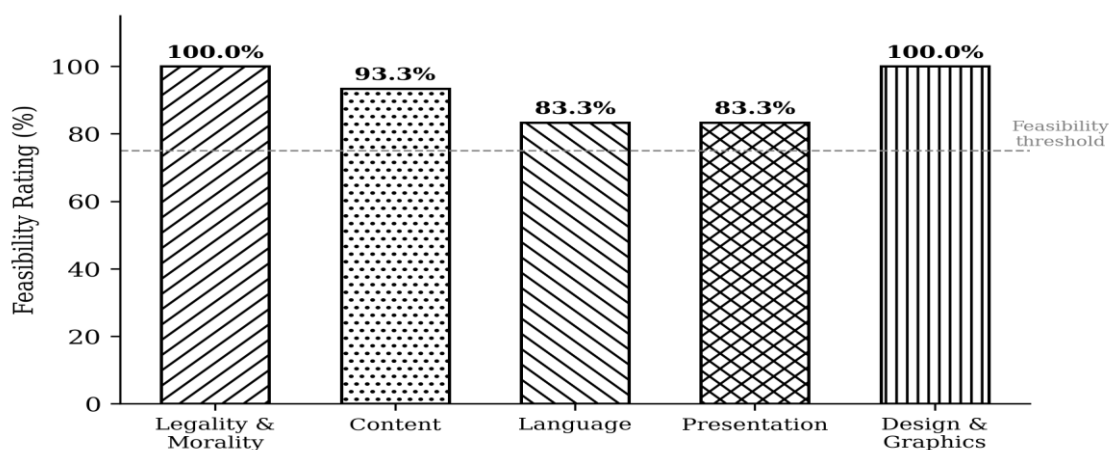


Figure 2. Expert Feasibility Ratings of the Corrosion E-Book Across “Pusat Perbukuan” Criteria

The contextual feasibility evaluation confirmed that the e-book satisfactorily fulfilled five contextual criteria: relating, experiencing, applying, cooperating, and transferring, as all three validators rated each criterion as adequate. Similarly, the creative thinking orientation checklist confirmed that the e-book presented authentic challenges, encouraged multiple solution pathways, contained open-ended questions fostering original ideas, and promoted collaborative idea-sharing, all elements endorsed unanimously by the validators.

After didactic reduction, the comprehensibility test was administered to the same cohort of 20 students across all 60 texts. The average comprehensibility score was 92% (94% for Texts 1–20, 92% for Texts 21–40, and 91% for Texts 41–60), with all texts classified as easy. Text 16, which had previously scored 45% in the characterization stage, improved to 75% after reduction, confirming that sentence reformulation combined with diagrammatic support effectively lowered the comprehension barrier.

Improvement in concept understanding

The Wilcoxon signed-rank test results for concept understanding are presented in Table 1. All 20 students showed an increase in scores from pretest to posttest (20 positive ranks, 0 negative ranks, 0 ties). The obtained W value of 0 was less than the critical W of 98 at $\alpha = 0.05$, leading to rejection of the null hypothesis. The difference between pretest and posttest scores was therefore statistically significant.

Improvement in creative thinking skills

The Wilcoxon signed-rank test for creative thinking skills yielded an identical statistical pattern: 20 positive ranks, 0 negative ranks, 0 ties, $W = 0$, W critical = 98 at $\alpha = 0.05$ (Table 2). The null hypothesis was rejected, confirming a statistically significant improvement in creative thinking skills after the intervention.

Table 1. Wilcoxon Signed-rank test results for concept understanding

	N	Sum of Ranks
Negative Ranks	0	0
Positive Ranks	20	210
Ties	0	0
W	0	
W critical ($\alpha = 0.05$)	98	

Table 2. Wilcoxon Signed-rank test results for creative thinking skills

	N	Sum of Ranks
Negative Ranks	0	0
Positive Ranks	20	210
Ties	0	0
W	0	
W critical ($\alpha = 0.05$)	98	

The distributional shift in both outcomes is visualized in Figure 3. For concept understanding (Figure 3a), 14 students scored in the low category on the pretest and none in the high category; on the posttest, 18 students reached the high category and only 2 remained in the low category. For creative thinking skills (Figure 3b), 13 students were in the low category on the pretest; on the posttest, 18 reached the high category and none remained in the low category. Both panels illustrate a pronounced upward migration from the low to the high category, corroborating the statistical significance established by the Wilcoxon tests.

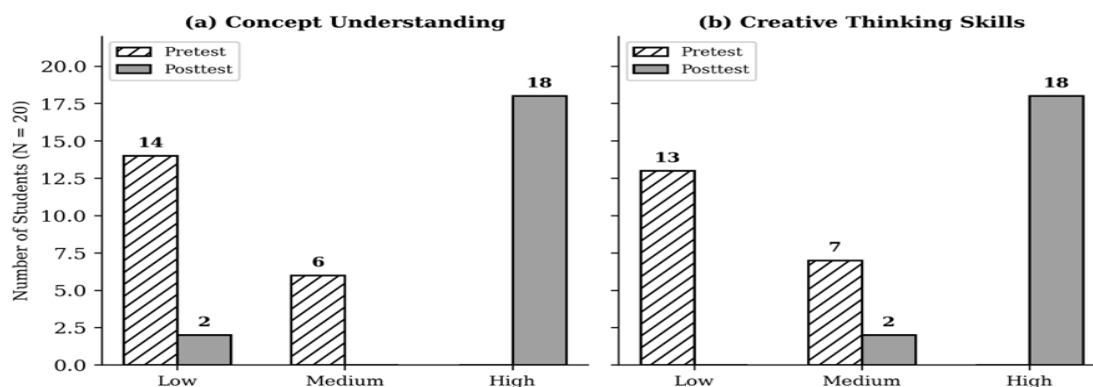


Figure 3. Distribution of Students by Score Category on Pretest and Posttest for (A) Concept Understanding and (B) Creative Thinking Skills (N = 20)

Correlation between Concept Understanding and Creative Thinking Skills

Spearman’s rank-order correlation analysis of posttest scores yielded a coefficient of $r = .985$ ($p < .05$), indicating a very strong positive relationship between concept understanding and creative thinking skills. The coefficient of determination ($r^2 = .970$) suggests that approximately 97% of the variance in one variable is shared with the other within this sample (Table 3).

Table 3. Spearman correlation between concept understanding and creative thinking skills (Posttest)

Statistic	Value
Spearman’s r	.985
r^2	.970

Discussion

The significant improvement in concept understanding can be attributed to the synergy between the contextually grounded e-book and the CBL instructional framework. The 4STMD-

based development process ensured that the corrosion content was not only scientifically accurate but also logically sequenced and calibrated to students' comprehension level through characterization and didactic reduction. The integration of three levels of chemical representation, macroscopic observations of chassis corrosion, submicroscopic depictions of electron transfer at the iron surface, and symbolic half-reaction equations, enabled students to form coherent mental models of redox processes rather than relying on rote memorization of rules (Connolly, 2023; Hagerman & Alcántara-García, 2023). This finding aligns with prior research demonstrating that context-based chemistry instruction enhances conceptual understanding (Karslı Baydere, 2021; Wiyarsi et al., 2020; Zhang et al., 2020).

The CBL framework played a complementary role by structuring the learning experience around an authentic challenge. The essential question, "Can a chassis be coated without painting?", required students to move beyond surface comprehension and actively investigate how different corrosion-protection strategies operate at the chemical level. During the Investigate phase, students used the e-book as their primary resource to formulate and answer guiding questions, thereby engaging in self-directed knowledge construction. This process, in which the e-book served both as an information source and as a scaffold for inquiry, is consistent with findings that CBL promotes deeper conceptual engagement compared to conventional instruction (Iwatani et al., 2020; Membrillo-Hernández et al., 2021; Alani & Grewal, 2024; Chen, 2023; Jr & Tan, 2025).

The statistically significant improvement in creative thinking skills across all four Torrance indicators reflects the deliberate design of both the e-book and the instructional sequence. The e-book incorporated open-ended problems and multiple-solution scenarios within the chassis coating context, requiring students to generate diverse ideas (fluency), consider alternative approaches to corrosion prevention (flexibility), propose novel solutions such as unconventional sacrificial-anode configurations (originality), and elaborate on their reasoning with chemical evidence (elaboration). The Nano Challenge activity further reinforced these skills by tasking students with designing and evaluating a corrosion-protection strategy under realistic constraints. These results are consistent with research showing that CBL effectively develops creative thinking when paired with authentic, discipline-relevant challenges (Ardiansyah et al., 2021; Schutte et al., 2023; Mittal, 2021; Sopakitiboon et al., 2023; Tran et al., 2020).

The very strong positive correlation between concept understanding and creative thinking ($r = .985$) suggests that the two outcomes developed in tandem rather than independently. This finding is theoretically coherent: students who achieved deeper understanding of corrosion mechanisms were better positioned to generate creative solutions, while the process of creative problem-solving itself deepened their engagement with the underlying concepts. The integrated design of the e-book, which embedded creative thinking prompts within conceptual content rather than treating them as separate add-ons, may account for the strength of this relationship. Previous studies have reported similar positive associations between conceptual mastery and higher-order thinking in chemistry learning (Busyairi et al., 2022; Siahaan et al., 2021; Ali et al., 2025; Azumi et al., 2024; Gulsara et al., 2025).

The chassis coating context proved to be more than a motivational wrapper; it functioned as a substantive vehicle for learning. By situating redox chemistry within the maintenance of a structural component that students encounter in their vocational practice, the e-book made abstract concepts, such as the electrochemical series and sacrificial-anode protection, immediately applicable. Students could see, for instance, that the decision to use magnesium strips rather than zinc for cathodic protection of a chassis is grounded in the relative positions of Mg, Zn, and Fe in the Volta series. This alignment between chemical theory and vocational practice supports the argument that authentic contextualization enhances both understanding and motivation in TVET chemistry education (Deva et al., 2025; Haryani et al., 2021; Bouiti et al., 2024; Hagerman & Alcántara-García, 2023; Hedberg et al., 2025).

This study contributes theoretically to the field of chemistry and vocational education by demonstrating the integration of the Four Steps Teaching Material Development (4STMD) method and Challenge-Based Learning (CBL) within a contextual vocational framework. The findings strengthen the theoretical assumption that meaningful contextual learning, supported by

systematic instructional material development, can simultaneously enhance students' conceptual understanding and higher-order thinking skills, particularly creative thinking. Furthermore, the very strong correlation between concept understanding and creative thinking skills provides empirical support for constructivist learning theories, which emphasize that deeper conceptual mastery facilitates students' ability to generate innovative ideas and solve authentic problems creatively.

Practically, this study offers an alternative instructional model for chemistry learning in vocational schools through the use of challenge-based digital teaching materials relevant to students' vocational fields. The developed e-book can serve as a practical resource for teachers to bridge the gap between abstract chemistry concepts and real-world industrial applications, particularly in automotive engineering contexts. In addition, the integration of authentic challenges, contextual problems, and multiple chemical representations can improve student engagement, motivation, and active participation during the learning process. The findings also encourage educators to design more innovative and student-centered instructional materials that support both conceptual learning and creative skill development.

For policymakers, this study highlights the importance of supporting the development and implementation of contextualized digital learning resources in vocational education. Educational authorities and curriculum developers may consider integrating challenge-based and industry-relevant learning approaches into the vocational curriculum to strengthen students' higher-order thinking skills and workforce readiness. The findings also suggest the need for policies that encourage teacher training in innovative instructional design, digital pedagogy, and contextual learning approaches such as 4STMD and CBL. Furthermore, investment in digital infrastructure and the provision of accessible technology-based learning resources are essential to support the effective implementation.

CONCLUSION

This study successfully developed a challenge-based corrosion e-book with a vehicle chassis coating context using the Four Steps Teaching Material Development (4STMD) method for vocational high school students in the Automotive Light Vehicle Engineering program. The developed product demonstrated a very high level of feasibility based on expert evaluations covering content, language, presentation, graphic design, contextual relevance, and creative thinking orientation. In addition, the comprehensibility test indicated that the e-book was easy for students to understand after the didactic reduction process was applied to difficult sections of the material. The integration of vocational contexts with macroscopic, submicroscopic, and symbolic chemical representations made corrosion concepts more meaningful and relevant for vocational students.

The implementation of the e-book within a Challenge-Based Learning (CBL) framework significantly improved students' concept understanding and creative thinking skills. The Wilcoxon test results confirmed statistically significant improvements in both variables after the intervention, while the Spearman correlation analysis revealed a very strong positive relationship between concept understanding and creative thinking skills. These findings indicate that contextual challenge-based chemistry learning not only helps students achieve deeper conceptual understanding but also encourages them to generate innovative ideas and solutions. Therefore, the integration of the 4STMD method, CBL approach, and vocational context can serve as an effective model for developing instructional materials to support chemistry learning in vocational education.

This study has several limitations that should be acknowledged. First, the research employed a one-group pretest–posttest design without a control group, which limits the ability to attribute the observed improvements solely to the implementation of the challenge-based e-book and the CBL approach. Second, the sample size was relatively small and involved only 20 students from a single vocational high school in Bandung, Indonesia, thereby limiting the generalizability of the findings to broader educational contexts. In addition, the use of convenience sampling and

the short duration of the intervention may not fully capture the long-term impact of the e-book on students' conceptual understanding and creative thinking development.

Future studies are recommended to employ quasi-experimental or true experimental designs involving larger and more diverse samples from multiple vocational schools to strengthen the validity and generalizability of the findings. Further research may also investigate the long-term retention of concept understanding and creative thinking skills after the implementation of challenge-based digital learning materials. In addition, future researchers are encouraged to adapt the 4STMD and Challenge-Based Learning approach to other chemistry topics or vocational fields and to integrate more interactive multimedia features, such as simulations or augmented reality, to further enhance students' engagement and higher-order thinking skills.

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