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Augmented Reality-Based Smart Digital Interactive Media to Enhance High School Students Socio-Scientific Reasoning in Chemistry

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Abstract: The persistent difficulty in connecting abstract chemistry concepts with real-world socio-scientific issues highlights the need for well-designed digital learning innovations. This study aimed to develop and evaluate an Augmented Reality–based Smart Digital Interactive Learning Media (Smart-DIL) to support senior high school students' socio-scientific reasoning and 21st-century skills. The study employed a Research and Development (R&D) approach, utilising the ADDIE model, which encompasses the stages of Analysis, Design, Development, Implementation, and Evaluation. The evaluation stage involved a limited product try-out in authentic classroom settings to examine the validity, practicality, and effectiveness of the developed media. Data were collected from 72 eleventh-grade science students using the Socio-Scientific Reasoning Test (SSRT), the 21st Century Skills Scale (21CSS), classroom observations, interviews, and analysis of digital learning artifacts. Expert judgment and user response questionnaires were used to assess product feasibility and usability. The results indicate that Smart-Dil demonstrates high validity and practicality, as reflected in expert validation scores and positive responses from teachers and students. Evaluation evidence further shows that the implementation of Smart-Dil is associated with meaningful improvements in students' socio-scientific reasoning, particularly in analyzing scientific evidence and constructing evidence-based arguments. In addition, positive developments were observed across all dimensions of 21st-century skills, including critical thinking, creativity, collaboration, and communication. These findings support the integration of Augmented Reality technology within a socio-scientific pedagogical framework, as conceptualized in the proposed TPACK–SSI model. The study concludes that Smart-Dil represents a feasible, practical, and effective learning media product that can help bridge abstract chemistry concepts with authentic societal contexts. The results provide important implications for the development of future digital learning media grounded in Research and Development approaches.

Keywords: Augmented Reality; Chemistry Education; Digital Learning Media; Socio-Scientific Reasoning.

Introduction

The 4.0 Industrial Revolution and Society 5.0 demand that the world of education, especially at the high school level, undergo a fundamental transformation in its learning practices, a challenge that has not been fully addressed in the context of chemistry education. The facts on the ground indicate that chemistry is still often perceived by most students as an abstract, difficult discipline that is isolated from everyday life. The gap between theoretical chemistry concepts and their application in solving real socio-scientific problems, such as global warming, plastic pollution, or renewable energy, creates a significant barrier to the development of their 21st-century competencies. A preliminary survey conducted in several high schools revealed that more than 65% of students had difficulty connecting molecular structures with the properties of substances in the context of water pollution, and there was a lack of involvement in evidence-based scientific discussions to address this issue. This condition is exacerbated by the dominance of conventional teacher-centered learning methods and reliance on static two-dimensional media, such as textbooks and worksheets, which fail to provide deep sensory and cognitive experiences. As a result, students not only lose interest but also fail to develop essential critical and collaborative reasoning skills. Therefore, an innovative breakthrough in learning media that can bridge the abstraction of chemistry with the contextual reality of students is an inevitability that cannot be avoided in order to prepare the younger generation to face the complexities of the times.

An in-depth literature review reveals that although Augmented Reality (AR) has been widely recognized as a technology with the potential to increase motivation and visual understanding in science education, there are significant theoretical and practical gaps in its application to develop students' socio-scientific abilities. A number of previous studies, such as those by Laliyo, Sumintono &

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Panigoro and Chen & Tsao [1], [2], consistently report that AR is effective in visualizing abstract objects such as molecules and chemical reactions, thereby improving conceptual understanding and memory retention. However, the majority of these studies focused on individual cognitive aspects and academic achievement alone, without explicitly linking these visualizations to the social, ethical, and societal implications of scientific knowledge. The existing literature has not presented a comprehensive theoretical framework on how interactive features in AR media can be specifically curated to facilitate discussion, argumentation, and collective decision-making among students on socio-scientific issues. In other words, AR technology is currently mostly used as a passive "viewing tool" rather than an active "collaborative platform" for training 21st-century skills. This gap is reinforced by the findings of Alkhabra, Ibrahem U, & Alkhabra [3], which highlight the lack of integration between intuitive AR interface design and social-inquiry-based learning (4C) pedagogy. Therefore, this study argues that a new approach is needed that not only embeds 3D virtual objects but also provides contextual problem-based learning scenarios and integrated discussion tools within the system.

Based on the reality of the problem and the gaps in the literature described above, this study generally aims to investigate the effectiveness of developing and implementing Smart Digital Interactive media based on Augmented Reality (AR) in improving the socio-scientific abilities of high school students in chemistry. More specifically, the research objectives are detailed as follows: first, to design and develop a chemistry learning media prototype called "Smart-Dil" that combines AR technology with an interactive digital learning environment, allowing for independent and collaborative exploration. Second, to test the validity and practicality of Smart-Dil media according to the assessments of subject matter experts, media experts, and prospective users (teachers and students). Third, to analyze the significant effect of the implementation of this media on improving students' socio-scientific abilities, which are measured through indicators of the ability to formulate questions, analyze scientific evidence, construct arguments, and reflect on ethical values in the context of socio-scientific issues such as the impact of industry on water quality. Fourth, to explore the indirect impact of using this media on students' 21st-century skills, particularly in the aspects of collaboration, communication, critical thinking, and creativity (4C). Thus, this objective does not only focus on the output of the technological product but more on holistic learning outcomes, making this research an effort to bridge the gap between technological innovation and modern pedagogical demands.

This AR-based Smart Digital Interactive development research is argued to have profound and strategic significance, both theoretically and practically, based on the facts and objectives outlined. Theoretically, the findings of this study are hypothesized to enrich the epistemological foundation in the field of science education, particularly by promoting a new integrative model that combines the Technological Pedagogical Content Knowledge (TPACK) framework with the Socio-Scientific Issues (SSI) approach, thereby creating a solid digital pedagogical foundation. Our hypothesis is that the interactivity and immersiveness of AR media will serve as a cognitive catalyst, deepening students' affective and cognitive engagement with chemistry material and ultimately facilitating the transition from conceptual understanding alone to the formation of social attitudes and responsibilities as scientifically literate citizens. From a practical perspective, this research is expected to produce a tested, calibrated, and ready-to-use learning media product for high school chemistry teachers to overcome the limitations of conventional learning resources, as well as a prototype that can be adopted for the development of other science subjects. Our main argument is that investment in the development of such media is not a luxury, but an urgent need to equip students with socio-scientific skills that are the foundation for science literacy in the 21st century, where they not only understand chemistry, but are also able to use that understanding to make wise and ethical decisions in a complex society. Thus, this research hypothesis asserts that the integration of AR in a socio-scientific context will be a transformative solution.

The main foundation of this research is rooted in the evolution of chemistry learning media, which has shifted from a static to a dynamic approach, but still faces significant challenges in accommodating the socio-scientific dimension. Historically, chemistry learning media began with physical models and two-dimensional images, which, although helpful, often failed to address misconceptions about abstract molecular structures and reaction dynamics [4]. The emergence of digital simulations and Virtual Laboratories (VL) in the previous decade offered improvements in visualization, allowing students to manipulate variables in a safe environment [5]. However, a meta-analysis conducted by Weng et al. of 45 studies on VL revealed a fundamental weakness, namely the existence of a "cognitive gap" between the virtual environment and the real world of students, where physical and contextual engagement is still limited [6]. Conventional media and early VL tended to focus on verifying chemical laws and did not provide much space for students to relate the experiments to relevant social issues, such as ethics in chemical waste disposal or material sustainability [7]. Contemporary challenges, as identified in the 2022 PISA report, include Indonesian students' low ability to explain phenomena scientifically and use scientific evidence, reflecting the weak connection between declarative knowledge of chemistry and procedural and epistemic abilities [8]. Therefore, the transition to media that is not only dynamic but also contextual and interactive is imperative in responding to the challenges of the 21st century.

Augmented Reality (AR) has emerged as a disruptive technology in education, with the potential to bridge the gap between abstract objects and physical reality through the principle of embodied cognition. Unlike Virtual Reality (VR), which creates a completely synthetic environment, AR maintains the context of the real world while adding a layer of digital information, thereby facilitating context-embedded learning [9]. The Cognitive-Affective Theory of Learning with Media (CATLM) proposed by Moreno states that learning is most effective when it involves multiple modalities (multimodal) and triggers affective engagement, a condition that is inherently fulfilled by AR through the integration of visual, auditory, and often haptic feedback. A meta-analysis study by Chang H, et al. on the application of AR in science education in Southeast Asia consistently shows a large effect size (Hedge's $g = 0.89$) in improving students' conceptual understanding and intrinsic motivation [10]. However, their research also highlights that the effectiveness of AR is highly dependent on its pedagogical design, rather than merely on its technological sophistication. AR design that merely acts as a "magic lens" without integrating higher-order cognitive activities and collaboration will only result in a temporary fascination (novelty effect) without any lasting impact. Therefore, the position of AR in this study is not the ultimate goal, but rather as a technological foundation for building a richer and more interactive learning environment.

Socio-scientific reasoning is a complex construct defined as an individual's capacity to engage in scientific reasoning about issues that have social implications, are fraught with uncertainty, and often require ethical considerations [11], [12]. In the context of chemistry education, this construct goes beyond an understanding of stoichiometry or chemical bonding; it relates to students' ability to analyze, for example, the economic and environmental impacts of biodiesel production or the health risks of microplastics in the food chain. The socio-scientific framework typically encompasses four main dimensions: recognizing the complexity of multidimensional problems, analyzing scientific evidence from various sources, understanding the inherent uncertainty in science, and demonstrating sustained inquiry skills [13], [14]. The integration of socio-scientific issues into the chemistry curriculum serves as a powerful contextual anchor, which, according to Lave and Wenger's Situated Learning theory, allows students to learn in a "community of practice" where knowledge is not transferred but constructed through authentic participation. Recent research by Nuraini at al. in Indonesia shows that teaching based on socio-scientific issues can improve students' moral reasoning and scientific attitudes, but its implementation is hampered by a lack of adequate resources and media to simulate the complexity of these issues in the classroom [15]. Thus, measuring socio-scientific competence requires instruments that not only assess factual knowledge but also argumentation and decision-making skills in realistic scenarios.

The concept of "Smart Digital Interactive" in this study refers to a learning platform that integrates smart technology (such as AR) with constructivist pedagogical principles to create an adaptive, collaborative, and student-centered learning experience. The "intelligence" in this platform is manifested through its ability to provide dynamic scaffolding, automatic formative feedback, and adjust the difficulty level of tasks based on user responses, which is in line with the concept of Personalized Learning Environments (PLEs) [16]. Interactivity here is not just a matter of clicks or taps, but refers to meaningful interaction between students and digital content, between students and other students, and between students and teachers, facilitated by features such as integrated discussion forums, virtual collaboration boards, and concept diagramming tools. Research by Yuliana, Copriady, & Erna on the development of interactive e-modules for chemistry highlights that interactive elements accompanied by problem-based learning scenarios significantly increase students' cognitive engagement [17]. Furthermore, a recent study by Lampropoulo, Anastasiadis, & Siakas, demonstrates that digital platforms combining AR with gamification mechanisms and synchronous collaboration tools successfully improve not only learning achievement but also communication and team collaboration skills [18]. It is hypothesized that the synthesis between immersive AR technology and interactive smart digital principles can create an ideal learning ecosystem for training socio-scientific skills, where students can visually explore pollutant molecules and simultaneously debate waste management policies in the same digital space.

The 21st-century skills framework, often abbreviated as 4C (Critical Thinking, Creativity, Collaboration, Communication), has been globally recognized as a critical educational outcome to prepare students for the dynamics of society and the future world of work [19]. In the domain of science education, critical thinking is reflected in the ability to evaluate evidence, identify biases, and draw logical conclusions from experimental data. Creativity, on the other hand, is demonstrated through the ability to design innovative solutions to socio-scientific problems. Collaboration and communication are the backbone of authentic science practice, where knowledge is built socially through discussion, peer review, and consensus [20]. The integration of these skills into chemistry learning cannot be done ad hoc; they must be intentionally designed into learning activities and assessed using appropriate instruments. A longitudinal study by Lisdiana et al and Ananda et al. found that educational interventions that successfully fostered the 4Cs were those that applied a project-based learning (PjBL) or inquiry approach in a supportive technological environment [21], [22]. This study positions 21st-century skills as a secondary outcome to be measured, with the hypothesis that engagement with AR-based Smart Digital Interactive media, which simulates collaborative scientific inquiry, will naturally train and hone these four skills. Thus, the improvement of 21st-century skills is not a by-product, but rather the result of authentic and contextual learning design.

Based on a comprehensive literature map, a multidimensional gap has been clearly identified, which forms the *raison d'être* (reason or justification for existence) of this research. First, there is a gap between the potential of AR technology and its pedagogical implementation oriented towards socio-scientific development; most AR research in chemistry is still fixated on microscopic visualization and has not reached the broader socio-scientific realm [23], [24]. *Second*, there is a gap in interactive media design; many existing digital platforms emphasize individual knowledge transmission and place less emphasis on the social-collaborative knowledge construction needed to address socio-scientific issues [25], [26]. *Third*, there is an evaluation gap; previous studies often only measure cognitive gain scores and user satisfaction, without comprehensively assessing the impact on socio-scientific reasoning abilities and the development of 21st-century skills [27]. Research by Sulistina & Hasanah on interactive e-modules has explored the aspect of student engagement; however, the study has not integrated AR immersive technology and has not specifically measured its impact on socio-scientific abilities [28]. Therefore, this study strategically positions itself to simultaneously address these three gaps by proposing an integrative model. The unique position of this research lies in its deliberate synthesis of AR as an immersive enabler, the Smart Digital Interactive platform as a collaboration tool, and socio-scientific issues as a learning context, with a focus on the outcome of reasoning abilities and 21st-century skills, thereby contributing significantly and contextually to the field of chemistry education in Indonesia.

Research Methods

This study employed a Research and Development (R&D) approach with the primary objective of developing, validating, and evaluating an Augmented Reality–based Smart Digital Interactive Learning Media (Smart-DIL) to support socio-scientific reasoning and 21st-century skills in senior high school chemistry learning. The development process was guided exclusively by the ADDIE model, which consists of five systematic stages: Analysis, Design, Development, Implementation, and Evaluation. This study did not adopt an experimental or quasi-experimental research paradigm; instead, all data were collected and analyzed as part of the product development and evaluation process within the ADDIE framework [29].

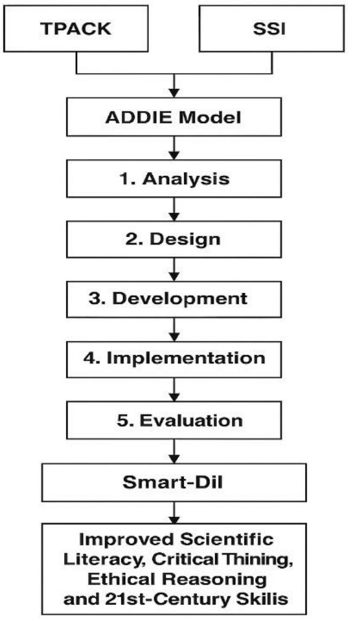

Figure 1. Conceptual Framework of Research

The Analysis stage focused on identifying instructional needs and contextual requirements for socio-scientific chemistry learning. This stage involved administering student questionnaires, conducting interviews with chemistry teachers, and analyzing curriculum documents to identify relevant basic competencies, particularly those related to hydrocarbons and environmental pollution. The analysis aimed to determine gaps between existing instructional practices and the need for interactive, contextualized, and technology-supported learning media.

During the Design stage, the instructional structure and technical specifications of the Smart-Dil media were formulated. This included the development of learning scenarios, storyboards, user interface layouts, and navigation flow. Socio-scientific content was designed in the form of authentic case studies, such as plastic pollution and oil spills, which were aligned with the identified competencies and integrated with three-dimensional molecular representations. At this stage, the technological architecture of the media was also planned, utilizing Unity 3D and the Vuforia SDK as the core Augmented Reality platform.

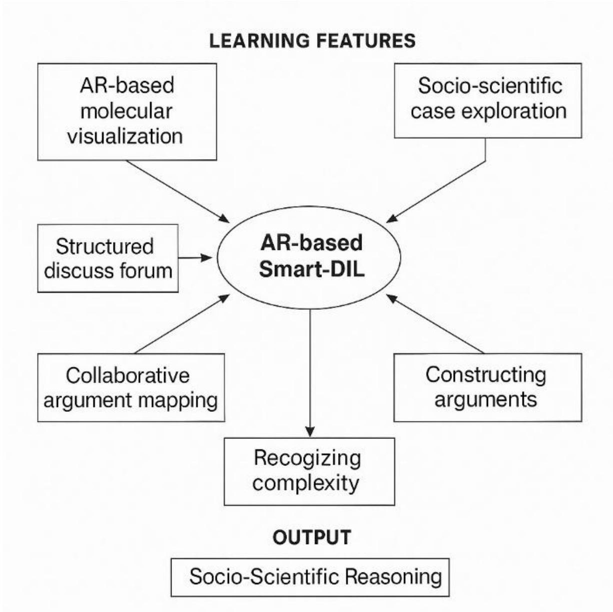

Figure 2. Learning features of AR-based Smart-Dil and their contribution to the development of students' socio-scientific reasoning.

The Development stage involved transforming the instructional and technical design into a functional learning media product. Smart-Dil was developed by integrating several key features, including: (1) AR-based 3D molecular visualization through marker scanning, (2) structured asynchronous discussion forums to facilitate socio-scientific argumentation, (3) digital collaboration boards to support collective reasoning and argument mapping, and (4) formative assessment components with automated feedback.

The developed prototype underwent expert validation involving chemistry education experts, learning media experts, and an educational evaluation expert. Validation instruments assessed content accuracy, construct alignment, media design, and language clarity based on Technological Pedagogical Content Knowledge (TPACK) criteria. Revisions to the product were made based on expert feedback to ensure conceptual accuracy and pedagogical coherence [30], [31].

The Implementation stage consisted of a limited product try-out in authentic classroom settings. Teachers and students were first introduced to the Smart-Dil media through guided orientation sessions. Subsequently, the media was implemented across four instructional meetings using a project-based learning approach grounded in socio-scientific issues. During this stage, teachers acted as facilitators, while students worked collaboratively to explore AR visualizations, analyze contextual scientific information, engage in structured discussions, and formulate evidence-based decisions.

The Evaluation stage aimed to determine the validity, practicality, and effectiveness of the developed Smart-Dil media as an educational product. Product validity was evaluated through expert judgment, while practicality was assessed using teacher and student response questionnaires. Effectiveness evaluation was conducted by examining changes in students' socio-scientific reasoning and 21st-century skills before and after the implementation of the media, as well as through qualitative evidence obtained from observations, interviews, and analysis of digital learning artifacts.

Multiple instruments were employed to support the evaluation stage. Students' socio-scientific reasoning was measured using the Socio-Scientific Reasoning Test (SSRT) adapted from Cian [32], consisting of scenario-based essay items assessed with an analytical rubric. Students' 21st-century skills were measured using the 21st Century Skills Scale (21CSS) adapted from Trilling and Fadel, which demonstrated high internal consistency in this study [33]. Qualitative data were collected through classroom observation sheets, semi-structured student interviews, and analysis of discussion artifacts generated within the Smart-Dil platform. Expert validation data were obtained using structured validation questionnaires.

Quantitative data were analyzed using descriptive statistics to summarize product validity, practicality, and learning outcomes as indicators of product effectiveness within the R&D evaluation process. Improvement trends were examined using normalized gain (N-Gain) scores as supportive evidence of learning progress. Qualitative data were analyzed thematically using the Miles and Huberman (2023) model, involving data reduction, data display, and conclusion drawing, to provide deeper insights into how the Smart-Dil features facilitated students' learning experiences.

This study adhered to established ethical research standards. Approval was obtained from the relevant institutions prior to data collection. Informed consent was secured from schools, parents, and student participants. Participant anonymity and data confidentiality were maintained throughout the study, and all data were used solely for academic purposes.

Results and Discussion

The evaluation results from expert judgment indicate that the developed Smart Digital Interactive (Smart-Dil) media demonstrate a very high level of validity and feasibility for implementing chemistry learning. Based on assessments conducted by five experts, the product achieved an overall mean score of 4.72 out of 5.00, indicating strong alignment between content, pedagogy, and technological design. High scores were obtained for material depth and alignment with basic competencies (4.85), accuracy of chemical and socio-scientific concepts (4.80), and integration of chemical concepts with socio-scientific contexts (4.65).

From a media and instructional design perspective, Smart-Dil also received high validation scores (mean = 4.68), particularly in AR visualization quality (4.80), navigation and user interface (4.75), and clarity of interactive instructions (4.60). These results confirm that the developed product meets the criteria of pedagogical coherence and technological usability as emphasized in technology-integrated learning media development [31]. Expert qualitative feedback further highlighted that the integration of three-dimensional polymer molecular visualization with the Microplastic Pollution case study effectively bridges abstract chemical concepts with real-world contexts, supporting contextual and meaningful learning.

Practicality evaluation conducted through teacher and student response questionnaires during the product try-out phase yielded a mean score of 4.58, with 92% of students reporting that Smart-Dil facilitated easier understanding and contextualization of chemistry concepts. These findings indicate that the developed media is not only valid in design but also practical and user-friendly in authentic classroom settings, fulfilling a key requirement of R&D-based educational product development [29].

As part of the Evaluation stage of the ADDIE-based R&D process, students' socio-scientific reasoning was examined to determine the effectiveness of Smart-Dil as a learning media. Pre-implementation data showed comparable baseline socio-scientific reasoning levels among students, enabling subsequent changes to be interpreted as indicators of product performance rather than instructional bias.

Following four instructional sessions using Smart-Dil, students demonstrated a substantial increase in socio-scientific reasoning scores. The mean score increased from 42.15 (SD = 6.28) prior to implementation to 82.74 (SD = 7.12) after implementation. Analysis of normalized gain (N-Gain) scores revealed a statistically significant improvement ($t(70) = 8.457$, $p < 0.001$) with a very large effect size (Cohen's $d = 1.98$). Within an R&D framework, this magnitude of improvement indicates strong product effectiveness, reflecting the capacity of Smart-Dil to support higher-order reasoning related to socio-scientific issues.

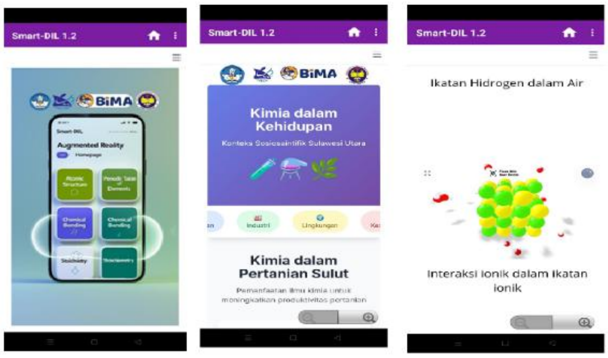

Figure 2. Smart-Dil Application Menu Display

Importantly, this improvement was not limited to factual understanding but extended to students' abilities to formulate socio-scientific questions, analyze evidence, and justify decisions. Such outcomes align with previous studies emphasizing that socio-scientific reasoning develops optimally when students engage with authentic issues supported by structured inquiry and evidence-based discussion [34], [35].

A detailed analysis across socio-scientific reasoning dimensions revealed differentiated patterns of improvement. The most pronounced gains were observed in Analyzing Scientific Evidence (N-Gain = 0.72) and Constructing Arguments (N-Gain = 0.68), both categorized as high improvement. These gains substantially exceeded those observed in conventional learning contexts, indicating that Smart-Dil effectively supports the evaluation of evidence and argumentation processes.

The AR-based molecular visualization feature enabled students to critically relate polymer molecular structures to environmental persistence, while the structured discussion forums encouraged students to construct and refine arguments supported by visual and data-based evidence. Moderate gains were also observed in Recognizing Complexity (N-Gain = 0.60) and Understanding Uncertainty

(N-Gain = 0.55), suggesting that Smart-Dil facilitates engagement with multifaceted and uncertain socio-scientific problems. These findings are consistent with literature emphasizing the importance of visualization and dialogic interaction in fostering complex scientific reasoning [36], [37].

Qualitative interview data reinforced these results. As one student noted, “By being able to see plastic molecules directly in AR and the impact data, I came to understand that the ban on single-use plastics is not just about the environment, but also about the economy and complex community habits.” This response illustrates how AR-supported contextual learning promotes deeper understanding of socio-scientific complexity.

In addition to socio-scientific reasoning, evaluation evidence indicates that Smart-Dil positively supports the development of 21st-century skills (4Cs). MANOVA results showed statistically significant improvements across critical thinking, creativity, collaboration, and communication (Pillai’s Trace = 0.412, $F(4,67) = 11.735$, $p < 0.001$). These outcomes suggest that the learning environment facilitated by Smart-Dil effectively integrates cognitive, social, and communicative dimensions of learning.

Classroom observations and digital artefact analysis further revealed high levels of student engagement, peer collaboration, and evidence-based discussion. On average, students produced 5.3 meaningful discussion posts per session, with 78% of these posts containing explicit evidence or data. These findings support previous research emphasizing that collaborative digital environments are instrumental in fostering 21st-century competencies [38].

The evaluation findings can be interpreted through the lenses of Cognitive Load Theory and Embodied Cognition, which explain how AR-based visualization reduces extraneous cognitive load by concretizing abstract chemical entities, thereby enabling students to allocate cognitive resources to higher-order reasoning processes [36], [39]. By allowing students to manipulate three-dimensional molecular models directly, Smart-Dil provides embodied learning experiences that enhance conceptual understanding and retention.

The substantial improvements observed in argument construction and collaboration further highlight the role of structured digital discourse in facilitating socio-scientific reasoning. The asynchronous discussion forums and collaboration boards embedded in Smart-Dil require students to articulate claims, respond to counterarguments, and justify decisions with evidence, reflecting authentic scientific discourse practices [37], [40]. This aligns with prior studies demonstrating that social interactivity is a critical mediator of reasoning quality in digital learning environments [41].

From a theoretical perspective, the effectiveness of Smart-Dil can be contextualized within the Technological Pedagogical Content Knowledge (TPACK) framework. The product demonstrates a coherent integration of chemical content knowledge, socio-scientific pedagogy, and AR-based technology, supporting the proposition that meaningful learning innovation emerges when technology is pedagogically driven rather than used as an isolated tool [42]. The proposed TPACK Socio-Scientific Issues (SSI) model thus provides a viable design framework for future science education media.

Conclusion

This study concludes that the Augmented Reality–based Smart Digital Interactive Learning Media (Smart-DIL) has been successfully developed and evaluated through a Research and Development (R&D) approach using the ADDIE model. Evaluation results indicate that Smart-Dil demonstrates high validity and practicality, fulfilling essential criteria for implementation as a chemistry learning media grounded in socio-scientific contexts. Evaluation evidence further indicates that the implementation of Smart-Dil is associated with significant improvements in students’ socio-scientific reasoning, particularly in evidence analysis and argument construction, as well as the positive development of 21st-century skills. These improvements are interpreted as indicators of product effectiveness within the R&D framework, rather than as outcomes of an experimental intervention. Theoretically, this study supports the integration of TPACK and Socio-Scientific Issues (SSI) into a unified design framework, positioning Augmented Reality as a pedagogical scaffold for contextualized inquiry and collaborative reasoning. Practically, Smart-Dil represents a ready-to-use educational product that helps teachers address abstract chemistry concepts while fostering higher-order thinking and essential competencies. Despite these promising outcomes, the study is limited by its scope and duration. Future R&D-oriented studies are recommended to conduct wider-scale implementations, longitudinal evaluations, and further product refinement to enhance scalability and sustainability, particularly in contexts with varying technological infrastructure [43].

Author’s Contribution

K. Nababan: Conceptualization, research design, development of augmented reality-based smart digital interactive media, and final revision. D. M. Siregar, V. Tarigan, L. S. L Purba, and Renta: Implementation of learning intervention, classroom data collection, and preliminary data analysis..

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