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Development of a Three-Dimensional DNA Structure Model Based on Integrated Waste Recycling SDG's at SMAN 1 Seulimeum Aceh Besar

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Abstrak: Materi struktur DNA sulit dipelajari siswa karena bentuknya tidak dapat dilihat langsung dan komponennya kompleks. Penelitian ini bertujuan merancang model struktur DNA tiga dimensi berbasis daur ulang sampah. Metode yang digunakan adalah R&D (Research and Development) dengan model 4-D yang dimodifikasi (tahap *define*, *design*, *develop*). Subjek penelitian terdiri dari 1 ahli materi, 1 ahli media, dan 25 siswa kelas XII SMAN 1 Seulimeum, Aceh Besar. Teknik pengambilan sampel menggunakan purposive sampling. Data dianalisis secara deskriptif kuantitatif dengan teknik persentase. Hasil penelitian menunjukkan tingkat kelayakan produk sebesar 96,64% (sangat layak), dengan rincian: uji keterbacaan produk 92,42%, validasi ahli media 100%, dan validasi ahli materi 97,5%. Model struktur DNA tiga dimensi berbasis daur ulang sampah terbukti efektif membantu siswa memahami materi DNA.
Kata kunci: Daur ulang sampah; DNA; model tiga dimensi.

Abstract: DNA structure material is difficult for students to learn because its form cannot be seen directly and its components are complex. This study aims to design a three-dimensional DNA structure model based on waste recycling. The method used is R&D (Research and Development) with a modified 4-D model (define, design, develop stages). The research subjects consisted of 1 material expert, 1 media expert, and 25 grade XII students of SMAN 1 Seulimeum, Aceh Besar. The sampling technique used purposive sampling. Data were analyzed using descriptive quantitative techniques with percentage methods. The results showed a product feasibility level of 96.64% (very feasible), with details: product readability test 92.42%, media expert validation 100%, and material expert validation 97.5%. The three-dimensional DNA structure model based on waste recycling proved effective in helping students understand DNA material.

Keyword: Waste recycling; DNA; three-dimensional model.

1. Introduction

The process of learning about DNA structure in 12th grade high school, or what is now known as phase E in the independent curriculum in genetic biology, often faces significant challenges due to its abstract nature and molecular complexity. This genetic material is composed of a three-dimensional double helix configuration consisting of deoxyribose sugar, phosphate groups, and nitrogen base pairs that cannot be observed directly [1]. Mastery of the concept of DNA structure is critical to understanding genetic mechanisms, including DNA replication and various cell division patterns. This obstacle is exacerbated by the reliance on conventional two-dimensional image-based learning media that cannot comprehensively represent the spatial dynamics of DNA molecules [2]. As a result, students in many educational institutions, including SMAN 1 Seulimeum Aceh Besar, rely more on memorization techniques without understanding the integration between the components that form the functional structure of DNA [3]. This condition urges the need for innovation in learning media that is concrete and interactive in order to connect theoretical understanding with practical application.

On the other hand, environmental problems caused by the accumulation of plastic waste and inorganic materials continue to be an urgent global issue. Educational institutions, as the spearhead of social change, bear an important responsibility in fostering environmental awareness among the younger generation. The transformation from a linear consumption pattern to a circular economy through sustainable recycling practices is a necessary solution [4]. The reality in Aceh Besar shows that the domestic waste management system is still not optimal, where various materials of economic value such as cardboard, plastic bottles, and cartons end up in landfills without being recycled. The findings of Yusrizal and Hadi [5] reinforce that the conversion of inorganic waste into creative educational media can realize the

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The development of modern science education needs to be in line with the global development agenda through the Sustainable Development Goals (SDGs). Two SDGs points relevant to this study are goal 4 on Quality Education and goal 12 on Responsible Consumption and Production [6]. Goal 4 emphasizes the importance of expanding access to quality education through the development of affordable innovative learning media, while goal 12 focuses on responsible resource management and waste minimization. The implementation of Education for Sustainable Development (ESD) in biology learning, according to Wulandari and Suryadarma [7], is a key strategy in achieving these SDG targets.

Based on these conditions, this study aims to develop a three-dimensional DNA structure model that utilizes recycled materials integrated with SDG principles. This innovation not only serves as an educational tool to improve students' conceptual understanding of DNA architecture but also functions as an instrument for instilling ecological awareness and social responsibility. Consistent with the research by Sari and Adlim [8], the development of a 3D DNA model made from plastic waste has been proven to be effective in improving student learning achievement. Meanwhile, the study by Amin and Fausan [9] emphasizes the urgency of developing eco-innovation-based biology learning media in the context of sustainable development.

Research and development of teaching aids for DNA material is actually quite extensive. Previous researchers, for example, have created digital DNA models using augmented reality technology to make them more interactive [10], or designed 3D DNA model kits from ordinary plastic materials to help students visualize the molecular structure [11]. On the other hand, a project-based learning approach that utilizes local resources has also been proven successful in improving students' environmental literacy, as applied in the research by Pratiwi and Sari [12]. Unfortunately, these two lines of research still run independently of each other . Existing DNA teaching aids are generally designed only to solve learning difficulties and do not address environmental sustainability issues. Conversely, existing environmental projects rarely produce specific scientific products for complex biological concepts such as DNA. Therefore, this research is considered necessary to bridge this gap. The novelty of this research lies in its attempt to bring together things that are usually separate. The researchers did not simply create a new DNA teaching aid, but designed it as a creative solution to an environmental problem. The scarcity of studies that simultaneously integrate these three aspects makes this finding an initial prototype for the development of sustainable science teaching aids in the future.

The adoption of three-dimensional media made from recycled waste is based on two strategic considerations. The physical representation of 3D models allows for tactile exploration and realistic visualization of the double helix configuration of DNA, which cannot be adequately represented through two-dimensional media. Empirical evidence from Khusniati and colleagues [1] reveals that the three-dimensional approach significantly improves students' conceptual understanding of molecular biology material. At the same time, the use of waste materials not only minimizes production costs but also embodies the principle of sustainable consumption and production (SDG 12). Thus, the implications of this research, which involves combining 3D teaching aids with recycled waste, not only boost academic results but also build environmental awareness and facilitate educators in the form of teaching media.

2. Research Method

This study used the Research and Development (R&D) method with a modified 4-D model, which includes three stages of development: define, design, and develop [13]. The study focused on developing a three-dimensional DNA structure model based on waste recycling using a conventional approach without involving digital technology. The research was conducted at the Biology Laboratory of SMAN 1 Seulimeum, Aceh

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Besar. The research subjects were 12th grade students. The location was chosen based on the availability of recycled raw materials and supporting facilities for manual model making. The research subjects consisted of 1 material expert, 1 media expert, and 25 students (respondents) to test the readability of the product.

Development Procedures

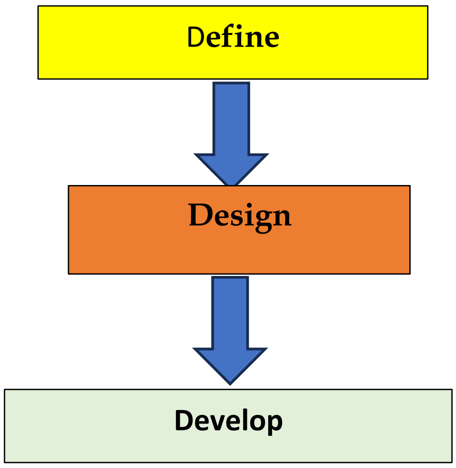

Figure 1. Stages of Research Methods Scheme

a. Define stage

In this stage, the researcher first analyzed the media requirements by observing the existing learning process at SMAN 1 Seulimeun Aceh Besar. The researcher also conducted direct interviews with biology teachers at the school regarding the challenges of teaching DNA structure. Next, the researcher identified the types of waste that could be used for the development of three-dimensional media.

b. Design stage

In the design stage, the researcher first created a manual sketch of the DNA model using digital sketches. This three-dimensional DNA structure model was generally designed in the form of a room equipped with an information center about the DNA structure. This media also utilizes batteries to directly move the DNA structure. The recycled materials used were used cardboard and toothpicks. In addition, common materials that are often used, such as colored HVS paper, colorful origami paper, mica paper, sticky notes, and plasticine, were also used.

c. Development stage

At this stage, researchers developed the production of 3D DNA teaching aids that had been sketched out in the design stage. After that, researchers conducted media expert validation, material expert validation, and product readability validation among students at SMAN 1 Seulimeum Aceh Besar. If all stages of validation showed good to very good results, then the media was ready for production.

During the validation process, researchers prepare validation sheets for each media expert and material expert, as well as product readability sheets.

Development Flow

Define Stage

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Observation → Interview → Needs Analysis

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Design Stage

↓

Manual Sketches → Material Mapping

↓

Development Stage

↓

Prototype, Media Expert Validation, Material Expert Validation, Product Readability

↓

Final Product

Figure 2. Development Stage Frameworks Scheme

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Data Collection Instrument

1. Subject matter expert validation sheet (scientific accuracy aspect)
2. Media expert validation sheet (aesthetic and durability)
3. Product readability questionnaire

Data Analysis

Data was analyzed using descriptive statistics with percentage techniques. Product feasibility criteria referred to validator assessments on a scale of 1-4, which were converted into percentages. Each percentage will be converted into a bar chart according to the instrument sheet, which is divided into three parts: the media expert validation sheet, the material expert validation sheet, and the product readability sheet. The results of these percentages will be clarified using descriptive narratives in the discussion section.

Table 1. Feasibility Criteria for Product Evaluation

Percentage Range	Category
91% – 100%	Very suitable
80% – 90%	Eligible
60% – 70%	Fairly suitable
< 50%	Not feasible

Likert scale calculation formula: Percentage = $\frac{\sum Actual\ Score}{\sum Maximum\ Score} x\ 100\%$[14]

3. Results and Discussion

The three-dimensional DNA structure model based on recycled waste is a media- based product created to assist the teaching and learning process at SMAN 1 Seulimeum Aceh Besar, as determined by the results of a needs survey completed by educators at the beginning of the observation. This product also fulfills the values of SDG point 4 on quality education, which is to ensure equitable learning by maximizing the teaching and learning process, and SDG point 12 on responsible consumption and production through waste recycling, which has been innovated into a learning medium.

In making the product, the basic material used is used cardboard, which is used as the initial foundation in the form of a room with right, left, and back walls. In the middle, the DNA structure is formed using a balloon pipette wrapped in hvs and assembled with colorful origami as a marker for nitrogen bases. Plasticine and toothpicks are added as phosphate sugar hooks. The base is covered again with hvs and a special place is made for the placement of the dynamo so that the DNA structure can rotate like a double helix. Next, on the cover base, HVS is marked with colored origami pieces corresponding to those assembled on the DNA structure skeleton as markers for the difference between purine and pyrimidine bases. An on/off button is also added as an indicator to turn on the product. The walls of the room are marked with information about the DNA structure, its function, and all the elements contained in the product. Furthermore, the DNA structure skeleton is also connected to the top or roof of the room using toothpicks, used cardboard, and bottle caps so that the DNA can rotate stably. This product is also equipped with a question ball as an interactive learning tool to test students' understanding after studying the DNA structure model. After the product was completed, its feasibility was tested through product readability, media expert validation, and material expert validation.

Figure 3. Documentation product

Figure 4. Product testing was conducted on 12th grade students of SMAN 1 Seulimeum, Aceh Besar, Aceh, Indonesia.

The product readability test was conducted on 25 students to evaluate the clarity of instructions, ease of understanding, and overall usability of the developed media. The results are presented in Table 2.

Table 2. Product Readability Results

No	Code	Score	Respondents	Percentage (%)
1	P1	94	25	**94%**
2	P2	94	25	**94%**
3	P3	94	25	**94%**
4	P4	94	25	**94%**
5	P5	89	25	**89%**
6	P6	89	25	**89%**
7	P7	93	25	**93%**

The total score obtained was 647 out of a maximum possible score of 700, resulting in a percentage of **92.42%**. The media expert validation was conducted to assess the quality, usability, and suitability of the developed learning media. The results are presented in Table 3.

Table 3. Media Expert Validation Results

No	Code	Score	Validator	Precentage (%)
1	P1	4	1	**100**
2	P2	4	1	**100**
3	P3	4	1	**100**
4	P4	4	1	**100**
5	P5	4	1	**100**
6	P6	4	1	**100**
7	P7	4	1	**100**
8	P8	4	1	**100**
9	P9	4	1	**100**
10	P10	4	1	**100**
11	P11	4	1	**100**
12	P12	4	1	**100**
13	P13	4	1	**100**
14	P14	4	1	**100**

The total score obtained was 56 out of a maximum score of 56, resulting in a percentage of **100%**.

Material expert validation was conducted to evaluate the accuracy and relevance of the content presented in the learning media. The results are shown in Table 4.

Table 4. Material Expert Validation Results

No	Code	Score	Validator	Precentage (%)
1	P1	4	1	**100**
2	P2	4	1	**100**
3	P3	4	1	**100**
4	P4	3	1	**100**
5	P5	4	1	**100**
6	P6	4	1	**100**
7	P7	4	1	**100**
8	P8	4	1	**100**
9	P9	4	1	**100**
10	P10	4	1	**100**

The total score achieved was 39 out of a maximum score of 40, resulting in a percentage of 97.5%. The average percentage was obtained by calculating the mean of the three assessment aspects. The result shows an overall average of 96.64%. Based on the research findings, the development of a three-dimensional DNA structure model based on recycled waste demonstrates a high level of feasibility as a learning medium. This is indicated by the results of data analysis covering three main assessment aspects, namely product readability by students, media expert validation, and material expert validation, with an average percentage of 96.64%. The product readability test on 25 respondents showed a percentage of 92.42%, indicating that this model successfully facilitated students' understanding of the abstract structure of DNA. The three-dimensional physical representation not only aids in the visualization of the double helix, but also clarifies the spatial relationships between the components of DNA, such as deoxyribose sugar, phosphate groups, and nitrogen bases [15]. Direct interaction with the model enables a kinesthetic learning approach and strengthens sensory memory, which is an important element in understanding complex scientific concepts [16].

In addition, the effectiveness of innovative learning media in biology learning has been supported by previous studies published in BIOTIK Journal. Hanim et al. reported that the use of interactive learning media can improve students' learning outcomes as well as their understanding of biological concepts [17]. This indicates that the use of concrete and visual media, such as the three-dimensional DNA model developed in this study, is important in helping students understand abstract material.

Furthermore, the application of project-based learning has also been shown to increase student creativity and involvement in the learning process. Oviana et al. explained that learning activities involving active student participation through projects are able to improve both cognitive and affective aspects of learning [18]. This is in line with the characteristics of the developed media, which not only serves as a visual aid but also supports interactive and student-centered learning. In addition, the use of innovative approaches such as gamified and blended learning has been reported to improve students' scientific literacy and critical thinking skills [19]. This shows that the development of learning media should not only focus on delivering material but also on creating meaningful learning experiences. Therefore, the three-dimensional DNA model based on recycled waste developed in this study is relevant to current biology learning trends that emphasize active, contextual, and student-centered learning

The media expert assessment by Mrs. Malahayati, S.Pd, a biology teacher for grade XII at SMAN 1 Seulimeum, reached 100%, confirming that the use of recycled materials as raw materials for models is a strategic approach. In addition to economic and practical aspects, this approach integrates the principle of sustainable consumption into the learning process, while also serving as a concrete implementation of the circular economy in the context of science education [20]. The transformation of waste into learning media also reduces the ecological footprint of commercial teaching aid production, in line with the principles of green education and green chemistry in science learning [21].

Expert validation of the material by Mrs. Malahayati, S.Pd, a biology teacher, achieved a score of 97.5%, indicating that this model is not only scientifically accurate but also successfully integrates the dimensions of the Sustainable Development Goals (SDGs) into genetics biology learning. This integration is a concrete example of the -ESD approach, which is designed to address 21st-century learning challenges relevant to the global context [22]. By linking DNA material to local waste management issues, learning becomes more contextual and place-based, thereby increasing student engagement and meaningful learning [23].

The use of recycled waste materials is a creative and innovative solution for creating media products in remote areas that are difficult to access using digital media. Facility limitations are also resolved with the use of recycled waste. This approach turns material constraints into opportunities by utilizing available local resources, such as plastic waste, cardboard, and toothpicks, to produce affordable and sustainable educational media. Previous research also supports this by showing that local waste recycling can be the main raw material for making community media, such as information boards, handmade books, and visual aids, thereby reducing dependence on digital infrastructure and conventional supply chains that are often inaccessible in remote areas [24]. More than just a technical solution, this practice empowers communities through creative processes, improves media literacy, and fosters environmental awareness, thereby creating an independent and contextual media ecosystem.

Although the validation results were very positive, widespread implementation of this model faces several challenges. Teachers' commitment to and understanding of the STEM-ESD approach are necessary, making educator capacity building a critical factor [25]. In addition, the scalability and quality standardization of models made from recycled materials require further attention. Long-term evaluation is also needed to measure the sustainable impact of this model, not only on conceptual understanding but also on students' environmental awareness and behavior [26]. The developed model contributes doubly to improving science literacy and sustainability literacy. This model helps students understand science content in depth, while developing the capacity to make responsible decisions related to consumption and production, which are core aspects of sustainability literacy [27]. Thus, this teaching aid serves as a bridge connecting pure science learning with education for sustainable development

4. Conclusion

The three-dimensional DNA structure model based on recycled waste has successfully demonstrated a positive impact in helping students understand three- dimensional DNA structure material, which is often challenging due to its complex material and visuals. With an average score of 96.64%, the media is categorized as highly suitable for use in learning. This three-dimensional DNA structure model not only has an impact in terms of education. It also successfully represents the recycling of waste materials such as cardboard, paper, plastic, and others as a solution for sustainable development.

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