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Development of Innovative Chemistry Teaching Materials for Molecular Geometry Using Recycled Materials

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Abstract: The limitations of molecular geometry learning media in Indonesia often pose challenges in understanding abstract chemistry concepts, while commercial molecular models are relatively expensive for most educational institutions. This study aims to develop a prototype molecular model using recycled materials as an economical and sustainable alternative learning medium. An exploratory approach was employed in the prototype development, involving six students and one chemistry education lecturer. The materials used included plastic pipettes, marbles, skewers, bottle caps, and used cardboard, which were processed through a series of systematic stages. The research resulted in two distinct prototypes: the "Alkane Series" Model, showcasing a series of hydrocarbons from methane to propane (CH_4, C_2H_6, C_3H_8), and the "Molecule Shape" Model, visualizing various geometric shapes of inorganic compound molecules (SO_2, CO_2, H_2O, BF_3, NH_3, CH_4). Durability evaluations indicated that both models exhibited good resilience after more than 50 repeated uses, while safety testing confirmed their compliance with usage standards in educational settings. The "Alkane Series" Model effectively visualized the pattern of atom addition in the alkane homologous series, while the "Molecule Shape" Model successfully demonstrated the variations in molecular geometry shapes, ranging from linear to tetrahedral. The use of recycled materials not only provides an economical solution to the limitations of learning media but also supports the implementation of education for sustainable development. Although standardization for large-scale production still requires further research, the findings of this study open opportunities for the development of recycled material-based learning media for other chemistry concepts.

Keywords: Alkane, chemistry learning media, inorganic compound molecules, molecular geometry, prototype development, recycled materials, sustainable materials, teaching materials.

Introduction

Chemistry education at the secondary and higher education levels often faces challenges in visualizing abstract concepts (Marfu'ah et al., 2022; Marfu'ah & Anwar, 2018), particularly in the topic of molecular geometry. Molecular geometry is a fundamental aspect of chemistry that explains the three-dimensional shape of a molecule based on the arrangement of its atoms (Blatov & Serezhkin, 2000; Comba et al., 2009; De Keer et al., 2021; Ebenso et al., 2021; Feng et al., 2024; Ghose & Crippen, 1986; Gross et al., 2018; Gui et al., 2020; Jespersen & Hyslop, 2021; Kumar et al., 2017; Li & Kaneko, 2000; Macili et al., 2023; Mills & Dean, 1996; Nithyabalaji et al., 2024; Orpen, 1993; Phillips, 1966; Ramberg, 2017; Tossell & Gibbs, 1977; H. Wang et al., 2018; T. Wang et al., 2021). A strong understanding of this concept is essential as it is closely related to the physical and chemical properties of a compound, including polarity, reactivity, and intermolecular interactions.

In the context of chemistry education in Indonesia, limited learning resources, especially three-dimensional molecular models, remain a major obstacle. Commercial molecular models available in the market are often relatively expensive (Honarparvar et al., 2014; Ooms, 2000), making it difficult for many educational institutions to provide them in adequate quantities.

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This can hinder the learning process and students' understanding of molecular geometry concepts.

On the other hand, Indonesia faces serious challenges regarding waste management, particularly plastic waste. Data from the Ministry of Environment and Forestry indicates that plastic waste production in Indonesia reaches millions of tons per year. Repurposing plastic waste and other recycled materials in the educational context can not only mitigate environmental impacts but also create innovative solutions to the problem of limited learning resources (Boonpracha et al., 2024; Bridgens et al., 2018; Debrah et al., 2021; Hasheminezhad et al., 2024; Mihai et al., 2021; Mong et al., 2023; Sandu et al., 2020).

Innovation in the development of educational media utilizing recycled materials aligns with the principles of Education for Sustainable Development (ESD) (Acosta-Castellanos & Queiruga-Dios, 2022; Araneo, 2024; Brown, 2023; Egana del Sol, 2020; Glavič, 2020; Shishakly et al., 2024; Zainudin et al., 2021; Zguir et al., 2021). This approach not only supports the achievement of learning objectives but also fosters environmental awareness among learners. The use of readily available materials from the surrounding environment, such as plastic pipettes, marbles, skewers, bottle caps, and used cardboard, can serve as an effective and economical alternative in creating molecular models.

Previous studies have demonstrated the effectiveness of using recycled materials in chemistry education (Ncube et al., 2023; Padwal et al., 2022; Xie et al., 2020; Zuin et al., 2021). However, the majority of these studies have been limited to the development of simple models and have not thoroughly explored the potential variations in shapes and structures that can be created. This research aims to bridge that gap by developing a more comprehensive prototype of molecular models using recycled materials.

The innovation in developing educational media for molecular geometry is also in line with the 21^{st} century learning paradigm, which emphasizes creativity, innovation, and problem-solving (Almazroui, 2023; Avdiu et al., 2025; Martinez, 2022). The use of recycled materials not only provides practical solutions to the limitations of educational media but also stimulates the creativity of both educators and learners in developing alternative educational resources.

Materials and Methods

Study area

This research was conducted at a university in South Sumatra, involving a team consisting of six students and one supervising lecturer from the Chemistry Education Study Program. The methodology employed was an exploratory approach (Armstrong, 1970) through the development of molecular geometry prototypes, without conducting empirical tests on students' understanding. The development of the prototypes took place from February to May 2024, focusing on the exploration and development of geometric shapes of molecules.

Procedures

The research on developing teaching materials for molecular geometry employs an exploratory approach through a series of systematic stages. The initial phase begins with a comprehensive literature review on the concept of molecular geometry and molecular shapes, followed by the identification of potential recyclable materials that can be utilized. The research team collected various materials such as plastic pipettes, marbles, skewers, bottle caps, and used cardboard, which were then selected based on criteria for durability and safety of use. During this process, the team also created initial design sketches that considered proportionality and the accuracy of molecular structure representation.

Following the design phase, the research proceeded to the prototype development stage, which involved a series of experiments to determine the most effective techniques for processing recyclable materials. The research team conducted various trials to develop a robust yet flexible inter-component connection system, allowing for the assembly and disassembly of models repeatedly. This process resulted in two different prototype models that illustrate various molecular geometric shapes, including linear, trigonal planar, and tetrahedral forms. The initial prototypes then underwent a series of refinements based on internal team evaluations to ensure the accuracy of molecular structure representation and ease of use.

The final stage of the research procedure involved validation of the prototypes by subject matter experts to ensure the accuracy of the chemical concepts represented. During this process, the team also evaluated the practical aspects and safety of using the models in a learning context. The entire development process was documented in detail, including the challenges faced and the solutions applied, to provide guidance for similar developments in the future.

Data analysis

The data analysis process in this study was conducted using qualitative descriptive methods, focusing on several key aspects. The research team performed an in-depth analysis of the material feasibility, which included durability testing of components and evaluation of safety aspects for use. Each recycled material employed was assessed in terms of its resistance to repeated use, ease of maintenance, and potential safety risks for users. The accuracy of molecular structure representation was the primary focus of the analysis, where the team compared the developed models with standard representations of molecular geometry found in chemical literature.

The analysis also encompassed the practicality of use in learning, which involved evaluating the ease of assembly, flexibility in depicting various molecular structures, and the portability of the models. The research team documented every challenge encountered during the development process along with the solutions implemented, providing valuable insights for future model refinement. The results of this analysis were then integrated to provide a comprehensive overview of the potential and limitations of the developed models as teaching aids for molecular geometry.

Results and Discussion

Result

The development of molecular geometry teaching materials using recycled materials resulted in two distinct prototype models. The first model, named "Alkana Series," showcases a series of simple hydrocarbons comprising methane (CH_4), ethane (C_2H_6), and propane (C_3H_8). This model employs a unique approach by utilizing plastic pipettes shaped and painted to represent chemical bonds, while the connections between bonds utilize a joint system developed from modified bottle caps. The uniqueness of this model lies in its ability to illustrate the progression of structures from simple to complex molecules within a single series, aiding students' understanding of the patterns of carbon and hydrogen atom addition in the homologous series of alkanes. The Alkana Series product is documented in Figure 1.

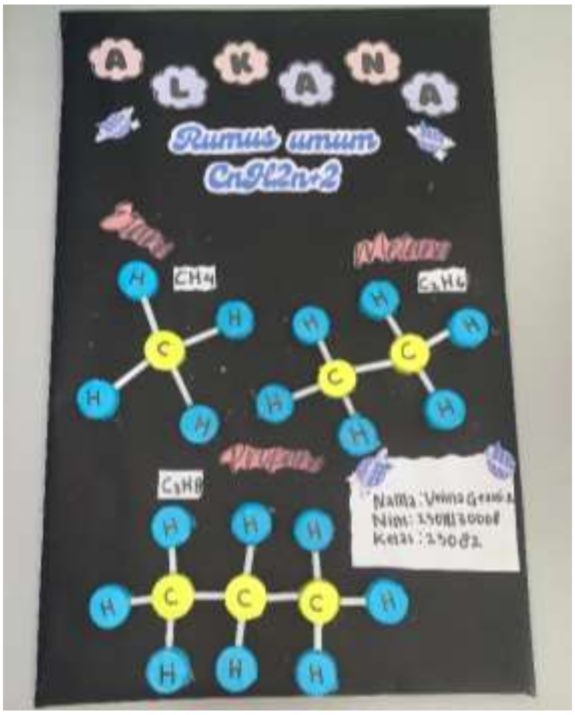

Figure 1. Molecular shapes of The Alkana series

The second model, referred to as "Molecule Shape," visualizes various geometric shapes of molecules from inorganic compounds such as SO_2, CO_2, H_2O, BF_3, NH_3, and CH_4. This model is developed using a combination of colored marbles to represent atoms connected by white rods as chemical bonds. Each molecule in this model is labeled with the compound's name, facilitating identification and learning. The variation in color and shape applied to this model successfully illustrates the differences in molecular geometry characteristics, ranging from the linear shape of CO_2 to the tetrahedral shape of CH_4. The Molecule Shape product is documented in Figure 2.

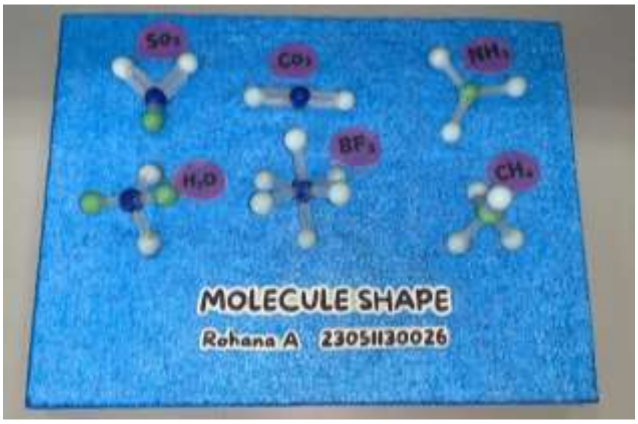

Figure 2. Molecular shapes of inorganic compounds.

Durability testing results indicate that both models exhibit good resistance to repeated use. The "Alkana Series" model, with a joint system developed from modified skewers and bottle caps, demonstrates consistent structural stability after over 50 assemblies and disassemblies. Meanwhile, the "Molecule Shape" model, featuring a joint system based on plastic pipettes, maintains its flexibility in demonstrating various molecular bond angles without significant deformation.

Safety evaluations indicate that both models meet safety standards for educational use. The use of non-toxic paint and materials that have undergone sterilization minimizes contamination risks. Potentially sharp edges have been smoothed, and the size of the components is designed to be large enough to prevent choking hazards, especially for use at the secondary school level.

Discussion

The development of molecular models utilizing recycled materials in this research demonstrates significant potential in addressing the constraints of chemical learning resources. The successful creation of two distinct prototypes with complementary characteristics and functions highlights the flexibility of the approaches employed. This finding aligns with Abdinejad et al. (2021), Govindarajan et al. (2012), Jones & Spencer (2018), Kaumal (2017), Kelley (2021), Penny et al. (2017), and Rahmawati et al. (2020), who emphasized the importance of varied learning media in enhancing the understanding of chemical concepts.

The "Alkane Series" model developed contributes uniquely to the learning of basic organic chemistry. The progressive visualization from methane to propane enables students to directly observe the pattern of atom addition within the homologous series of alkanes, a concept that is often difficult to grasp through two-dimensional images. This approach supports Piaget’s constructivist learning theory, wherein the understanding of abstract concepts is reinforced through concrete experiences (Agrawal, 2007; Anderson & Thompson, 2021; Bozdemir, n.d.; Fosnot, 2013; Gash, 2014; Kay & Kibble, 2016).

Meanwhile, the "Molecule Shape" model, with its diverse molecular geometric forms, provides a comprehensive solution for learning about inorganic molecular structures. The model's ability to represent various bond angles and molecular shapes, from simple linear CO_2 to complex tetrahedral CH_4, meets the need for adaptive learning media. These findings reinforce the results of Oke & Alam (2010), Rayan & Rayan (2017), and Wijayanti et al. (2019) regarding the effectiveness of three-dimensional models in enhancing the understanding of molecular geometry concepts.

The sustainability aspect of this research is reflected in the selection and processing of recycled materials. The use of plastic pipettes, marbles, and bottle caps not only reduces production costs but also contributes to the reduction of plastic waste. This aligns with the concept of education for sustainable development proposed by UNESCO (2018) and supports the implementation of green chemistry education as advocated by Aubrecht et al. (2019), Chen et al. (2020), Etzkorn & Ferguson (2023), Kumar et al. (2022), and Zuin et al. (2021).

The durability and safety of the developed models are crucial aspects that have been successfully achieved through innovations in material processing techniques. The structural stability demonstrated after repeated use indicates the potential for long-term application, offering higher economic value compared to commercial models. These findings support Abdinejad et al. (2021), Mariotti et al. (2020), and Patel & Roberts' (2023) argument regarding the importance of cost-effectiveness considerations in the development of learning media.

Nevertheless, this research has several limitations that should be noted. The limitations on the types of recycled materials that can be used affect the variations of molecular shapes that can be represented. Additionally, standardization of the production process for larger-scale development still requires further research. This aligns with the observations made by Elias et al. (2003) and Sabelli & Harris (2015) regarding the challenges in scaling up the production of recycled material-based learning media.

In a broader context, the success of this molecular model development opens up opportunities for further exploration in utilizing recycled materials for chemistry learning media. The potential to develop models for other chemical concepts, such as crystal structures or reaction mechanisms, presents an intriguing area for future research. As suggested by Wu et al. (2001) the integration of digital technology with physical models could also be a direction for further development.

Conclusions

This study successfully developed two prototypes of molecular models made from recycled materials that can be utilized as teaching media for molecular geometry. The "Alkane Series" and "Molecule Shape" models demonstrate significant potential in visualizing abstract chemical concepts, particularly the structures of organic and inorganic molecules. The use of recycled materials not only provides an economical solution to the limitations of learning media but also supports the implementation of sustainable education. The durability and safety of the developed models meet the standards for educational use, although standardization of production for larger-scale applications still requires further research. The findings of this study open up opportunities for the development of recycled material-based teaching media for other chemical concepts.

Conflict of Interest: The authors declare that there are no conflicts of interest concerning the publication of this article.

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