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Designing a pedagogical framework to strengthen climate-integrated teaching skills for pre-service science teachers in support of the SDGs

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Abstract

This study aims to develop a climate change-based pedagogical framework to improve the teaching skills of pre-service science teachers. The research adopts the Borg & Gall development model, including needs analysis, development, validation, and implementation stages. Data were collected through expert validation, practical observations, and pre-test and post-tests assessing learning design and teaching implementation skills. Data analysis employed percentage agreement, paired t-tests or Wilcoxon tests, and n-gain analysis. The results indicate that a specifically designed pedagogical framework is essential to support the Sustainable Development Goals (SDGs), particularly sustainable climate change education, and is necessary for pre-service science teachers. Expert validation showed that the framework is highly valid, with content validity scores of 3.70, construct validity scores of 3.71, and reliability exceeding 88.00%. The framework was also rated as highly practical by lecturers (98.98%) and students (98.88%). Implementation in microteaching courses revealed significant differences between pre-test and post-test scores ($p < 0.001$), with a moderate increase in science lesson design and teaching skills integrated with climate change issues (n-gain = 0.32–0.38). Overall, the framework enhanced scientific understanding, pedagogical competence, technology integration, and ecological awareness, supporting SDGs 4 and 13.

Keywords: Climate change awareness, Designing, Pedagogical framework, Pre-service science teachers, SDGs, Teaching skills.

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Contents

Contribution of this paper to the literature
This study contributes in proposing a validated pedagogical framework that integrates climate change education into pre-service science teacher training by aligning pedagogical skills, sustainability competencies, and the SDGs, while systematically combining theory, expert validation, and practical instructional design within teacher education contexts.

1. Introduction

One of the biggest global challenges of the 21st century is climate change, which can have a significant impact on health, food security, ecosystems, and the social and economic life of communities. Therefore, it is necessary to prepare the younger generation to understand and respond to the climate crisis through scientific literacy, systemic thinking skills, and sustainable actions. In line with the Sustainable Development Goals (SDGs) framework, particularly SDG 13 (climate action), education is seen as a key pillar for increasing community capacity in climate change mitigation and adaptation (UNESCO, 2023).

Teacher education, especially for pre-service science teachers, needs to be strengthened and will be key to driving learning transformation to be more responsive to sustainability issues. This serves as a bridge between scientific knowledge, pedagogical practices, and the environmental realities faced by students. Training pre-service teachers based on environmental values increases their commitment to pro-environmental action (Biasutti & Frate, 2022). Behavioral change occurs through critical reflection and meaningful experiences (Mezirow, 1991). However, various studies have found that pre-service teachers' climate literacy is still suboptimal and not yet fully integrated into their teaching skills (Bozdogan, 2021; Liu, Roehrig, Bhattacharya, & Varma, 2020). This situation has the potential to weaken schools' ability to support the SDGs, which emphasize education for sustainable development, global citizenship, and environmental awareness. Therefore, teacher education requires a new approach that builds ecological knowledge, attitudes, and skills in an integrated manner.

One effort that can be made is through an integrated pedagogical framework on climate change issues. A comprehensive pedagogical framework based on climate change issues is needed to guide the learning process for pre-service science teachers. This is in line with the recommendations of Rahman, Noor, and Abdullah (2022) and Anderson and McLoughlin (2022), who recommend that pre-service teachers need a clear, structured, and evidence-based pedagogical framework to consistently integrate climate issues into their teaching. This framework will enable pre-service teachers to design, implement, and evaluate quality science learning processes that are in line with the SDGs and involve 21st-century competencies.

In Education for Sustainable Development (ESD), teachers are positioned as agents of social and ecological change. Strengthening inquiry-based, problem-based, and project-based learning is an important part of a pedagogical framework relevant to climate change issues (Hmelo-Silver & Eberbach, 2021; Salmi, Kaasinen, & Suomela, 2023). In addition, digital technology can be used to support climate change learning. According to Lehtonen, Salonen, and Cantell (2021), technologies such as climate simulations, data visualization, and environmental monitoring applications provide opportunities for pre-service teachers and students to analyze real-world phenomena using authentic data. This is in line with the principles of TPACK (Technological Pedagogical Content Knowledge), which emphasizes the need for a balance between scientific content, pedagogical strategies, and educational technology (Mishra & Koehler, 2006). The integration of technology also supports the SDGs target of improving digital competence in education.

Based on these conditions, this study aims to develop and test an integrated pedagogical framework for climate change issues to improve the teaching skills of pre-service science teachers and support the SDGs. This framework was developed through a development model and validated by experts to ensure its quality. Furthermore, the framework was tested through microteaching lectures to assess its practicality and effectiveness. The research findings strengthen the role of teacher education in achieving the SDGs, particularly SDG 4 (quality education) and SDG 13 (climate action), and encourage the development of pre-service teachers capable of developing climate literacy in future generations.

2. Research Methods

The research method adopted a development model consisting of several stages, namely: needs analysis, development, validation, and implementation in learning (Borg & Gall, 1983). At the needs analysis stage, a literature study was conducted on the pedagogical framework aimed at providing pre-service science teachers with the tools to design and implement learning integrated with climate change issues, thereby supporting the achievement of the SDGs. Next, a survey was conducted to identify development needs, including the teaching abilities of pre-service science teachers. The results of this activity were used as the basis for the pedagogical framework development process. Previous studies have shown that needs analysis is a very important step to ensure that learning tools or media are relevant to the context (Al-Emran, Malik, & Al-Kabi, 2019; Branch, 2009).

The next stage is development. At this stage, efforts to support the SDGs are carried out by incorporating climate change issues into a designed pedagogical framework. The pedagogical framework is designed to help pre-service science teachers plan, implement, and evaluate the learning process. This framework links learning theory, learning objectives, instructional strategies, educational technology, and assessment so that teaching practices are coherent, evidence-based, and integrated with climate change issues. A good pedagogical framework is able to define the structure of learning and guide educators to create meaningful, adaptive, learner-centered learning experiences, and each element of learning supports the achievement of learning objectives (Al-Fraihat, Joy, Masa'deh, & Sinclair, 2020; Biggs & Tang, 2011; Ouyang & Jiao, 2021).

The next stage is validation. At this point, the developed pedagogical framework is validated in terms of construct and content. Construct validity for a pedagogical framework means that the elements, indicators, or components of the framework reflect the conceptual domain being measured (Hair, Hult, Ringle, & Sarstedt, 2021; Knekta, Runyon, & Eddy, 2019). Content validity means that the structure created truly reflects the underlying learning theory and pedagogical principles (Boateng, Neilands, Frongillo, Melgar-Quiñonez, & Young, 2018; Haynes, Richard, & Kubany, 1995; Polit & Beck, 2021). In addition, the validity evaluation is accompanied by recommendations for the developed pedagogical framework. Subsequently, revisions are made according to the validator's recommendations to refine it. Expert validation is an important stage to ensure construct and content validity, as well as support its effectiveness (Reeves & Hedberg, 2003; Wahyuni, Fikriyah, Adiansha, & Safitri, 2021). The validity scores are categorized as follows: "very valid" if the average score is $3.25 \leq P < 4.00$; "valid" if the average score is $2.50 \leq P < 3.25$; "less valid" if the average score is $1.75 \leq P = 2.50$; and "not valid" if the average score is $1.00 \leq P < 1.75$. Next, determine the reliability using the percentage of agreement, $R = ((1-((X-Y)/(X+Y))) \times 100\%$, where R = coefficient of percentage of agreement, X = frequency of aspects observed by observers by giving high frequencies, and Y = frequency of aspects observed by observers by giving low frequencies. Based on the calculation results, it can be said to be reliable if it has a percentage ≥ 75% (Borich, 2019).

The final stage of this research was to test the pedagogical framework in microteaching lectures. The implementation used a one-group pre-test and post-test design, O1 X O2 (Fraenkel & Wallen, 2009). This design can be easily implemented, but it has limitations in terms of internal validity because the changes produced cannot be fully attributed to the treatment, as they may be influenced by external factors (Campbell & Stanley, 1963; Creswell & Creswell, 2018). In its implementation, before the group of pre-service science teachers was given learning using the developed pedagogical framework, a pre-test was first conducted on designing and teaching science integrated with climate change issues (O1). Then, they were given learning using the developed pedagogical framework (X). After the learning process was completed, they were given a post-test (O2). The sample size consisted of 60 pre-service science teachers from teacher training colleges in Central Java, Indonesia, which are under the Ministry of Religious Affairs.

The sample consisted of classes A and B, each with 30 participants. The sample was taken using a cluster random sampling technique. This technique is easier to do because it is applied to groups or classes, so it does not require much time (Fraenkel & Wallen, 2009). Class selection was done randomly so that the research results can still be generalized to the entire population.

The data collection methods and instruments in this stage are: (a) data on the practicality of the developed pedagogical framework are collected using a learning observation sheet; and (c) data on the effectiveness of the pedagogical framework are collected using a design assessment and teaching skills (performance test). The collected data are then analyzed. Practicality data are analyzed using percentage calculations. Data from the design and implementation assessment results are analyzed statistically for their average score ($\alpha = 5\%$) with: (a) paired-sample t-test or non-parametric analysis Wilcoxon's test (Gibbons & Chakraborti, 2011; Şimşek, 2023); (b) calculating the average n-gain with the formula: n-gain = (post-test score – pre-test score) / ideal score – pre-test score), with the following categories: high if n-gain ≥ 0.70; moderate if 0.70 > n-gain ≥ 0.30; and low if n-gain < 0.30 (Coletta, 2023; Hake, 1998).

3. Study Results

3.1. Needs Analysis Results

The needs analysis indicates that strengthening climate literacy and pedagogical skills of pre-service science teachers is a strategic need that directly supports SDG 4 (Quality Education) and SDG 13 (Climate Action). Teacher education that integrates climate change issues into instructional design and practices will increase the likelihood that the next generation of students will acquire the necessary knowledge, critical thinking skills, and competencies for sustainable action.

Recent empirical studies confirm that teacher training programs emphasizing inquiry-based learning, projects, and the use of real-world data enhance climate issue teaching readiness and link the material to real-world action (Monroe, Plate, Oxarart, Bowers, & Chaves, 2019; Salmi et al., 2023). In addition to pedagogical aspects, the need for technology integration and the use of scientific data are also relevant to achieving SDG targets. Previous research has shown that TPACK skills and practical experience using digital tools accelerate pre-service teachers' conceptual understanding and facilitate contextual learning that encourages students to monitor their local environment (Lehtonen, Niemi, & Kumpulainen, 2021; Li, Cao, & Wang, 2021). Therefore, the pedagogical framework developed must include a digital competency development component and field practice modules that connect local data with SDG targets.

Furthermore, the needs analysis highlights the importance of the values and social action dimensions. Using approaches that encourage the transformation of pro-environmental attitudes and behaviors in pre-service teachers can align with the SDGs, namely responsible consumption and production, and partnerships for the goals through school collaboration.

Evidence from recent studies shows that training programs that incorporate environmental values education and concrete action projects increase ecological empathy and commitment to sustainable practices (Biasutti & Frate, 2022; Ouyang & Jiao, 2021). Consequently, the development of a pedagogical framework must integrate cognitive (scientific knowledge), affective (ecological values and empathy), and conative (action/project) aspects to make teacher education's contribution to achieving the SDGs more tangible and measurable.

3.2. Development Results

A pedagogical framework was developed based on climate change issues with the aim of enabling pre-service science teachers to design and implement integrated learning with climate change issues. This pedagogical framework encompasses enhancing scientific knowledge, developing pedagogical skills, utilizing technology and digital media, developing environmental values and social action, and evaluating and reflecting. The pedagogical framework is presented in Table 1.

Table 1. Pedagogical framework based on climate change issues to support the SDGs for pre-service science teachers.

No	Pedagogical framework	Steps for Implementing	Learning Theories that Support	Research Results that Support	The Link to SDGs	Time
1	Increase in Scientific Knowledge	a. Provide in-depth understanding of climate change (Greenhouse effect, carbon cycle, mitigation and adaptation). b. Conduct field studies and analyze climate change data. c. Provide special meetings to discuss climate data and phenomena.	Cognitive development (Piaget, 1952); Cognitive-constructivism (Vygotsky, 1978).	Inquiry learning and field activities enhance climate understanding and literacy (Kiemer, Gröschner, & Seidel, 2021; Rahman et al., 2022). In learning, these activities are needed to bridge theoretical concepts with real experiences so as to encourage comprehensive understanding (Díaz Palencia & Roa González, 2024).	SDG 4: Sustainable Education, SDG 13:Climate Literacy.	2 weeks
2	Pedagogical Skills Development	a. Training pre-service teachers to implement inquiry-based learning, problem-based learning (PBL), and project-based learning (PjBL). b. Designing integrated learning with climate change issues. c. Practicing environmental case studies and projects.	Social-Constructivism (Vygotsky, 1978).	PBL improves critical thinking and problem-solving skills related to climate issues (Hmelo-Silver & Eberbach, 2021; Kivunja, 2020).	SDG 4: Quality Education, SDG 13: Climate Action.	2 weeks
3	Use of Technology and Digital Media	a. Climate simulation training, data visualization, and environmental monitoring applications. b. Utilizing digital media (video, digital maps, analytical tools). c. Developing digital content for climate materials.	TPACK (Technological Pedagogical Content Knowledge).	TPACK integration improves scientific literacy & the effectiveness of digital science learning (Li et al., 2021; Ouyang & Jiao, 2021). Electronic and digital media can improve climate literacy and be used effectively in the science learning process (Achmad, Zulfiani, & Solihin, 2024; Chananil, Julakarn, & Promsatien, 2025; Erfariyah, Jaenudin, & Permana, 2024; Khaerunnisa, Muhyidin, Sjaifuddin, & Yuhana, 2025).	SDG 4: Digital Competence, SDG 13: Climate Data Analysis.	1 weeks
4	Environmental Values-Based Education and Social Action	a. Facilitate discussions on environmental ethics and generational responsibility. b. Promote environmental action projects: recycling, energy efficiency, reforestation, and carbon footprint campaigns. c. Develop pro-environmental attitudes and ecological empathy.	Transformative Learning (Mezirow, 1991).	Environmental values education increases ecological empathy and pro-environmental commitment (Biasutti & Frate, 2022; Monroe et al., 2019).	SDG 13: Climate Action	1 weeks
5	Evaluation and Reflection	a. Practice climate-based evaluation of the effectiveness of learning. b. Conduct systematic reflection after teaching. c. Encourage ongoing professional development and collaboration among educators.	Experiential Learning (Kolb, 1984).	Reflection increases pedagogical awareness and adaptive abilities of pre-service teachers (Loughran, 2020; Mälkki & Lindblom-Ylänne, 2022).	SDG 4: Improving the Quality of Education	1 weeks

3.3. Validity of the Developed Pedagogical Framework

A climate change-based pedagogical framework to support the SDGs for pre-service science teachers emphasizes the crucial role of teachers in developing a generation that is aware of and concerned about increasingly pressing environmental challenges. Climate change is one of the most significant global issues, impacting various aspects of human life, from health to the economy, and especially our planet's ecosystem. Education is essential for raising awareness, knowledge, and abilities required to meet this issue, especially in science courses.

A pre-service science teacher must master science and be able to relate it to real-world issues related to climate change. This is in line with the idea that, in the face of the global climate crisis, 21st-century science education must focus on developing ecological skills and systemic thinking abilities (Anderson, 2020; Monroe et al., 2019). Pre-service science teachers can develop learning that enhances critical thinking and problem-solving skills, as well as student active engagement in climate change mitigation and adaptation through the application of inquiry-, problem-, and project-based pedagogical approaches (Evans, Stevenson, Lasen, Ferreira, & Davis, 2017; Salmi et al., 2023). Teachers help students do good things in their daily lives, both at school and in the wider community (Hadjichambis & Paraskeva-Hadjichambi, 2020).

The climate change-based pedagogical framework emphasizes three main points: adequate scientific knowledge, pedagogical expertise, and the ability to connect global environmental issues with local contexts (Karpudewan, 2019; Stevenson, Nicholls, & Williams, 2021). Teachers must understand scientific concepts and recognize their important role in teaching students about climate literacy, in accordance with this framework (Liu et al., 2020). Science learning integrated with climate change issues enables students to gain a deeper understanding of the relationship between natural systems, human actions, and environmental sustainability (UNESCO, 2023).

In addition, digital media and technology also play an important role in facilitating complex and abstract science learning. Students can explore climate phenomena contextually and directly through digital applications, simulations, and real-time data (Lehtonen et al., 2021). Therefore, education about climate change is not just theory; it also helps people learn ethics, empathy for the environment, and social responsibility. It is very important for pre-service science teachers to instill in students an awareness of the importance of individual and collective responsibility in maintaining the balance of the ecosystem (Bardsley & Bardsley, 2021). It has been proven that environmental initiatives, such as natural resource conservation, carbon emission reduction, and school greening, can increase students' sense of ownership and active participation in preserving the Earth (Anderson & McLoughlin, 2022). With this method, students not only gain knowledge but also become activists for change who help solve climate change issues at both the local and international levels (Wals, Brody, Dillon, & Stevenson, 2014).

The validity of the created instructional framework was then evaluated. A pedagogical framework must satisfy both construct validity and content requirements to be classified as a high-quality product. Construct validity relates to consistency or design logic, while content validity pertains to relevance or currency (Nieveen, McKenney, & Van Den Akker, 2013; Plomp & Nieveen, 2020). Table 2 displays the established educational framework's content and construct validity scores.

Table 2. Results of the pedagogical framework validity assessment.

No.	Aspect	Validity		Reliability	
		Score	Criteria	Percentage of agreement coefficient-R (%)	Criteria
Content validity					
1.	The need for developing a pedagogical framework	3.70	Very Valid	90.80	Reliable
2.	The pedagogical framework is designed based on current knowledge	3.70	Very Valid	90.20	Reliable
	Average	3.70	Very Valid	90.05	Reliable
Construct validity					
1.	Theoretical support	3.75	Very Valid	88.40	Reliable
2.	Support from previous research results	3.70	Very Valid	88.40	Reliable
3.	Steps in the pedagogical framework support the objectives	3.72	Very Valid	90.02	Reliable
4.	Timing of each stage	3.70	Very Valid	88.80	Reliable
5.	Supportive environment	3.68	Very Valid	88.80	Reliable
	Average	3.71	Very Valid	88.88	Reliable

Table 2 shows that the developed pedagogical framework has the criteria of being highly valid in terms of content and construct. The average content validity score is 3.70, and the average construct validity is 3.71. This score is >3.25 and is declared reliable with a coefficient of percentage of agreement >75%. The validator also provided suggestions for the developed pedagogical framework, namely: 1) it is necessary to emphasize that when pre-service teachers design science lessons, they must still adapt the material in schools; 2) in providing an understanding of climate change issues, it is necessary to provide an outline and detail of the material; and 3) the pedagogical provision, if necessary, provides an understanding of the advantages and disadvantages of the inquiry model, problem-based learning, and project-based learning. Basically, these suggestions are not substantial and do not change the structure of the developed pedagogical framework. Next, revisions are made.

3.4. Implementation of the Pedagogical Framework

The pedagogical framework was implemented in microteaching lectures. Data obtained at this stage examined the practicality and effectiveness of the pedagogical framework during its implementation in lectures.

The practicality of the pedagogical framework in this study was demonstrated by its ability to be used in microteaching lectures. Observations indicated that the developed pedagogical framework was used effectively. A questionnaire administered to the lecturers in charge of the courses indicated that they did not experience significant difficulties in using the pedagogical framework (Table 3). Therefore, the developed pedagogical framework was deemed practical and easy to operate. The challenges encountered were purely technical and did not disrupt the learning process.

Table 3. Practicality of the Pedagogical Framework.

No	Aspect	User	
		Lecture	Pre-service teacher
1.	The pedagogical framework is easy to apply in microteaching sessions, including designing learning.	98.96%	98.88%
2.	Each component of the pedagogical framework, from opening to closing, can be implemented smoothly without requiring complex technical skills.	98.96%	98.88%
3.	The pedagogical framework does not create new problems in microteaching lectures.	99.02%	98.88%
	Average	98.98%	98.88%

The effectiveness of the pedagogical framework is demonstrated by the improvement in teaching skills integrated with climate change issues among pre-service science teachers. The teaching skill scores of pre-service science teachers are presented in Tables 4 and 5.

Table 4. Scores on designing learning by pre-service science teachers.

No.	Indicators	Class A		Class B	
		Pre-test	Post-test	Pre-test	Post-test
1	Learning Design Identity	8.0	9.0	8.5	9.0
2	Formulation of science learning objectives integrated with climate change issues to support the SDGs.	3.5	8.5	3.5	8.0
3	Selection of learning resources and infrastructure	4.5	9.0	4.0	8.5
4	Learning model and instructional methods selection	4.0	8.5	4.0	9.0
5	Formulation of key learning points incorporating climate change and SDGs.	5.0	7.0	5.0	7.5
6	Learning formulation related to meaningful learning (raising climate change issues to support the SDGs).	4.0	7.5	4.0	7.5
7	Prompting questions (connecting with climate change issues to support the SDGs)	4.5	7.5	4.0	8.0
8	Learning Preparation Formulation	5.0	8.0	5.5	8.0
9	Learning Activity Steps	5.0	7.5	6.0	8.0
10	Formulation of steps for developing thinking skills in learning related to understanding climate change, adaptation, and mitigation.	4.5	7.5	4.0	8.0
11	Supporting documents and learning resources are linked to climate change issues to support the SDGs.	4.0	8.5	4.0	8.5
	Total Score	52.00	88.50	52.50	90.00
	Average	4.73	8.05	4.77	8.18

Table 5. Teaching skills scores of pre-service science teachers.

No	Indicators	Class A		Class B	
		Pre-test	Post-test	Pre-test	Post-test
1	Lesson opening skills	4.4	8.0	5.0	8.0
2	Skills in capturing and motivating students	5.0	7.5	5.5	7.5
3	Depth and breadth of material, including climate change issues supporting the SDGs.	5.0	7.0	4.5	7.5
4	Completeness of material (conceptual comprehension), including climate change issues supporting the SDGs.	4.0	7.0	5.0	7.5
5	Correctness of Concepts/Procedures related to climate change issues to support the SDGs	5.0	8.0	5.0	8.0
6	Skills in using learning methods, models, and approaches	4.5	7.5	5.0	7.5
7	Skills in developing varied interactions	4.5	7.0	4.5	7.0
8	Classroom management skills	5.0	8.0	5.5	8.0
9	Time management skills	5.0	7,5	4.0	7.5
10	Skills in organizing learning resources and/or teaching materials	5.5	7.0	5.5	7,5
11	Skills in using information technology in learning and connecting them to climate change issues to support the SDGs.	5.0	7.5	5.0	7.5
12	Skills in using learning media	4.5	8.0	4.5	8.0
13	Skills in writing on the whiteboard	5.0	8.0	5.0	9.0
14	Voice volume and intonation	5.0	8.0	5.0	8.0
15	Use of good and correct language, oral and written	5.0	8.0	5.0	8.0
16	Skills in using nonverbal communication (Gestures)	5.5	8.0	5.5	9.0
17	Skills in assessing processes, including issues related to climate change issues to support the SDGs	5.0	8.0	5.5	9.0
18	Skills in assessing learning outcomes, including issues related to climate change issues to support the SDGs	5.0	9.0	5.0	9.0
19	Skills close the lesson	4.0	8.0	4.0	8.0
	Total Score	91.9	147.0	94.0	151.5
	Average	4.84	7.74	4.95	7.97

Tables 4 and 5 show the pre-test and post-test scores for pre-service science teachers' integrated climate change teaching skills (lesson design and implementation). The analysis was then conducted, and the results are presented in Table 6.

Table 6. Results of normality, homogeneity, and paired t-test/wilcoxon tests for pre-service science teachers' integrated climate change teaching skills scores.

Class	Test	∑	Average	Std. Dev.	Normality	Homogenity	Paired t-test/Wilcoxon	n-gain	
					p(α = 0.05)	p(α = 0.05)	(α = 0.05)		
Skills in developing integrated learning designs for climate change issues									
A	Pre	30	4.73	2.78	0.068	0.109	t = -32.22; p< 0.001	0.37	Moderate
	Post	30	8.05	3.02	0.151				
B	Pre	30	4.77	3.34	0.078	0.228	t = -45.71; p< 0.001	0.38	Moderate
	Post	30	8.18	3.01	0.198				
Skills in implementing integrated learning on climate change issues									
A	Pre	30	4.84	2.58	0.241	0.045	t = -54.98; p< 0.001	0.32	Moderate
	Post	30	7.74	2.56	0.881				
B	Pre	30	4.95	3.42	0.221	0.108	t = -32.66; p< 0.001	0.34	Moderate
	Post	30	7.97	2.86	0.122				

4. Discussion

The research results indicate that the development of a climate change-based pedagogical framework is essential for the education of pre-service science teachers. This framework addresses the real needs of the educational world regarding the low climate literacy and ecological competence of the younger generation. These findings align with UNESCO (2023) recommendation that climate education must be systematically integrated at all levels to support Education for Sustainable Development (ESD), particularly its contribution to SDG 4 (Quality Education) and SDG 13 (Climate Action). Because it gives students a real-world framework to comprehend the connection between scientific phenomena, human activity, and environmental sustainability, climate change has become a critical emphasis of global science education. These results are consistent with Monroe et al. (2019), who highlighted the necessity of including climate education in the curriculum to improve the younger generation's ecological competency.

According to Table 2, the pedagogical framework's extremely high content validity score of 3.70 indicates that the scientific knowledge components align with the skills required of instructors in the twenty-first century. Constructivism and inquiry-based approaches have been shown to strengthen conceptual understanding of climate change, as supported by Rahman et al. (2022), who found that inquiry-based learning activities, experimental activities, and environmental data analysis improved pre-service teachers' conceptual understanding of climate phenomena.

Table 2 shows construct validity (a score of 3.71), demonstrating that the developed pedagogical framework was based on logical consistency and strong supporting learning theory. The structure of the pedagogical framework refers to the integration of cognitive theory, constructivism, transformative learning, and experiential learning. This finding aligns with Kiemer et al. (2021), who stated that a good pedagogical framework must provide systematic steps that enable pre-service teachers to connect context, content, and reflective practice. This ensures that the pedagogical framework is not only theoretically sound but also applicable in real-life learning situations.

These findings are supported by research by Hmelo-Silver and Eberbach (2021), which claims that problem-based learning promotes the creation of evidence-based activities and a comprehensive awareness of climate challenges. Meanwhile, integrating educational technology into the TPACK-based pedagogical framework helps pre-service educators use climate simulations, data visualizations, and environmental analysis applications. These results are in line with Li et al. (2021) and Ouyang and Jiao (2021), which show that the application of technology in science learning improves students' scientific literacy and helps pre-service science teachers explain abstract concepts. These findings have a direct link to the SDGs as they promote the improvement of individual and organizational capabilities to address and adapt to climate change and encourage the use of technology for sustainability.

In order to promote ecological consciousness in pre-service teachers, the created pedagogical framework also incorporates social action and environmental values-based education. This is important because climate education includes affective and moral elements in addition to cognitive ones. An environmental values education curriculum enhances ecological empathy and pro-environmental commitment in pre-service teachers, according to research by Biasutti and Frate (2022). Teachers with ecological character and sustainability consciousness are thus produced by the instructional framework in addition to being academically competent.

According to Table 3, the pedagogical framework's use in microteaching courses demonstrated a very high degree of practicality (average scores of 98.98% and 98.88%), both from the viewpoints of instructors and students. This suggests that the pedagogical framework is adaptable to classroom learning environments and simple to deploy. These outcomes are consistent with Plomp and Nieveen (2020) findings that a pedagogical product is deemed high quality if its instructions are simple to comprehend, do not present major challenges, and can be tailored to different learning environments. The learning process was not hampered by the technical difficulties that emerged during deployment because they were not significant and could be resolved right away. This demonstrates how well the instructional framework works with the infrastructure and classroom environment. According to Kivunja (2020), a learning tool's practicality is based on how adaptively it may be used in different learning environments.

Tables 4, 5, and 6 show the significant variations in pre-test and post-test scores for creating and executing integrated climate change learning, which demonstrate the efficacy of the pedagogical framework. There was a significant difference between before and after the pedagogical framework treatment, as indicated by the analysis's p-value <0.001. Additionally, the two tested classes' increased pre-test and post-test scores (n-gain 0.32–0.38; moderate category) show that the microteaching process gives pre-service science teachers practical experience putting a climate-based learning method into practice. This method is consistent with the experiential learning theory (Kolb, 1984), which highlights the significance of the cycle of conceptual application, reflection, and concrete experience. Indeed, microteaching continuously enhances the pedagogical capacity of pre-service teachers, as shown by Mutlu (2022).

According to Vygotsky (1978) theory, cooperation and interaction during microteaching also promote the co-construction of knowledge. Collaborative microteaching enhances the reflective abilities, pedagogical comprehension, and practical preparedness of pre-service teachers, according to research by Zhang and Tang (2020). These cooperative contacts increase pre-service teachers' abilities as facilitators of science learning responsive to the climate crisis by assisting them in discussing climate challenges and mitigation measures in a scientific and social context within the framework of a pedagogical framework.

Students can argue, discuss, and offer feedback on learning tactics using climate change-based microteaching, which speeds up the development of their pedagogical expertise. Higher-order cognitive abilities and pedagogical comprehension are both improved in this collaborative learning setting. Collaborative interactions in microteaching greatly enhance pre-service teachers' conceptual comprehension and teaching abilities, according to research by Zhang and Tang (2020). Pre-service teachers' climate literacy has been demonstrated to increase in learning environments that allow for scientific discussion and group reflection (Bozdogan, 2021). In the meantime, it has been demonstrated that the efficacy of pre-service science teacher competency development is significantly impacted by the incorporation of learning technologies within a pedagogical framework.

Overall, the research results show that a pedagogical framework based on climate change can improve pedagogical competence, or the ability to create and carry out science lessons that incorporate aspects of science, technology, environmental values, and social action, all of which have a significant impact on attaining the SDGs. This is consistent with the idea of transformative learning (Mezirow, 1991), which highlights the significance of altering viewpoints via critical analysis of international issues. The professional identities of pre-service science teachers who are concerned about the environment and capable of instructing a generation that is more climate-conscious can be shaped by learning that incorporates climate change problems. These results are also supported by a number of earlier investigations. For example, Biasutti and Frate (2022) demonstrated how teaching environmental principles to teachers might boost their commitment to pro-environmental activities and ecological empathy. According to a study by Anderson and McLoughlin (2022), educators who possess a high level of climate literacy are better equipped to incorporate sustainability concerns into their teaching. In order to help accomplish the SDGs, this pedagogical framework has the potential to improve pre-service science teachers' professional preparedness for the climate catastrophe and help them develop their professional identities as change agents. However, it should be noted that the design of trials or the application of pedagogical frameworks is not without its limitations, namely internal validity. This is because changes in learning outcomes cannot be confirmed as being entirely caused by the treatment; instead, external factors such as history, growth, trial effects, and instruments can influence them. Furthermore, when there is no control group, the design cannot eliminate the threat of causality. Therefore, analysis and conclusions must be made with caution (Campbell & Stanley, 1963; Creswell & Creswell, 2018). This poses a challenge for future research.

5. Conclusion

The results of this study conclude that the developed climate change-based pedagogical framework has proven to be highly valid, practical, and effective in improving the skills of designing and implementing integrated climate change learning for pre-service science teachers. This pedagogical framework not only strengthens pedagogical skills but also instills ecological awareness and sustainability values that align with the demands of 21st-century learning and the achievement of the SDGs, particularly SDGs 4 (quality education) and 13 (climate action). The implications of these findings confirm that this pedagogical framework is worthy of adoption in teacher education programs and teacher training college curricula as a model for sustainability-oriented learning, while also serving as a basis for developing educational policies that encourage schools and higher education institutions to systematically integrate climate change issues into the learning process to develop a generation of educators who are adaptive, climate literate, and capable of acting as agents of change in addressing the global environmental crisis.

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