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Differentiated challenge-based learning: An innovative learning model for enhancing student scientific literacy

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Abstract: Amidst the complexity of today's global challenges, developing scientific literacy skills is crucial for fostering critical awareness and encouraging active community participation in responding to social and environmental issues. This study aims to determine the validity, practicality, and effectiveness of DCBL. It is a Research and Development (R&D) study that employs the ADDIE model to develop a Differentiated Challenge-Based Learning (DCBL) model. The study involved 1,589 high school students and 47 teachers in Bali during the needs analysis stage, 43 students and six teachers during the practicality test stage, and 381 11th-grade high school students during the effectiveness test stage. Data were collected through questionnaires and scientific literacy tests. Data analysis was conducted using descriptive analysis. The findings indicate that DCBL has been tested as valid with an Aiken's V value of 0.953 and very practical with a score of 3.35. Although the ANOVA analysis results showed a significance value of 0.001 ($p<0.005$), the effect size is still relatively small (0.165). It was concluded that the DCBL learning model can be applied to improve scientific literacy skills. The research implications are that the application of the DCBL model provides a more adaptive and meaningful learning alternative. Through a combination of challenge-based and differentiated learning, teachers can accommodate the diversity of students' abilities, interests, and learning styles, while fostering active engagement in understanding scientific concepts through real-life contexts.
Keywords: *DCBL, Innovative learning model, Challenge-based learning, Differentiated learning, Scientific literacy.*

1. Introduction

The rapid pace of social, scientific, and technological change presents numerous challenges to the younger generation, including global diseases, environmental issues, climate change, the greenhouse effect, deforestation, and automation through advances in artificial intelligence technology [1-4]. The complexity of these modern challenges requires scientific literacy skills, which make it an essential skill in the 21st century [5-7]. Scientific literacy includes students' ability to engage with science or socio-science related issues, to solve everyday problems with scientific ideas, and as part of reflective citizenship [8-10].

Indonesian students perform below the OECD average in mathematics, reading, and science, as indicated by international assessment results [8, 11]. Furthermore, the report indicates that Indonesian students' science literacy skills are mostly at level 2, while almost no students are at levels 5 or 6. These results reflect that Indonesian students are only able to recognize correct explanations for known scientific phenomena and can use that knowledge to identify, in simple cases, but are unable to apply their knowledge of science in a variety of situations, including unfamiliar situations, in creative and independent ways [12-14]. The 2022 PISA results indicate that Indonesia's scores are among the

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lowest since its first participation 21 years ago, reflecting a significant decline in students' performance in mathematics, reading, and science [15-17].

These findings indicate the need for serious efforts to improve students' science literacy. If not properly addressed, these shortcomings not only impede students' academic performance but also hinder the broader goal of fostering responsible and scientifically literate citizens. Improper learning approaches, particularly those that do not involve contextual problem-solving processes, can reduce students' ability to understand science concepts [18-20]. In this context, conventional learning strategies that are unidirectional and teacher-centered are no longer considered adequate to face the challenges of the 21st century [21-23]. This is supported by the results of the needs analysis observation, where the main problems for teachers in implementing innovative learning lie in the lack of ability and active involvement of students, as well as the less effective implementation time of innovative learning [17, 24]. Therefore, a learning approach is needed that can relate scientific knowledge to real life and encourage students to think critically through an active, collaborative process in problem solving. Such a process allows students to engage in providing scaffolding that has a positive impact not only on learning outcomes but also on science literacy skills [25-27].

One of the latest innovative learning models that has been widely applied and can be used to improve students' skills includes critical thinking, creative thinking, conceptual knowledge, procedures, attitudes, and science literacy. This model is challenge-based learning (CBL) [28-30]. CBL prioritizes challenges in the learning process. Challenges in learning enable student engagement in lifelong learning through the application of new technologies and skill development [31-33].

CBL has been defined as a new active learning strategy that builds on the practice of problem-based learning, where students work on real-world problems in collaborative teams [9, 34, 35]. Challenges in the form of real-life problems, whether at the local, national, or global level, can strengthen their motivation to conduct research and find solutions that address the realities of their environments [36, 37]. This approach is recognized for combining scientific knowledge with real action, as well as providing students with the opportunity to be actively involved as reflective and responsible problem solvers. Therefore, CBL is considered to be superior to problem-based learning and project-based learning [26, 38].

However, despite the various advantages offered by CBL, there are findings that should be of important concern for the successful implementation of PBL in the field. Previous research found that CBL was not effective when applied to students with low independence, motivation, and interest in learning [16, 39]. This indicates that, in the absence of responsiveness to individual learner diversity, learning strategies such as CBL may lose their inclusivity and potentially exert counterproductive effects on the learning process [40]. For this reason, continuous efforts are needed to meet the needs of all students in the diverse student population in the classroom. The challenge, then, is how to maintain CBL's strengths while accommodating individual differences. Conversely, differentiated instruction (DI) addresses learner variability by adapting content, process, and product based on students' readiness, interests, and learning profiles [32, 41, 42].

This research is supported by several previous studies showing that Challenge-Based Learning (CBL) is effective in improving students' critical thinking, collaboration, and problem-solving skills [34]. However, it still faces limitations in accommodating differences in abilities, interests, and learning styles. Meanwhile, the Differentiated Instruction (DI) approach has been shown to adapt learning strategies to individual student needs, but it lacks the emphasis on authentic and collaborative contexts that characterize 21st-century learning [36]. The gap between these two approaches raises the need for a learning model that is not only contextual and challenge-based but also adaptive to student diversity. Therefore, the development of the Differentiated Challenge-Based Learning (DCBL) model is an innovation with novel value by integrating the collaborative and authentic nature of CBL with the adaptive principles of DI to create relevant, meaningful, and equitable learning experiences for all students.

This research aims to develop and test the validity, practicality, and effectiveness of the DCBL model in improving high school students' scientific literacy. Through this research, it is hoped that it can provide theoretical contributions to the development of challenge-based adaptive learning models, as well as practical contributions for teachers and schools in implementing learning strategies that are more responsive to the diversity of students and the demands of 21st-century learning.

2. Methods

This research and development used the ADDIE model as a stage of product development. ADDIE is among the most widely known and adopted instructional development models in education, as it offers a structured process aimed at producing effective instruction [36, 43]. The product developed in this study is a learning model referred to as Differentiate Challenge-Based Learning (DCBL).

The analysis was initiated to obtain an overview of student characteristics and DCBL development needs involving 1,589 students and 47 high school teachers in Bali. Furthermore, an initial draft of the DCBL was produced based on the results of the needs analysis. The development phase involved five pedagogues, three biology and language learners, and three media experts. The practicality and effectiveness tests of DCBL were conducted at SMA Negeri 4 Denpasar. The limited test stage, which in this case is referred to as a practicality test, was carried out after the DCBL product was tested as valid by involving 43 students and 6 teachers at SMA Negeri 4 Denpasar. The evaluation stage involved 381 XI high school students.

The instrument used was a needs assessment questionnaire on the development of the DCBL learning model for teachers, consisting of seven questions related to DCBL and nine questions related to students' science literacy skills. Questionnaires on a scale of 1-4 were also used to assess the validity of DCBL. For the practicality test, a questionnaire was used with the following indicators: 1) ease of use, 2) time efficiency, 3) suitability with learning objectives, 4) syntax implementation, and 5) DCBL attractiveness.

Data analysis at the needs and practicality analysis stage was carried out descriptively, while the Aiken formula was used to determine the validity of DCBL products, and covariance analysis tests were conducted to test the effectiveness of DCBL on students' science literacy skills. The validity test of DCBL products using the Aiken formula was also calculated [44], where the validity range extends from 0 to 1. If the Aiken index is less than 0.4, it is considered to have low validity; an Aiken index between 0.4 and 0.8 indicates moderate validity; and if it is more than 0.8, it is considered to have high validity [9, 45].

$$V = \Sigma S / [n(C-1)]$$

Figure 1.
Aiken's Formula.

Information:
S: R – Lo
V: Aiken Index
S: The score given by the rater is subtracted from the lowest score
R: Score given by rater
Lo: Lowest Assessment Score
C: Highest Rating Score
n: Number of raters

The pretest-posttest control group was employed to test the effectiveness of the DCBL model. The sample used consisted of 381 high school grade XI students, and DCBL was applied to biology subjects, especially the topic of the respiratory system in humans. Science literacy test instruments were used to

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measure students' science literacy skills. The science literacy instrument in this study was compiled and developed based on the TOSLS science literacy test instrument. As a result, 15 science literacy test questions were produced with nine indicators as follows: 1) identify a valid scientific argument, 2) evaluate the validity of sources, 3) evaluate the use and misuse of scientific information, 4) understand elements of research design and how they impact scientific findings and conclusions, 5) create graphical representations of data, 6) read and interpret graphical representations of data, 7) solve problems using quantitative skills, including probability and statistics, 8) understand and interpret basic statistics, 9) justify inferences, predictions, and conclusions based on quantitative data. The instruments used have been tested for validity and reliability, with Pearson correlation values ranging from 0.260 to 0.769 for validity and a reliability score of 0.731. Generally, an alpha value above 0.7 is considered acceptable to indicate good internal consistency.

3. Results

The results and discussions in this study include a needs analysis in the preliminary research study, validity test, practicality or feasibility test, and DCBL effectiveness test. The results of the analysis of students' characteristics show that students have a positive perception of the learning process related to the development of science literacy skills, where 74.8% of students agree that learning in the classroom has been able to improved science literacy skills. However, 43.8% or as many as 696 out of a total of 1,589 students stated that they had low science literacy skills. These results indicate a gap between students' perceptions of the learning process and their perceptions of mastery of scientific skills.

By combining the strengths of CBL and the principle of differentiation, the DCBL holds strong potential to address the demands of heterogeneous classrooms and to bridge the gap between students' perceptions and their achievement of scientific literacy skills. The urgency of developing the DCBL model is reinforced by the results of the teacher needs analysis, which revealed that 98% of teachers supported its development. Based on the results of the analysis of DCBL development needs and student characteristics, a DCBL syntax consisting of six steps was formulated (Table 1).

Table 1.
DCBL Syntax.

No	Syntax	Learning Activity
1	Confronting Differentiated Challenges	a. Introduction of the Big Idea b. Elaboration of Essential Questions Formulating essential questions based on the presented big idea. c. Identifying differentiated challenges Selecting relevant, engaging challenges that are appropriate to students' abilities and feasible to implement. d. Group formation Students are grouped according to the same selected challenge (3–5 students).
2	Ideation	Ideation is carried out through the 'chained idea writing' technique within student groups.
3	Data Collection (Literacy Process)	The teacher guides students to gather information from various sources
4	Research and Revision	Developing evidence-based, reliable solutions. This stage allows students to revise the initial solutions generated during stages 2 and 3.
5	Solution: Presentation or Implementation	This activity involves presenting the proposed solution or implementing it in an authentic real-world context.
6	Evaluation	This activity may include formative evaluation at each stage and summative evaluation at the end of the learning process.

The learning model product in the form of DCBL Syntax, as outlined in Table 1, was subsequently validated using Aiken's V formula to assess content validity. If the Aiken index is less than 0.4, it is considered to have low validity; an index between 0.4 and 0.8 indicates moderate validity; and an index above 0.8 signifies high validity. Overall, the validity assessment of the DCBL model across instructional design, content and language, and media yielded an average Aiken's V index of 0.953 on a scale from 0 to 1. This result indicates that the DCBL model is valid and appropriate for further implementation in the practicality testing phase. This means that DCBL has met the standards in terms of structure and model components.

Although the construct validity score was quantitatively high at 0.95, revisions were still necessary based on experts' qualitative evaluations. One of the key suggestions involved enhancing the social system component by incorporating clearer mechanisms for teacher and student reflection. This input corresponds to the statement by previous studies that reflection activities must be carried out when a student has difficulties in carrying out the task. Such reflection is essential, as it prompts students to engage in mental and behavioral responses to their own performance efforts.

From the content and language validity components, the validity score is 0.96 with very valid criteria. These findings demonstrate that the content of the model has been developed with the principles of instructional alignment. Moreover, in terms of language use, the model demonstrates adherence to the principle of linguistic simplicity, ensuring clarity and ease of comprehension for users. Furthermore, the validation result by the instructional design expert yielded an average Aiken's V of 0.95 for the instructional model design aspect. His score indicates that the media design component of the DCBL model is considered valid.

The results of the DCBL model's practicality test, in general, from the five aspects assessed, were in the practical to very practical category. The five aspects include: 1) ease of use with a score of 3.39 (very practical), 2) time efficiency with a score of 3.42 (very practical), 3) conformity with learning objectives with a score of 3.35 (very practical), 4) syntax implementation with a score of 3.25 (practical), and 5) attractiveness of DCBL with a score of 3.33 (very practical). From the content and language validity components, the validity score is 0.96, indicating very valid criteria. These findings suggest that users regard the DCBL syntax as coherent and clear steps, facilitating ease of implementation. This is in accordance with the findings of Suastika et al. [46] and Fromm and Ifenthaler [47], which state that the learning model must be clear to facilitate understanding for teachers and students, making the learning process more engaging, meaningful, and effective. Based on these findings, the DCBL model demonstrates sufficient validity and practicality to be applied on a larger scale in the next phase of effectiveness evaluation. Furthermore, the results of the DCBL effectiveness test in improving students' science literacy skills are shown in Table 2.

Table 2.
The Result of the Effectiveness Test.

Tests of Between-Subjects Effects
Dependent Variable: Posttest Literacy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1107.958a	2	553.979	253.144	0.000	0.573
Intercept	791.135	1	791.135	361.514	0.000	0.489
Pre-test Literacy	902.700	1	902.700	412.495	0.000	0.522
Group	163.914	1	163.914	74.901	0.000	0.165
Error	827.213	378	2.188			
Total	356696.000	381				
Corrected Total	1935.171	380				

Note: a. R Squared = .573 (Adjusted R Squared = 0.570)

Analysis of covariance (ANCOVA) results, as shown in Table 2, indicate that the DCBL model had a statistically significant effect, with a significance value of 0.000. While the ANCOVA results confirmed a statistically significant effect of the MPTB model, the obtained partial eta squared value of 0.165 suggests a small effect size, implying that the practical impact of the model may be limited and warrants further investigation.

The effect size report in this study is appropriate to use partial eta squared with ANCOVA analysis. This is because ANCOVA describes the effects of variables and other independent interactions, providing a clearer picture of the unique contributions of the independent variables of interest. The value of the power of the effect is based on empirical findings, which state that Cohen's general guidelines on small, medium, and large effect sizes tend to assume the effect size is larger than it actually is. Therefore, researchers are advised to use new values that have been empirically calculated, with the following provisions for Pearson's correlation r = 0.12 (small), 0.20 (medium), and 0.32 (large) [48].

Table 3 presents the adjusted mean results, indicating that the analysis controlled for the covariate (pretest), thereby enhancing the accuracy of the treatment effect estimation. Thus, this result supports a high degree of statistical validity, suggesting that the observed differences are the result of the DCBL intervention rather than pre-existing disparities in students' prior knowledge.

Table 3.
Adjusted Mean Result

Estimates				
Dependent Variable: Post-test Literacy				
Experimental	**Mean**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	**Upper Bound**
Control	29.870a	0.106	29.661	30.079
Group	31.183a	0.108	30.971	31.396

Note: a. Covariates appearing in the model are evaluated at the following values: Pre-test Literacy = 27.10.

The standardized mean score of scientific literacy in the DCBL group (M = 31.183, SE = 0.108) was significantly higher than that of the control group (M = 29.870, SE = 0.106). The non-overlapping 95% confidence interval between the two groups further supports this difference. These findings show that the DCBL learning model applied in the experimental group is effective in improving students' scientific literacy.

4. Discussion

The data analysis results show that the Differentiated Challenge-Based Learning (DCBL) model developed is proven valid, practical, and effective, making it suitable for use in learning. This is due to the following factors. First, the DCBL model can improve scientific literacy in students. The DCBL model integrates challenge-based learning with differentiated learning according to students' abilities and needs. The challenge-based learning approach exposes students to real-life problems relevant to everyday life, thus accustoming them to finding solutions [49-51]. This process fosters scientific inquiry skills, such as observing, formulating scientific questions, seeking evidence, and drawing conclusions based on data [52-55].

In previous learning activities, low student scientific literacy was caused by ineffective teaching methods that focused on theory and were non-contextual [35, 56]. However, the DCBL model includes elements of differentiated learning that allow teachers to adjust the level of difficulty, learning style, and student interests, so that each individual can learn at their optimal developmental level without feeling overwhelmed. The use of technology in this process enriches students' digital literacy skills, which are an essential part of scientific literacy in the modern era [57-59]. In this context, the Differentiated Challenge-Based Learning (DCBL) model emerges as a relevant alternative, as it not only offers contextual and authentic challenge-based learning but also incorporates the principle of differentiation by considering students' abilities, readiness, interests, and learning styles [26, 60].

Second, the Differentiated Challenge-Based Learning (DCBL) model bridges diverse learning needs with a contextual, challenge-based approach. The implementation of the DCBL model can build deeper conceptual understanding, positive scientific attitudes, and comprehensive scientific thinking skills in students. Each student has different abilities, interests, learning styles, and background knowledge, so a flexible and adaptive learning model is needed [47, 61]. DCBL provides room for teachers to adjust learning strategies, content, and products to suit each student's characteristics through the principle of differentiated instruction [62-64]. At the same time, the challenge-based learning approach presents contextual challenges. This allows students to learn through meaningful experiences within a context they understand, while remaining within the same challenging framework [65, 66].

This approach not only ensures equitable learning opportunities but also fosters intrinsic motivation because students perceive learning as having personal meaning. Through challenge-based activities, students learn to connect theory with practice, develop critical thinking skills, and construct knowledge through direct experience [16, 51, 67]. Therefore, DCBL is effective in bridging individual differences while maintaining the relevance and depth of contextual learning.

Third, the Differentiated Challenge-Based Learning (DCBL) model fosters enthusiasm for learning. This model also increases motivation and scientific curiosity because students are actively involved in finding solutions to problems they find meaningful. Collaborative and reflective activities in DCBL help students develop critical thinking skills, scientific argumentation, and science communication [51, 68]. Learning is designed to be more meaningful, challenging, and tailored to the abilities and interests of each individual. The challenges presented are not merely academic assignments but learning experiences that demand creativity, collaboration, and critical thinking, making the learning process engaging and challenging for students [69, 70]. The combination of contextual relevance, meaningful challenges, and appropriate differentiation enables DCBL to create a positive, enthusiastic learning atmosphere and strengthen students' enthusiasm for exploring and understanding knowledge more deeply.

This model enables differentiated learning activities in terms of resources, processes, and products. Learning environments designed with cognitive and social constructivist principles can enhance creativity [2, 71]. The effectiveness of the intervention is closely related to the strengths embedded in the Differentiated Challenge-Based Learning (DCBL) model, which is explicitly designed to integrate the principles of differentiated learning and a challenge-based approach. This model is based on social constructivist and cognitive constructivist theories, enabling personalized learning experiences that are contextually meaningful and cognitively engaging. The core advantage of DCBL lies in its ability to present varying levels of challenge, allowing learning to be tailored to students' readiness, interests, and learning profiles. Teachers perceive differentiated learning, in other words, challenge differentiation, at the "challenge confrontation phase" of DCBL.

The implications of this study suggest that implementing DCBL can enrich science learning strategies in secondary schools, providing teachers with an alternative way to create more adaptive and meaningful learning processes. However, this study still has limitations, namely the model's relatively small effect on improving scientific literacy. Therefore, further research is recommended to extend the implementation period, involve more teachers and different subject contexts, and develop teacher training guidelines to ensure more consistent and impactful DCBL implementation.

5. Conclusion

This study confirms the critical need for the development of the Differentiated Challenge-Based Learning (DCBL) model. The DCBL model has proven successful in bridging the limitations of conventional Challenge-Based Learning (CBL) models, which tend to be uniform. The main strength of the DCBL syntax is its ability to maintain the depth of investigation of CBL while ensuring accessibility and individual relevance through integrated challenge differentiation in the initial steps. This makes DCBL an inclusive, meaningfully challenging, and highly effective learning model for fostering 21st-century skills. Empirically, ANCOVA analysis confirms that the application of the DCBL model is significantly more effective in improving student science literacy than problem-based learning.

Thus, the DCBL model can be adopted as a new adaptive and flexible learning model at the school level for science subjects. However, this study acknowledges its limitations, namely the relatively small effect size observed in the improvement of science literacy. This is likely due to the short implementation period. Therefore, further research is highly recommended to overcome this methodological constraint by extending the duration of implementation, implementing it on broader biology topics, or even in other science fields such as physics or chemistry.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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