MOJES MALAYSIAN ONLINE JOURNAL OF EDUCATIONAL SCIENCES JANUARY 2025, 13 (1)

THE EFFECT OF ANALOGIES AND MODELS APPROACH ON UNDERSTANDING OF NUCLEAR RADIATION AMONG SCIENCE TEACHERS

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ABSTRACT

Education in nuclear science and technology faces challenges in enhancing teachers' understanding of nuclear radiation. The lack of understanding among teachers regarding nuclear radiation, which impacts student learning and teaching attitudes, warrants further research. International comparisons and the local context in Malaysia emphasise the importance of deeper teacher education to ensure accurate knowledge dissemination and shape a positive public perception of nuclear technology. Therefore, this study aimed to evaluate the effect of using analogies and models to address these challenges. A quasi-experimental study involved 60 secondary school science teachers teaching Form 3 and 4 in Malaysian public secondary schools, equally divided into experimental and control groups. The experimental group was taught using analogies and models, while the control group followed traditional lecture methods. This study used ANCOVA to adjust for pre-test scores and analyse post-test results. The findings revealed significant improvements in understanding in the experimental group. The experimental group achieved a mean post-test score of 67.63, higher than the control group's 55.24 ($F(1, 57) = 29.699$, $p < 0.001$, $\eta^2 = 0.343$). These findings demonstrate that the analogy and model approach effectively enhances teachers' understanding of nuclear radiation, with important implications for improving science education. Using analogies and models significantly enhances teachers' understanding of nuclear radiation, supporting the theories of constructivism and conceptual change. This approach is effective not only for teaching complex topics but also for improving the quality of education in schools. Additionally, these implications guide policymakers to integrate analogy and model-based training into professional development programs, strengthening teachers' capacity to teach challenging science topics.

Keywords: *Nuclear Radiation, Science Teachers, Understanding, Analogies and Models*

INTRODUCTION

Nuclear technology is crucial in various Science, Technology, Engineering and Mathematics (STEM) fields, including engineering, medicine, and manufacturing, particularly in the Fourth Industrial Revolution (4IR). In Malaysia, the Malaysian Nuclear Vision 2030, led by the Malaysian Nuclear Agency, aims to advance nuclear science and technology locally. Aligned with this, the Malaysian Education Blueprint 2013–2025 emphasizes the need for a skilled workforce to remain competitive globally. Under the 4IR policy, Malaysia seeks to cultivate a workforce proficient in 21st-century skills, integrating nuclear science into education and industry to enhance productivity and efficiency.

Efforts under the Malaysian Nuclear Vision 2030 focus on improving public proficiency in nuclear science through education, research, and public awareness programs. Malaysia also prioritizes nuclear safety by developing infrastructure and collaborating with international bodies. However, the country faces significant challenges in nuclear readiness. One key issue is the limited dissemination of nuclear knowledge, exacerbated by insufficient public education and agnotology (the deliberate spread of ignorance) (Lee, 2019). Negative public perceptions, misconceptions about nuclear power, and weak government policies hinder acceptance. Global nuclear incidents, such as Fukushima (2011), have intensified public scepticism (Pauzi et al., 2018).

Financial constraints limit outreach programs, and a lack of awareness about nuclear career opportunities reduces youth interest in the field (International Atomic Energy Agency, 2021). The 2021 Global Energy Talent Index reports that nuclear energy careers are declining in popularity due to safety concerns and the increasing appeal of alternative technologies. This lack of readiness is further influenced by past nuclear-related incidents and persistent societal taboos surrounding nuclear energy (Pavlov et al., 2020).

Education is pivotal in addressing these issues, yet teachers face challenges integrating nuclear science into learning. Teacher proficiency in nuclear technology directly influences students' understanding, as demonstrated by Morales López and Tuzón Marco (2022). Nuclear concepts' abstract and complex nature further complicates learning (Aykutlu et al., 2015). Studies on in-service and pre-service teachers reveal gaps in nuclear radiation knowledge, affecting science instruction (Cardoso et al., 2020; Yeşiloglu, 2019). Many students find nuclear science difficult, unengaging, and uninteresting (Resbiantoro et al., 2022), a challenge linked to teachers' instructional proficiency. Choy and Cheah (2009) emphasize that teachers' insufficient understanding significantly impacts students' mastery of scientific concepts.

Given these challenges, this study explores science teachers' understanding of nuclear radiation in Malaysian secondary schools and how constructivist strategies influence their comprehension. Science teachers play a key role in fostering nuclear literacy among students, making it essential to enhance their knowledge. The study applies two learning theories to achieve this: 1. Constructivism, which promotes learning through prior knowledge, active engagement, reflective thinking, and contextual understanding (Piaget, 1968). 2. The Conceptual Change Model (Posner et al., 1982) addresses misconceptions and facilitates deeper scientific understanding.

The study investigates teachers' initial understanding of nuclear radiation and introduces a models-and-analogies approach to enhance comprehension. Models and analogies are effective tools for conceptual change, helping teachers and students grasp nuclear concepts more effectively. The study aims to improve science education and advance nuclear readiness in Malaysia by incorporating these strategies.

Understanding of Nuclear Radiation Concepts Among Science Teachers

Nuclear radiation is a crucial topic in science education, addressing issues related to health, safety, environmental protection, and scientific progress. Radiation occurs when unstable atoms emit energy or particles during radioactive decay, and it is applied in various fields such as energy production and medicine (Neumann, 2014; Yeşiloğlu, 2019). Different types of radiation—alpha, beta, gamma rays, and neutron radiation—have varying properties and shielding requirements, making the topic challenging to teach (Pfützner et al., 2012; Santos Silva & Trindade, 2022). Despite its significance, nuclear radiation remains difficult to teach due to its abstract nature and negative associations with disasters like Chernobyl and Fukushima (Kuroda et al., 2020). There is also a general lack of awareness about natural radiation sources, such as the sun and radon (Kartal Tasoglu et al., 2015). Research indicates that many teachers struggle with nuclear radiation concepts due to insufficient training and misconceptions (Yesiloglu, 2019). Their attitudes, influenced by media and limited experience, often overemphasise the dangers, affecting students' perceptions (Morales López & Tuzón Marco, 2022).

Understanding is a key element in effective science education, as it helps build higher-order cognitive skills such as analysis and evaluation (Bloom, 1976; Von Glasersfeld, 1995). However, science teachers and students often struggle to grasp abstract scientific concepts like nuclear radiation (Mubarak, 2012). In Malaysia, low comprehension in core science subjects like Physics and Chemistry has been highlighted, with this issue being linked to teachers' limited subject knowledge and reliance on rote memorization (Grospietsch & Mayer, 2018; Mesutoglu & Birgili, 2017). Effective teaching should move beyond memorization, providing meaningful learning experiences that connect new knowledge to students' existing understanding (Eshetu et al., 2022). However, teachers often face challenges due to time constraints, administrative duties, and a lack of professional development (Rohaida, 2017). Limited use of real-world examples and innovative teaching methods also makes it difficult for students to understand abstract concepts like nuclear radiation (Cardoso et al., 2020). Many science teachers lack knowledge of nuclear science due to inadequate university-level training (Oztürk & Bozkurt Altan, 2019). Among the lack of understanding experienced by teachers are difficulties in distinguishing between the concepts of pollution and irradiation, an unawareness of natural sources of radiation such as radon, and concerns regarding radiation sources related to food (Plotz & Fitzgerald, 2021; Siersma et al., 2021). These lacks of understanding are often passed on to students, leading to persistent misconceptions (Kartal Tasoglu et al., 2015). Improving teachers' subject knowledge through targeted interventions is necessary to address these issues (Cardoso et al., 2020; Pilakouta & Sinatkas, 2020).

Various studies have explored nuclear education, including nuclear energy and radiation-related educational approaches (Aref et al., 2019; Jurakulov, 2023). For instance, Jurakulov used models and simulations to enhance student understanding of nuclear processes and principles. These studies emphasize the importance of raising awareness about the benefits and risks of nuclear radiation. However, previous studies focus more on exploring public perceptions and attitudes towards nuclear radiation, while others examine the associated safety and risks (Lyons et al., 2020; Pauzi et al., 2018). Minimal studies, however, concentrate on improving the understanding of nuclear radiation concepts among in-service science teachers, despite literature suggesting that teachers often hold misconceptions about this topic (Morales López & Tuzón Marco, 2022). Therefore, this study aims to address these gaps through analogies and models approach to enhance in-service teachers’ understanding of nuclear radiation. This approach provides a more comprehensive understanding of science teachers’ knowledge of nuclear radiation. This study will evaluate the effectiveness of analogy- and model-based teaching interventions in enhancing teachers’ conceptual understanding through a quasi-experimental design. Given the complexity of teaching nuclear radiation, innovative instructional methods are essential. Analogies and models have proven effective in improving comprehension by connecting abstract scientific concepts to familiar experiences (Bondar & Bozhok, 2020). This study employs these techniques to enhance teachers’ understanding of nuclear radiation, enabling them to present the topic more accessible to students (Glynn et al., 1991). Well-trained teachers in nuclear radiation are better equipped to provide a balanced perspective, addressing both the benefits and risks of nuclear technology (Sabharwal & Gerardo-Abaya, 2019). Therefore, ensuring teachers possess the necessary knowledge and pedagogical tools is crucial in dispelling common misconceptions and improving nuclear literacy.

Enhancing teachers’ understanding of nuclear radiation is vital for advancing science education, particularly as nuclear technology becomes critical in addressing global challenges. However, teaching this complex subject remains a significant challenge. Integrating analogy- and model-based approaches into teacher training can empower educators to equip students with the knowledge and skills needed to engage with nuclear technology responsibly.

Constructivism and Conceptual Change Theories

This study is grounded in Constructivism and Conceptual Change Theories, which provide insights into how science teachers develop their understanding of nuclear radiation. Specifically, these frameworks explain how teachers build awareness and restructure their conceptual knowledge through instructional strategies such as analogies and models. Constructivist Theory, as proposed by Dewey, Piaget, and Vygotsky, emphasizes that individuals actively construct knowledge through experiences, where new information is integrated with prior knowledge through social interaction, reflection, and participation in learning activities (Liu & Chen, 2010). Therefore, constructivist teaching methods, such as using analogies and models, encourage teachers to go beyond mere memorization and instead engage in active learning, helping them re-evaluate and integrate new concepts (Baviskar et al., 2009). Furthermore, Conceptual Change Theory (Posner et al., 1982) explains how individuals modify their beliefs when confronted with conflicting information, asserting that meaningful learning occurs when new concepts replace or restructure outdated ones through cognitive conflict. This theory establishes four essential conditions for conceptual change: dissatisfaction with existing concepts, intelligibility, plausibility, and fruitfulness of new concepts (Baydere et al., 2020). Hence, addressing misconceptions about nuclear radiation requires an instructional approach that challenges pre-existing beliefs and encourages teachers to restructure their knowledge through reflection and active engagement.

Based on these theories, this study proposes an intervention using analogy- and model-based approaches to assess changes in teachers' understanding of nuclear radiation concepts. Additionally, the instructional approach aimed to create cognitive conflict, prompting teachers to re-evaluate their misconceptions and construct more scientifically accurate knowledge. The study incorporated hands-on activities, collaborative discussions, and interactive simulations to achieve conceptual change. For example, the balloon and powder analogy illustrated nuclear fission, while the UV flashlight and fluorescent paint demonstration helped teachers understand radiation detection, and the cloud chamber experiment enabled them to observe ionization tracks in real time. Furthermore, collaborative learning promoted social constructivism, as teachers engaged in group discussions to refine their understanding.

METHODOLOGY

A quasi-experimental study investigated the impact of analogies and models on science teachers' understanding of nuclear radiation. Quasi-experiments are commonly used when true experimental conditions are impractical, offering advantages such as easier data access and reliable evaluation methods (Creswell, 2014; Gopalan et al., 2020). The sample comprises 60 science teachers teaching Year 3 or 4 secondary school science subjects. Participants were randomly assigned to two groups: an experimental group (30 teachers), which received instruction using analogies and models, and a control group (30 teachers), which followed a traditional lecture-based approach. Both groups completed pre-tests and post-tests to assess their understanding of nuclear radiation.

Research Instruments

This study utilized two research instruments. First, a diagnostic test developed by Yumuşak et al. (2015) was adapted into a four-tier format, following the framework proposed by Subramaniam and Sreenivasulu (2013). The test comprised 15 selected items designed to assess higher-order thinking skills related to nuclear radiation. The questions were aligned with Science Year 3, Chapter 8 (Radioactivity) and Science Year 4, Chapter 12 (Nuclear Energy). Additionally, five structured activities incorporating analogies and models were implemented. These activities, inspired by the Ministry of Education's program, aimed to simplify complex nuclear radiation concepts. The activities covered key topics such as radioactive materials, atomic structure, ionizing radiation, nuclear energy, and radiation safety, ensuring alignment with the Year 3 and 4 Science syllabus.

Data Analysis Procedure

The study employs descriptive analysis and ANCOVA to explore science teachers' understanding of nuclear radiation. Descriptive analysis is used to summarize data and assess changes before and after interventions, while ANCOVA is used to measure the effect of teaching methods. The research utilizes a four-tier diagnostic test to evaluate scientific understanding, distinguishing between correct knowledge, overconfidence, and uncertainty. Scores from the test categorize teachers' knowledge levels of nuclear radiation concepts. Additionally, a cognitive score scale measures understanding proficiency from "Excellent" to "Very Weak," providing a detailed evaluation framework for teachers' understanding of nuclear science education. The pre-test was used as a covariate to control for individual differences in the intervention, ensuring that post-test differences were due to the treatment.

FINDINGS

Descriptive Statistics

The descriptive statistics (Table 1) indicate a significant improvement in the experimental group's understanding of nuclear radiation after instruction using analogies and models.

Table 1. *Mean Score and Standard Deviation Overall Understanding Level of Radiation Nuclear (Control group N=30, Experimental group N=30)*

Dependent measure		Control (n=30)		Experimental (n=30)	
		Mean	SD	Mean	SD
Level of Understanding on radiation nuclear	Pre-test	55.5	12.5	48.2	14.8
	Post-test	56.6	11.8	66.3	7.5
	Gain	1.1	.7	18.1	7.3

Note. SD: Standard deviation

The experimental group, which initially had a lower mean score (M = 48.2, SD = 14.8), exhibited a substantial post-test increase to M = 66.3 (SD = 7.5). Conversely, the control group showed only a minor improvement from M = 55.5 (SD = 12.5) to M = 56.6 (SD = 11.8). The experimental group's greater mean gain (ΔM = 18.1) confirms the positive impact of analogy- and model-based instruction.

A notable trend is the reduction in standard deviation (SD) in the experimental group from 14.8 to 7.5, indicating more consistent learning gains across participants, regardless of their initial knowledge level. Interestingly, the control group had a higher pre-test mean (55.5) than the experimental group (48.2), suggesting stronger foundational knowledge. However, despite this initial advantage, the experimental group significantly outperformed the control group in the post-test, highlighting the effectiveness of the intervention in bridging the knowledge gap.

Impact on Misconception Reduction

A comparative diagnostic question analysis (Table 2) further supports the effectiveness of the intervention in correcting misconceptions.

Table 2. *Comparative Analysis of Level Understanding of Diagnostic Question for Experiment and Control Groups*

Question	Experiment Group (N=30)								Control Group (N=30)							
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	SK		FP		FN		LK		SK		FP		FN		LK	
1	0	1	9	9	1	11	20	9	2	4	12	11	3	2	13	13
2	6	13	0	0	3	5	21	12	17	15	1	1	1	3	11	11
3	9	11	0	0	1	0	20	19	12	12	0	0	2	5	16	13
4	9	5	0	2	2	8	19	15	13	14	1	1	3	1	13	14
5	1	8	0	0	0	4	29	18	3	4	0	0	5	9	22	17
6	4	8	0	0	3	6	23	16	5	5	2	1	1	3	22	21
7	12	13	1	4	0	3	17	10	7	9	3	2	5	5	15	14
8	0	1	0	2	7	17	23	10	3	3	0	0	4	7	23	20
9	5	8	1	4	0	0	24	18	7	10	6	4	1	2	16	14
10	8	16	1	1	2	1	19	12	12	8	0	0	2	5	16	17
11	6	9	2	10	1	1	21	10	10	8	0	4	3	3	17	15
12	2	10	0	1	0	3	28	16	4	7	0	0	4	2	22	21
13	6	10	0	0	1	0	23	20	9	6	2	0	0	2	19	22
14	1	3	1	3	0	0	28	24	2	3	4	3	2	3	22	21
15	12	16	2	2	0	1	16	11	10	9	3	0	1	2	16	19

Note. SK: Scientific knowledge, LK: Lack of knowledge, FN: False negative, FP: False positive

The pre-test results for the experimental group (N=30) revealed low levels of scientific knowledge (SK), with many participants displaying a lack of knowledge (LK) or false positive (FP) responses. However, a substantial reduction in misconceptions was observed after the intervention. In Question 1, SK increased from 0 to 9 participants, while in Question 10, it rose from 8 to 16. Similarly, FP in Question 5 dropped from 4 to 0, whereas the control group saw no change in FP for the same question. These findings suggest that analogy- and model-based instruction not only enhances conceptual understanding but is also more effective in correcting misconceptions than traditional teaching methods. Before the intervention, many participants in the experimental group exhibited misconceptions, as seen in Question 7, where 17 participants demonstrated LK. After the intervention, LK decreased significantly from 17 to 10, reinforcing the effectiveness of the teaching approach in addressing knowledge gaps. In contrast, while the control group showed some improvement, the reductions in LK and FP were less pronounced. For instance, in Question 1, SK in the control group increased from 2 to 11, but certain misconceptions persisted, as seen in Question 5, where 18 participants continued to exhibit LK after the post-test.

Statistical Significance of the Intervention

A one-way Analysis of covariance (ANCOVA) was conducted to determine whether the analogy- and model-based intervention had a statistically significant effect on teachers' understanding after controlling for pre-test scores. Table 3 shows the results of the ANCOVA analysis.

Table 4. *Test of Between-Subjects Effects for ANCOVA on Dependent Variable Post-test of Understanding*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power[b]
Corrected Model	2923.893[a]	2	1461.946	20.232	<.001	.415	1.000
Intercept	6756.819	1	6756.819	93.507	<.001	.621	1.000
PRE	1522.226	1	1522.226	21.066	<.001	.270	.995
GROUP	2146.035	1	2146.035	29.699	<.001	.343	1.000
Error	4118.841	57	72.260				
Total	233486.000	60					
Corrected Total	7042.733	59					

Note. [a] R Squared: .415 (Adjusted R Squared: .395). [b] Computed using alpha: .05

To ensure the validity of the ANCOVA results, normality and homogeneity of variance tests were conducted. The Q-Q plot, skewness (-1 to 1), and kurtosis (-2 to 2) indicate that the data meet the normality assumption (Tsagris & Pandis, 2021). Additionally, Levene's test confirms that the variance between the experimental and control groups is homogeneous ($F(1,58) = 0.422$, $p = 0.519$), supporting the validity of the ANCOVA model. Therefore, all key ANCOVA assumptions were met, allowing the analysis to proceed in evaluating the effects of the analogy and model approach on science teachers' understanding.

The ANCOVA results demonstrate a significant effect of the analogy- and model-based intervention on post-test scores. The GROUP variable ($F = 29.699$, $p < .001$, Partial Eta Squared = .343) indicates that the intervention substantially impacted participants' understanding of nuclear radiation. Additionally, the model explains 41.5% of the variance in post-test scores (R Squared = .415, Adjusted R Squared = .395), a large effect size in educational research. The PRE variable ($F = 21.066$, $p < .001$, Partial Eta Squared = .270) shows that pre-test scores significantly influenced post-test performance, suggesting that participants' initial knowledge also influenced their learning outcomes. However, the GROUP variable has a slightly larger effect size than PRE (.343 vs. .270), confirming that the intervention contributed more to post-test improvement than prior knowledge alone.

The Intercept variable (F = 93.507, Partial Eta Squared = .621) has the largest effect size, indicating that the overall post-test scores significantly differ from zero. Furthermore, the observed power for all variables is 1.0, meaning that the study had sufficient sample size to detect significant effects, ensuring the reliability of the results.

Overall, these findings strongly validate the effectiveness of analogy- and model-based teaching methods in enhancing science teachers' conceptual understanding of nuclear radiation. The statistically significant group variable and large effect size confirm that this instructional approach has a greater impact than traditional teaching methods. The clear upward trend in post-test scores, numerical validation in descriptive statistics, and ANCOVA results all reinforce the effectiveness of this intervention. Additionally, the substantial learning gains in the experimental group and the reduction in misconceptions suggest that this teaching strategy should be integrated into teacher training programs to improve science education and promote deeper conceptual learning.

DISCUSSION

The study investigated whether analogies and model approaches significantly improved science teachers' understanding of nuclear radiation after controlling for pre-test scores. Using descriptive statistics, paired sample t-tests, and ANCOVA, it was found that these approaches had a notable impact. The experimental group showed a significant increase in understanding compared to the control group, which only saw moderate gains. Effect size analyses further confirmed the positive effect of the intervention. The study demonstrated that these teaching methods enhance nuclear radiation understanding. The analysis of post-test scores indicates that the experimental group had higher mean scores than the control group, highlighting differences in comprehension of nuclear radiation between the groups. ANCOVA results confirmed that the intervention was a strong predictor of post-test outcomes. The positive impact of the intervention is further validated by estimated marginal means, showing significant improvements in the experimental group's scores, confirming the effectiveness of using analogies and models. The study supports constructivist and conceptual change theories, showing that using analogies and models can enhance teachers' understanding of nuclear radiation. Group activities facilitated conceptual change, consistent with findings by Sevim (2013).

The study's findings are consistent with past research, demonstrating the effectiveness of analogies and models in teaching complex concepts. The studies reviewed focus on various aspects of nuclear science education, with differences in the topics covered and the specific approach taken. Yumuşak et al. (2015) concentrated on students' understanding of atomic models and radioactive decay, addressing misconceptions through computer-assisted instruction and conceptual change texts. Similarly, Cardoso et al. (2020) explored high school students' misconceptions about atomic models and radiation, applying interactive teaching methods to clarify radiation types and their applications. Xue et al. (2022) focused on improving students' understanding of atomic structure and nuclear radiation, comparing the effects of modelling and analogy in their teaching, but their focus was primarily on atomic models rather than nuclear radiation as a separate concept. Contrastingly, Sani (2012) concentrated on matter concepts, aiming to enhance teachers' understanding of atoms and molecules without addressing nuclear radiation. Bondar and Bozhok (2020) examined the broader use of analogies in science education, but their focus was not on nuclear science specifically. Lee (2014) focused on teaching heat energy, heat transfer, and insulation, which are more foundational concepts than the abstract and complex subject of nuclear radiation. Lastly, Iimoto et al. (2019) investigated nuclear science education in the Asia Pacific region, focusing on teacher training and nuclear science awareness without focusing on nuclear radiation. The key difference across these studies lies in their level of specificity: some address broader scientific concepts like atomic models or heat transfer, while others engage more deeply with specialized topics such as nuclear radiation, each with tailored teaching interventions aimed at improving understanding and correcting misconceptions.

Teaching approaches based on analogies and models enhance science teachers' understanding of nuclear radiation, positively impacting student learning in the long term. Teachers who master these concepts can deliver information more effectively, aiding students in comprehending radioactive decay, ionizing radiation, and the effects of radiation on humans and the environment. For example, the Sterile Insect Technique (SIT) model demonstrates the application of nuclear radiation in agriculture, helping students grasp this concept more concretely. A study by Treagust (2002) supports analogies and models that explain complex scientific concepts effectively, including nuclear phenomena that are difficult to observe directly. With guidance from knowledgeable teachers, students can develop a stronger understanding and make rational decisions related to nuclear science. This approach not only enhances short-term understanding but also supports students' scientific thinking in the long term. Therefore, it is appropriate to include it in nuclear science teaching strategies; however, further studies are needed to assess its long-term effects.

This study demonstrates the effectiveness of the analogy and model-based approach in enhancing science teachers’ understanding of nuclear radiation. However, several limitations must be considered in interpreting the findings accurately. One of the key limitations is the small sample size ($N = 60$), which restricts the generalizability of the results to a larger population. A small sample also increases data variability and reduces statistical power, making detecting clear patterns in the intervention’s effects more difficult. Additionally, the quasi-experimental design used in this study does not allow full control over external factors such as participants' teaching experience and academic background. While ANCOVA was used to adjust for initial differences in pre-test scores between the experimental ($M = 48.2$) and control groups ($M = 55.5$), it cannot fully eliminate bias resulting from these disparities. Another major limitation related to applying ANCOVA and its statistical assumptions is its reliance on several key assumptions, including normality, homogeneity of variance, and homogeneity of regression slopes. While normality and homogeneity of variance were confirmed (Levene’s test: $F(1,58) = 0.422$, $p = 0.519$), the assumption of homogeneity of regression slopes was not reported, which could introduce bias if violated.

Additionally, ANCOVA adjusts for pre-test differences but does not completely remove the impact of covariate imbalance, particularly when pre-test scores significantly differ between groups. This is relevant to the study as the control group had a higher mean pre-test score, potentially influencing the adjusted post-test results. Furthermore, ANCOVA only measures mean score differences and does not capture conceptual changes in understanding, which would be better explored through qualitative methods such as interviews or classroom observations.

Beyond ANCOVA-specific limitations, bias is another concern that may have influenced the findings. Selection bias could have occurred since teachers who participated were likely more interested in innovative teaching methods, which may have affected the effectiveness of the intervention. Response bias may have been present, where participants provided more positive responses because they were aware of being studied (Hawthorne effect). Additionally, instrument bias might have influenced the results if the test items did not fully capture teachers' understanding of nuclear radiation. The short intervention duration further limits the study, as it does not allow for an assessment of long-term retention of knowledge. Without follow-up assessments, it remains unclear whether the observed improvements in understanding persist over time.

Several steps were taken to mitigate these limitations. The study confirmed normality and homogeneity of variance assumptions before conducting ANCOVA to ensure statistical validity. Additionally, pre-test scores were included as a covariate to control for initial differences between groups, and effect size reporting (Partial Eta Squared = 0.343) indicated a moderate to large impact of the intervention. While these steps helped improve the reliability of the findings, they did not eliminate all constraints. It is recommended to increase the sample size, use randomized controlled trials (RCTs) to strengthen causality claims and employ a mixed-methods approach incorporating interviews and classroom observations to gain deeper insights into teachers' conceptual changes and address the issues in future research.

Additionally, the study’s delimitations must be acknowledged. The research specifically focused on science teachers, excluding educators from other disciplines, which may limit the generalizability of the findings to non-science teachers. The study also concentrated solely on the analogy and model-based approach without examining other instructional strategies, such as inquiry-based or problem-based learning. Furthermore, the study relied on pre-test and post-test scores as the primary assessment method rather than alternative evaluation tools such as think-aloud protocols, open-ended interviews, or classroom observations. The intervention was conducted over a short period, without long-term follow-up to determine the sustainability of the learning outcomes.

Implication and Future Research

The findings of this study have the potential to benefit teachers, students, and policymakers in various ways. A structured and multi-tiered approach is essential to effectively integrate analogy- and model-based teaching into teacher training and the national curriculum. Policymakers and educational institutions must establish clear guidelines and resources to support science educators adopting these methods. Teacher training programs should incorporate hands-on workshops, interactive case studies, and micro-teaching sessions to ensure effective application. Additionally, a national repository of teaching resources—including lesson plans, simulations, multimedia content, and worksheets—should be developed to provide standardized and accessible materials for educators. Continuous professional development (CPD) should also be incentivized through CPD credits and certification programs, encouraging sustained teacher engagement with these instructional strategies.

At the curriculum level, analogy- and model-based teaching should be systematically embedded in science textbooks and syllabi to ensure structured implementation across classrooms. Education policy reforms must standardize these methods by integrating them into pre-service teacher training, equipping future educators with the necessary skills. Collaboration with nuclear agencies, universities, and industry experts will enhance teacher training by providing expert-led workshops, updated resources, and real-world applications of nuclear science concepts. Pilot programs should be introduced in selected schools to assess the effectiveness of these approaches before full-scale implementation, with continuous monitoring and evaluation by national research institutions. This approach will strengthen teaching quality, enhance students' understanding of nuclear science, and inspire greater interest in related careers. Ultimately, embedding these strategies into teacher training and national curricula will contribute to developing a more skilled and knowledgeable workforce, ensuring long-term sustainability in science education and the nuclear industry.

Future research should explore the impact of analogies and models in advanced topics and the needs of pre-service teachers, using mixed methods for deeper insights. Additionally, understanding how teaching methods affect professional identity and gathering student perspectives will refine strategies, while emerging tools like augmented reality could enhance traditional methods. Continued research is essential to refining instructional strategies in nuclear education, focusing on subtopics, student engagement, and integrating new technologies to prepare science teachers better.

CONCLUSION

In conclusion, this study highlights the significant impact of analogies and model-based approaches in enhancing science teachers' understanding of nuclear radiation concepts. The findings provide strong evidence that these innovative teaching strategies not only improve conceptual clarity but also effectively address misconceptions, particularly in complex and abstract topics like nuclear radiation. The results align with the principles of constructivist and conceptual change theories, which emphasize active learning, cognitive engagement, and the restructuring of pre-existing knowledge for deeper understanding. By facilitating a shift from rote memorization to meaningful learning experiences, these methods empower teachers to convey challenging scientific concepts more effectively to their students. The implications of this study extend beyond individual classroom practices. Integrating analogy and model-based approaches into teacher professional development programs could be critical in addressing the broader Malaysian science education challenges. These methods offer an opportunity to bridge gaps in understanding, enhance teaching efficacy, and ultimately contribute to a more scientifically literate society. The Malaysian Nuclear Agency, in collaboration with the Ministry of Education, could play a pivotal role in standardizing these instructional strategies across educational institutions, ensuring consistent quality in delivering nuclear science topics.

Moreover, the study underscores the necessity of equipping teachers with robust pedagogical tools and resources to foster interest and competence in nuclear science among students. This is particularly relevant given the increasing importance of nuclear technology in addressing global challenges such as energy sustainability and climate change. A workforce well-versed in nuclear science and technology is critical for Malaysia's advancement toward its Nuclear Vision 2030 goals and for strengthening its competitiveness in the global arena. Future research should build on these findings to explore the long-term effects of analogy and model-based approaches on teacher professional identity, student outcomes, and public perceptions of nuclear technology. Additionally, investigating their application in advanced topics and incorporating emerging technologies such as augmented reality could further enhance the effectiveness of these strategies. By continuing to refine and expand instructional methods in nuclear education, this study contributes to the broader goal of improving science education and preparing teachers and students to responsibly and confidently engage with nuclear technology.

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