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Developing Multimodal Digital Materials for Energy Transformation at the Primary Education

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Abstract: This study aims to design multimodal digital materials on energy transformation in primary education in terms of validity, practicality, and effectiveness in improving students' conceptual understanding. The study employed design-based research by integrating the Rowntree model for the planning as well as development phases and Tessmer's formative evaluation (self-evaluation, expert review, one-to-one, small-group, and field test). The subjects of this study consisted of 33 fourth-grade students at SDN 1 Sumber Rezeki. Data were collected through practicality questionnaires, expert validation sheets, and tests, and analyzed using descriptive statistics, paired-sample t-test, and effect size analysis. The validation results showed that the multimodal digital materials were in the highly valid category (94.7%). The practicality test in the one-to-one showed practical category (71%-80%) and small-group evaluation stages fell into the very practical category (86%–92%). The effectiveness test showed a significant increase in learning outcomes, with the mean score improving from 53.42 (pre-test) to 82.90 (post-test) and an N-gain of 0.59 (moderate category) ($t = 8.383$, $p < 0.05$), with a Cohen's d effect size of 1.459, which is classified as a large effect.These findings indicated that the developed multimodal digital materials are valid, practical, and effective in improving students' understanding of energy transformation. This study implies that the integration of multimodal elements in digital learning materials can enhance meaningful and contextual science learning. It also serves as an innovative reference for developing instructional materials aligned with 21st-century learning.

Keywords: Multimodal digital materials; Design-based research; Energy transformation; Primary science education

Introduction

The ability to understand and use information is a key competency in 21st-century learning because it supports the development of critical thinking, communication, collaboration, and problem-solving in modern learning (Bandarsyah, 2021). At the primary school level, this ability is an important foundation for students to build meaningful conceptual understanding in various subjects, including science education (Abdullateef, 2021; Shadiev & Wang, 2022). Therefore, primary school learning needs to be systematically designed to facilitate conceptual understanding from an early age. However, previous studies have largely emphasized general literacy development without explicitly linking instructional material design to students' conceptual understanding in science learning (Bhat, 2023; Marleni et al., 2024; Rakhmawati & Mustadi, 2022).

In the context of science education in primary school, conceptual understanding requires not only the ability to read texts but also the ability to interpret information, relate concepts to learning experiences, and critically evaluate the meaning (Utami et al., 2025; Viono et al., 2023). The topic of energy transformation, as one of the conceptual topics in the fourth grade of primary school requires complex cognitive processes. It involves abstract representations, cause-and-effect

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relationships, and contextual phenomena in everyday life (Asikin, 2025). Therefore, learning about energy transformation requires a contextualized learning design that primary school students can easily understand. Nevertheless, many existing instructional practices still struggling to provide adequate representations that can bridge abstract scientific concepts with students' real-life experiences (Puspitasari, 2025; Walker & Nouri, 2025).

However, the reading comprehension skills of primary school students in Indonesia remain suboptimal. The results of the 2022 Programme for International Student Assessment (PISA) showed that only about 25% of Indonesian students have achieved basic reading proficiency. It was so far below the OECD average of 74% (Hafizha & Rakhmania, 2024; OECD, 2023). National data also indicated that some primary school students have not achieved minimum competency in understanding the information (Kemendikbud, 2025). This condition affects conceptual understanding, including abstract science concepts such as energy transformation (Cahya et al., 2025). These findings suggest that current learning approaches and materials have not yet effectively supported students in developing deeper conceptual understanding.

One of the factor contribute to this problem is the limited learning materials used in teaching process (Fredy et al., 2023; Yanti & Raharjo, 2025). In many primary schools, learning materials are still dominated by printed texts and one-way presentations that do not support students' active involvement in understanding concepts (Gunansyah et al., 2021). Learning materials that lack variety and visualization also limit students' opportunities to process information in depth, especially in energy transformation material that requires visual and contextual representation (Prasetyawan & Safitri, 2025; Safitri & Suningsih, 2025). Therefore, there is a need for innovative learning materials that can facilitate a more effective understanding of concepts. Although digital learning materials have been introduced, their design is often not systematically structured to integrate multiple modes of learning in a meaningful way.

These efforts align with multimodal learning theory, which emphasizes that understanding is built through the integration of various modes of representation, such as text, visuals, audio, and interactive activities (Kress et al., 2001). In line with this, multimedia learning theory states that learning becomes more effective when information is presented through a combination of text and visuals that are appropriately integrated (Mayer, 2009). The multimodal approach allows students to process information through multiple cognitive channels, thereby reducing cognitive load and improving conceptual understanding (Moreno & Mayer, 2007). In science education in primary schools, this approach is highly relevant to help students understand the abstract and dynamic concept of energy transformation (Mansour et al., 2025; Suratmi & Sopandi, 2022). However, previous studies have not sufficiently examined how multimodal principles are systematically implemented and evaluated within a science structured instructional design framework in primary education (Aloizou et al., 2025; Dhamayanti & Febrianti, 2020).

The development of educational technology encourages the use of digital learning materials in primary school learning process. Digital learning materials enable the presentation of material enriched with images, audio, video, and interactive activities, making learning more active and meaningful (Kiryakova, 2022). The development of multimodal digital materials is a relevant approach to support the understanding of energy transformation concepts through various learning representations (Afifulloh & Cahyanto, 2021; Fatmianeri et al., 2021). Previous research showed that multimodal digital materials were more effective than conventional in improving students' conceptual understanding and learning engagement (Hairinal et al., 2021). Despite these positive findings, some studies focus on effectiveness without providing a comprehensive development and evaluation process that ensures the quality of the learning materials (Inayah et al., 2023; Nurhasanah et al.,2025).

Several studies had examined the development of digital learning materials in primary schools, such as the development of a multiple intelligences-based learning model (Rahayuningtyas & Yuliyani, 2020), multi-application-based digital learning materials for science learning (Fanani et al., 2022), and digital e-modules on specific science topics (Salsabilah, 2023). However, these studies generally still focused on learning models or the use of technology in general. Studies that specifically emphasize the design and development of structured, multimodal digital materials to support the understanding of energy transformation concepts in primary schools remain limited. There is still limited research that specifically focuses on the systematic design, development, and empirical evaluation of multimodal digital materials tailored to support students' understanding of energy transformation concepts in primary education.

Based on this gap, this study addresses the lack of systematically developed and empirically evaluated multimodal digital materials by designing and evaluating a product that integrates text, visuals, audio, video, and interactive activities within a coherent instructional framework. The learning materials are designed to support students in understanding, interpreting, and applying energy transformation concepts in meaningful contexts.

This study offers novelty by integrating multimodal learning principles into a systematically designed digital learning product that combines text, visuals, audio, video, and interactive elements within a coherent instructional framework. In addition, this study applies a design-based research approach that integrates the Rowntree model and Tessmer's formative evaluation, ensuring that the developed materials are rigorously designed and empirically tested. Furthermore, this study provides empirical evidence of the validity, practicality, and effectiveness of multimodal digital materials in improving students' conceptual understanding of energy transformation in primary science education.

In line with these objectives, this study aims to: (1) develop valid multimodal digital materials that are appropriate for the characteristics of primary school students on energy transformation concept; (2) examine the practicality of using multimodal digital materials in science learning for fourth-grade primary school students; and (3) analyze the effectiveness of multimodal digital materials in improving primary school students' understanding of the concept of energy transformation.

Method

Research Desain

The study used a design research (Anderson & Shattuck, 2012) with the combination of Rowntree model for planning and development phase, as well as Tessmer model for the evaluation phases (Rowntree, 1994; Tessmer, 1993). The evaluation phases were included self evaluation, expert review, one-to-one evaluation, small group evaluation and field test. This model was chosen because it provided a systematic, flexible framework for developing instructional materials, especially digital materials. The study was conducted in the fourth grade of SDN 1 Sumber Rezeki, Sungai Lilin District, Musi Banyuasin Regency, Indonesia. The subjects of this study consisted of 33 fourth-grade students.

Research Procedures

The planning stage began with determining learning objectives and selecting development platforms. Next, the development stage involved designing storyboards and prototypes for multimodal digital materials that integrate text, visuals, audio, video, and interactive activities. The product was developed by using Google Sites to support access and navigation. Finally, the evaluation stage used formative evaluation (Tessmer, 1993) through self-evaluation, expert review, one-to-one evaluation, small-group evaluation, and field tests to assess the validity, practicality, and effectiveness of learning materials in a real learning context.

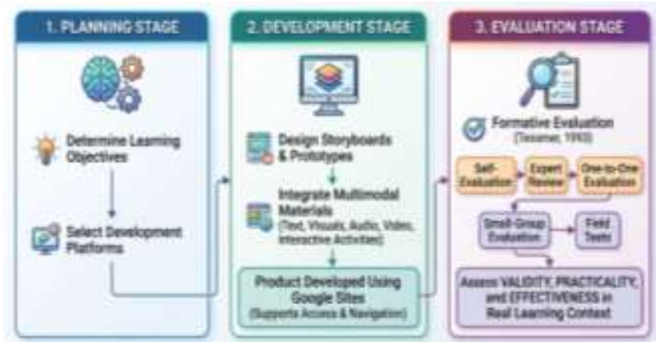

Figure 1. The Research Procedures

Data Collection Techniques

Data collection was carried out through practicality questionnaires, expert validation sheets, and tests. The questionnaires were used to identify the practicality of the product. Expert validation sheets for media, materials, and language were used to assess the suitability of the content, visuals, interactivity, and language of the learning materials as well as to identify the validity of the product. The practicality questionnaires and the expert validation sheets were adapted from (Nurcahyati, 2024). Tests were used to evaluate the effectiveness of the learning materials in improving students' learning outcome in the energy transformation concept.

Table 1. The Result of Validity Test

Item	Level Kognitif	Pearson Correlation	Sig.(2-tailed)	Ket
Q1	C1	.422*	0.020	Valid
Q2	C1	.560**	0.001	Valid
Q3	C1	.610**	0.000	Valid
Q4	C1	.427*	0.018	Valid
Q5	C2	.446*	0.014	Valid
Q6	C2	.695**	0.000	Valid
Q7	C1	.492**	0.006	Valid
Q8	C2	.569**	0.001	Valid
Q9	C3	.560**	0.001	Valid
Q10	C1	.561**	0.001	Valid
Q11	C2	.560**	0.001	Valid
Q12	C2	.730**	0.000	Valid
Q13	C2	.422*	0.020	Valid
Q14	C3	.609**	0.000	Valid
Q15	C3	.511**	0.004	Valid

Source: Primary Data Processing, 2025

Those items declared valid, a reliability test was conducted on the 15 items. the Cronbach's alpha value of 0.823 indicates that all items are reliable. This result suggests that the developed instrument meets both substantive and technical feasibility criteria and is therefore considered highly suitable for use as a data collection instrument in this study.

Data Analysis

Data analysis was conducted quantitatively and qualitatively. Qualitative data analysis was performed on expert comments on the expert validation sheets. The data was analyzed through categorization and conclusion drawing to describe the actual conditions in the field. Quantitative data analysis was performed on the media, material, and language expert validation sheets by calculating averages to determine the validity category of the developed multimodal digital materials. In addition, the average results and the product's practicality category were determined from the practicality questionnaires. Data from the tests were analyzed using a paired-samples t-test and an effect size test to assess the effectiveness of the developed multimodal digital materials.

Result and Discussion

Planning Stage

In the planning stage, learning objectives and the development platforms to be used were determined. The learning objectives were formulated to increase students' active involvement and understanding of energy transformation through the use of multimodal digital materials. The learning objectives were directed so that students would not only understand the concepts conceptually, but also be able to interpret information, relate the material to everyday contexts, and actively participate in the learning process. The formulation of these objectives took into account the characteristics of fourth-grade elementary school students and the availability of school technology, ensuring that the learning materials developed could be used effectively and sustainably. Table 2 shows the learning objectives of the developed multimodal digital materials.

Table 2. Learning Objectives

Main Topic	Learning Objectives	Activity Description
Meeting I Sources and Forms of Energy	• Students are able to explain the forms and sources of energy in everyday life correctly. • Students are able to identify the forms and sources of energy in everyday life correctly.	• Students read and interpret texts, illustrations, and concept maps to strengthen scientific literacy and digital literacy. • Students complete interactive exercises to classify forms and sources of energy and write reflection.
Meeting II Energy Transformation	• Students are able to explain energy transformations in the surrounding environment correctly. • Students are able to identify energy transformations in the surrounding environment correctly.	• Students analyze visual and textual information in the apperception to strengthen reading literacy and scientific reasoning. • Students complete tasks identifying energy transformations in everyday-life contexts and submit reflections.
Meeting III Utilization of Energy Transformation	• Students are able to explain the utilization of energy transformation in everyday life accurately.	• Students interpret information in video to strengthen contextual scientific literacy. • Students conduct simple observations related to energy utilization and write learning reflections.

Then, the platforms for the development of multimodal digital materials were determined. Table 3 presents the platforms used to develop multimodal digital materials, along with their functions in supporting material presentation, learning interactivity, and ease of access for primary school students.

Table 3. Development Platforms

Media Type	Main Platform	Supporting Platform	Purpose
Text	Google Sites	Canva	To present concepts and explanations of the material in a systematic manner
Images	Google Sites	Canva	To visualize concepts, attract attention, and support visual understanding
Video	Google Sites	YouTube	To demonstrate energy-related phenomena in real contexts and support concept exploration
Interactive Worksheets	Google Sites	Liveworksheet	To provide interactive digital exercises with immediate feedback
Experiment Worksheets	Google Sites	Canva	To guide simple experiments and develop students' science process skills
Quiz / Formative	Google Sites	Zep Quiz	To provide game-based formative assessments that are

Media Type	Main Platform	Supporting Platform	Purpose
Assessment			engaging and interactive
Concept Map	Google Sites	Canva	To help organize information and facilitate understanding of the material
Reflection Sheet	Google Sites	Google Forms	To encourage students to independently reflect on their learning experiences

These findings indicated that the planning stage has aligned learning objectives with higher-order thinking skills and contextual learning, which are essential for developing students' conceptual understanding in science (Yadav & Singh, 2026). This also reflected a shift from content-based instruction to competency-based learning (Tarmo & Kimaro, 2021). The platforms had been determined according to learning needs. These platforms supported the presentation of material in a multimodal format. The results of this planning stage formed the basis for developing effective, multimodal digital materials appropriate for the school environment. The use of multiple platforms demonstrated the practical implementation of multimodal learning principles, enabling the integration of text, visuals, audio, and interactivity.

Development Stage

In the development stage, flowcharts and prototypes were designed. This development concept was realized through the multimodal digital materials "*Si Petualang Energi*" (The *Energy Adventurer*), which combines informative text, visual illustrations, videos, discussion activities, interactive exercises, and digital evaluations to strengthen reading literacy, visual literacy, science literacy, and digital literacy. The flowchart illustrates the systematic use of the product.

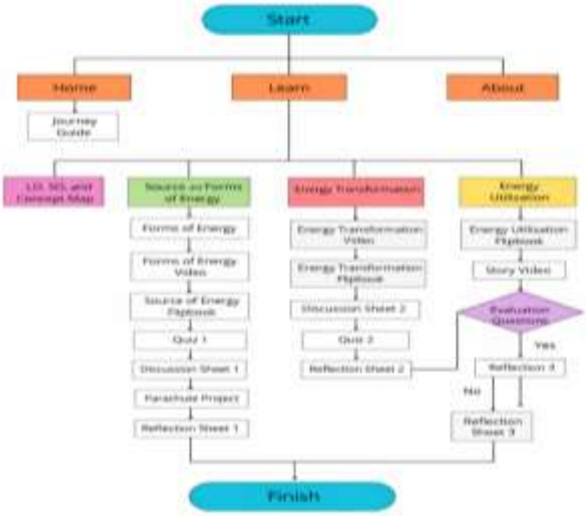

Figure 2. Flowchart of the Product

The flowchart of the developed multimodal digital materials shows a structured, systematic, and learner-centered learning flow. The learning flow starts on the Start page, which directs users to the Home, Learn, and About pages, reflecting the principles of user-friendly, user-needs-oriented digital learning design. The Home menu serves as an introduction that contains learning instructions so that learners get an initial overview of the flow, objectives, and how to use digital learning materials independently.

The Learning menu is the core of the learning process, presenting energy material in stages, including energy sources and forms, energy changes, and energy utilization. Each material is presented through various media such as text, video, and flipbooks to accommodate different learning styles and increase student engagement. The learning process is reinforced with quizzes, discussion sheets, project activities, and tiered reflections that serve as formative assessments and feedback on student understanding. At the end of the learning process, students complete evaluation questions as summative assessments and engage in reflection to assess their achievement of learning objectives, ensuring these learning materials support active, independent, and meaningful learning. Next, the researchers prepared a prototype for the evaluation stage.

Figure 3. Prototypes of the Product (SiPetualangEnergi)

This structured design indicated that the product not only delivers content but also facilitates a guided learning process, which is essential for supporting meaningful learning (Zhang & Tan, 2025). The inclusion of reflection, quizzes, and interactive activities aligned with constructivist learning principles that emphasize active student engagement (Singh, 2025). Each material was presented through various media such as text, video, and flipbooks to accommodate different learning styles and increase student engagement. Compared to conventional learning materials that are predominantly text-based, this multimodal design provides richer representations of abstract concepts such as energy transformation, making them easier for students to understand (Tang, 2023).

Evaluation Stage

a. Self Evaluation

The self-assessment results showed that the initial design of the multimodal digital materials is generally in line with the learning objectives, the characteristics of primary school students, and the curriculum requirements. However, several aspects still needed improvement, particularly the clarity of the material's identity, the consistency of the display design, and the readability of the presentation. The improvements made include adding titles to the flipbook on energy conversion, adjusting the background color of the learning icons on the "Learn" page, and improving the placement of titles and font size in the "Let's Understand" section. These revisions aim to improve the clarity, visual comfort, and quality of the digital learning materials before entering the expert validation stage. These improvements highlight the importance of usability and visual design in digital learning materials, which are often overlooked in previous studies. A clear and consistent interface can significantly enhance students' engagement and comprehension.

b. Experts Review

This stage aimed to determine the validity of the developed product. It focused on the validation process by several experts to ensure that the three aspects of material, media, and language have been thoroughly tested. The product was validated by three experts from Universitas Sriwijaya, representing distinct areas of expertise: elementary teacher education as the content expert, educational technology as the media expert, and Indonesian language education as the language expert. Table 4 showed the results of expert assessment of the product "*Si Petualang Energi*" (The Energy Adventurer).

Table 4. The Results of Expert Review

Validation	Average Percentage Score (%)	Category
Media Expert	92.3	Highly Valid
Content Expert	93	Highly Valid
Language Expert	99	Highly Valid
Average	94.7	Highly Valid

The results of expert validation of media, content, and language indicate that the digital learning materials are highly valid, with an average score of 4.74 (94.7%). The media aspect is rated excellent in terms of appearance, accessibility, and ease of use; the content aspect aligns with learning outcomes and student characteristics; and the language aspect is highly communicative and easy to understand. These findings indicate that integrating visual design, material substance, and appropriate language use has enhanced the overall quality of the learning materials, making the product suitable for learning and ready to proceed to the trial phase. This high validity indicated that the product meets academic, pedagogical, and technical standards. It also confirmed that the integration of multimodal elements was not only innovative but also appropriate and relevant to the curriculum (Trinova et al., 2025).

c. One-to-one Evaluation

One-to-one evaluation was conducted with three students of different ability levels: high, medium, and low. Table 5 showed the results of the product's practicality test at the one-to-one evaluation stage.

Table 5. Product Practicality in One-to-One Evaluation

Aspect	Average per Aspect	Percentage (%)	Category
Ease of Use	3.58	72	Practical
Engagement and Motivation	3.83	77	Practical
Understanding of Material	3.67	73	Practical
Visual Design and Interactivity	3.57	71	Practical
Suitability for Student Needs	4.00	80	Very Practical

The practicality test results show that digital learning materials are practical to very practical for use in learning. Ease of use, engagement and motivation, understanding of material, and visual design and interactivity are in the practical category, indicating that learning materials can be used effectively without significant obstacles. The suitability to student needs was categorized as very practical, indicating that the learning materials are relevant to students' characteristics and learning needs. These findings indicated that digital learning materials are suitable for learning, with opportunities for improvement in visual design and interactivity. This finding also suggested that the initial design was already user-friendly and aligned with students' needs. However, some aspects such as visual design and interactivity still required improvement.

d. Small Group Evaluation

At this stage, the practicality of the learning product was tested through a *small group evaluation* involving 9 students with low, medium, and high abilities. The activity began with an explanation of the objectives and how to use the product, followed by students trying to use it according to the learning instructions. During the process, the researcher observed any obstacles that arose. After the activity was completed, the students filled out a practicality sheet to provide assessments and feedback on the *"Si Petualang Energi"*(Energy Adventurer) digital learning material. Based on the results of the practicality test, the data is presented in Table 6.

Table 6. Product Practicality in Small Group Evaluation

Aspect	Average per Aspect	Percentage	Category
Ease of Use	4.27	86	Very Practical
Engagement and Motivation	4.50	90	Very Practical
Understanding of Material	4.59	92	Very Practical
Visual Design and Interactivity	4.54	91	Very Practical
Suitability for Student Needs	4.41	88	Very Practical

The result of product practicality in small group evaluation showed improvement from one-to-one evaluation. In the small-group evaluation showed higher results. All aspects reached the Very Practical category, with percentages between 86% - 92%. The largest improvements appeared in Understanding of Material (from 73% to 92%), Visual Design and Interactivity (from 71% to 91%), and Engagement and Motivation (from 77% to 90%). These results indicated that the revisions improved clarity, interactivity, and student engagement. The increase in Ease of Use (from 72% to 86%) also showed that the product became easier to use and more suitable for classroom implementation. This improvement demonstrated the effectiveness of iterative revisions in enhancing product usability and engagement. The most notable increased in understanding, interactivity, and motivation indicate that multimodal elements play a crucial role in supporting meaningful learning experiences. These findings were consistent with previous research (Hairinal et al., 2021), which found that multimodal digital materials can improve student engagement.

e. Field Test

This field test aimed to determine the effectiveness and feasibility of learning products in real learning situations. The field test began with a pretest given to 33 students. After the pretest, learning activities continued with classroom implementation of the multimodal digital materials *"Si Petualang Energi"* (Energy Adventurer). After the entire learning sequence using digital learning materials was completed, the researcher administered a post-test to assess students' understanding following participation in the learning process. The post-test was given to students using the same instrument as in the pretest, namely, 15 questions that had been declared valid and reliable, so that the measurement results could be compared objectively. The post-test results were further analyzed by comparing the pre-test and post-test scores to determine the extent of students' learning improvement. The improvement was calculated using the gain score as an indicator of learning effectiveness, and the results are presented in the Table 7.

Table 7. Results of Gain Score

Average of Pre-test	Average of Post-test	N Gain	Category
53.42	82.90	0.59	Moderate

The results show a clear improvement in students' learning outcomes. The average pre-test score was 53.42, which increased to 82.90 on the post-test. This improvement resulted in an N-gain score of 0.59, which falls into the moderate category. This result indicated that the developed materials were effective in improving students' conceptual understanding of energy transformation. The moderate N-gain reflects meaningful learning improvement, particularly considering the abstract nature of the topic. It also indicated that the learning intervention was moderately effective in improving students' understanding of the material. To determine how significantly the product affected students' learning outcomes, a paired sample t-test was conducted.

Table 8. Results of the Paired Sample T-test

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig (2-tailed)
				Lower	Upper			
PreTest - PostTest	29.48	20.20	3.51	36.64	22.32	8.38	32	.000

The results of the paired sample t-test showed a significant difference between the pretest and posttest scores. The average score difference is 29.48 with a t-value of 8.383, df = 32, and Sig. (2-tailed) = 0.000 ($p < 0.05$). The 95% confidence interval is in the range of 22.32 to 36.65, which does not cross zero, thus reinforcing the existence of a significant increase. These findings indicate that the use of learning products significantly improves student learning outcomes. In addition, an Effect Size Test was also conducted, with the data presented in Table 9.

Table 9. Results of Paired Sample Effect Size

				95% Confidence Interval	
		Standardizer[a]	Point Estimate	Lower	Upper
Pretest -	Cohen's d	20.20384	-1.459	-1.947	-.961
Posttest	Hedges' correction	20.44452	-1.442	-1.924	-.949

The results of the effect size analysis showed that the use of learning products has a very strong influence on improving student learning outcomes. Cohen's d = −1.459 and Hedges' g = −1.442 values are in the large effect category. The large effect size indicated that the intervention had a strong practical impact on student learning outcomes, not only statistically significant but also educationally meaningful. This supported the cognitive theory of multimedia learning (Mayer, 2009), which suggested that combining multiple representations enhances knowledge retention and understanding. These findings indicated that learning products are not only statistically significant but also have a substantive and practically meaningful impact on student learning outcomes. This showed that these multimodal digital materials are effective in improving learning outcomes in fourth-grade energy transformation material in elementary schools.

The findings of this study have important implications for both theory and practice. Theoretically, this study supported multimodal learning and multimedia learning theories by demonstrating that integrating multiple representations can significantly enhance conceptual understanding. Practically, the results suggested that teachers should adopt multimodal digital materials to support active, contextual, and meaningful learning, particularly for abstract science topics. Furthermore, this study highlighted the importance of using a systematic design and evaluation framework, such as design-based research, to ensure that learning materials are not only effective but also valid and practical. This approach could serve as a reference for future research and instructional design in primary education.

Discussion

The results of the study indicate that the developed multimodal digital materials are of excellent quality in terms of validity, practicality, and effectiveness. Expert validation demonstrated a very high level of feasibility among media, subject matter, and language experts. These findings confirm that the learning materials have met the standards of visual design, the accuracy of the energy transformation concept, and clarity of language, in accordance with the characteristics of elementary school students (Hernández et al., 2024). This high validity reflects a systematic development process based on expert evaluation, in line with Rowntree's model and Tessmer's formative evaluation (Rowntree, 1994; Tessmer, 1993).

The integration of various digital learning objects, namely text, visuals, videos, animations, and interactive activities, supports communicative and meaningful learning and increases student engagement (Maspul, 2024; Zakir et al., 2022). From a material perspective, the contextual presentation of energy transformation concepts strengthens knowledge construction and aligns with the principles of meaningful learning and ethnopedagogy (Chen, 2021; Viono et al., 2023). The linguistic aspect received the highest score, indicating that communicative and inclusive language plays an important role in increasing student motivation and learning engagement (Abdiyah & Subiyantoro, 2021; Costa, 2022; Suratmi & Sopandi, 2022).

One-to-one and small group evaluation results showed an increase in practicality from practical to very practical in all aspects, confirming the effectiveness of user feedback-based revisions in accordance with the principles of formative evaluation (Marita et al., 2025; Raharjo et al., 2023; Tessmer, 1993). Field tests confirmed the effectiveness of the learning materials, with an increase in learning scores showing a significant difference between pretest and posttest scores (average difference = 29.48; t = 8.383; df = 32; $p < 0.05$). The findings confirm a significant increase in learning outcomes after using digital learning materials. Furthermore, the effect size analysis showed Cohen's d = −1.459 and Hedges' g = −1.442, both in the large effect category. These results indicate that multimodal digital materials not only provide statistically significant differences but also have a strong practical impact on improving student learning outcomes.

Overall, this study is consistent with previous research findings on the effectiveness of digital learning materials in elementary schools (Fanani et al., 2022; Rahayuningtyas & Yuliyani, 2020; Wulandari et al., 2024), while offering novelty through the systematic development of multimodal instructional materials using the Rowntree model and Tessmer's formative evaluation. This approach contributes empirically and theoretically to the development of effective, contextually relevant digital instructional materials for science learning in elementary schools.

Conclusion

This study successfully developed and evaluated multimodal digital learning materials on energy transformation for primary school students using a design-based research approach that integrated the Rowntree model and Tessmer's formative evaluation. The main contribution of this study lay in addressing the gap between general literacy development and the need for structured instructional materials that explicitly support students' conceptual understanding in science learning. By systematically integrating text, visuals, videos, and interactive activities into a coherent learning framework, this study provided a validated model of multimodal digital learning materials that aligned with students' cognitive characteristics and facilitated meaningful learning.

The findings demonstrated that the developed materials achieved a high level of validity (94.7%), very practical usability, and strong effectiveness, as evidenced by a significant improvement in students' learning outcomes ($t = 8.383$, $p < 0.05$), a moderate N-gain (0.59), and a large effect size (Cohen's $d = 1.459$). These results confirmed that multimodal digital learning materials effectively bridged abstract scientific concepts and students' real-life experiences, thereby enhancing conceptual understanding in primary science education.

From a theoretical perspective, this study strengthened multimodal learning and multimedia learning theories by providing empirical evidence that integrating multiple representations within a structured instructional design can optimize students' cognitive processing and learning outcomes. From a practical perspective, the findings suggested that teachers could adopt multimodal digital learning materials as an effective and accessible tool to promote active, contextual, and student-centered learning, particularly for complex and abstract topics such as energy transformation. Additionally, this study offered a practical framework for schools and curriculum developers to design high-quality digital learning materials that meet the demands of 21st-century education.

Despite its contributions, this study was limited to a specific context, sample size, and short-term implementation. Therefore, future research is recommended to investigate the long-term impact of multimodal digital learning materials on students' conceptual retention, higher-order thinking skills, and transfer of learning across different science topics and educational levels. Furthermore, future studies could explore the integration of emerging technologies, such as adaptive learning systems or artificial intelligence, to enhance the personalization and effectiveness of multimodal learning environments.

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Author Contributions

Conceptualization, methodology, software, validation, formal analysis, and investigation: D.G.P.; resources and data curation: E.R.S. and S.; initial draft writing: D.G.P.; writing—review and editing: X.X.; visualization, supervision, and project administration: E.R.S. and S. All authors have read and approved the final version of the published manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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