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ORIGINAL ARTICLE

Socio-Scientific Issues in Focus: A Meta-analytical Review of Strategies and Outcomes in Climate Change Science Education

Joje Mar P. Sanchez[1,2], Marchee T. Picardal[1,2], Sunny R. Fernandez[1], Reginald Raymund A. Caturza[1,3]

[1]College of Teacher Education, Cebu Normal University, Cebu, Philippines, [2]Institute for Research in Innovative Instructional Delivery, Cebu Normal University, Cebu, Philippines, [3]Maricopa Unified School District, Maricopa, Arizona, USA

***Corresponding Author:** Joje Mar P. Sanchez; sanchezj@cnu.edu.ph

ABSTRACT

This meta-analysis evaluated how well learners' conceptual understanding, environmental attitudes, and pro-environmental behavior were improved by the Socio-Scientific Issues (SSI)-based approach based on the literature (2017–2021). The research analyzed various studies on the efficacy of SSI-based techniques, such as argumentation, case-oriented approaches, and problem-based learning. The findings showed a strong positive influence on learners' understanding of intricate environmental concerns and their propensity for sustainable conduct. While the study found that the SSI-based approach fosters critical thinking and involvement in several noteworthy ways, it also uncovered potential publication biases in certain aspects. Furthermore, the research stressed the necessity of context-specific strategies and interdisciplinary collaboration to improve the robustness and application of SSI-based interventions in climate change education. The results highlight how the SSI-based approach can cultivate proactive, environmentally conscientious, knowledgeable citizens ready to address urgent global concerns.

KEY WORDS: Conceptual understanding; environmental attitudes; meta-analysis; pro-environmental behavior; socio-scientific issues

INTRODUCTION

Authorities like the Intergovernmental Panel on Climate Change (IPCC, 2013) and religious figures like Pope Francis (2015) have highlighted the urgency of anthropogenic climate change, which is sometimes referred to as the "defining challenge of our time" (UNESCO, 2010). It has become essential to incorporate climate change education into school curricula in response to this pressing issue. According to Chang and Pascua (2017), these kinds of educational programs enable learners to participate in discussions about climate change in an informed and critical manner. The increasingly polarized view of the public on climate change calls for an intensified climate change education that targets not only cognitive and affective but also a holistic approach to science education for a more meaningful and relevant learning experience. In general, values, belief systems, and norms shape an individual's behaviors (Ajzen, 1991). In addition, the culture and tradition of people in society strongly influence their actions. Socio-Scientific Issues (SSIs) in teaching have a more contextualized approach, as they link learners to relevant issues that affect their daily lives and the environment. It also calls on their role as citizens and inhabitants of this planet (Hofstein et al., 2011). The recent report by Wan and Bi (2020) on the most common science concepts focused on the curriculum using the SSI approach, environmental issues, resources and energy, ecological systems, biotechnology, new materials, and safety and health was mentioned. However, climate change or global warming has not been explicitly identified. SSIs refer to controversial social issues (i.e., biotechnology and climate change) with conceptual and procedural links to science framed in open-ended problems with multiple plausible solutions intertwined with other fields of discipline (Sadler, 2011).

Beyond the conventional environmental sciences, climate literacy encompasses the complex interactions between people and their surroundings. The fundamental scientific concepts underlying climate and hydrological systems are still important. However, a holistic view of the global climate dynamics that consider the geographic, socio-political, and economic dimensions is necessary for an inclusive approach (Aikens et al., 2016; Hansen, 2010; Rebich & Gautier, 2005). As such, the best curriculum for climate change requires an interdisciplinary educational framework that develops scientific knowledge and civic skills (Ho and Seow, 2017; Wise, 2010; National Oceanic and Atmospheric Administration, 2007; Chang, 2012; Dalelo, 2011; Aikens et al., 2016; Milér et al., 2012). However, there is still a problem that many K–12 teachers may not have the necessary instructional resources to teach such integrated knowledge (Oversby, 2015) successfully, let alone the appropriate array of teaching strategies and techniques that can be utilized by teachers in teaching climate change using SSI-based approach. Often, teachers experience difficulty with a multidisciplinary approach with integrated learning experiences due to systemic educational frameworks that frequently support segregated subject delivery (Monroe et al., 2019; Fortner, 2001; Mooney et al., 2012; Schreiner et al., 2005; Tavoni and Levin, 2014; Henderson et al., 2017; Öhman and Öhman, 2013).

Complex environmental issues like climate change highlighted the critical role of science and technology and human participation in mitigating or aggravating its causes and effects. In the 21st century, the vision for scientific literacy was further illuminated with the framework on humanized science education (Choi et al., 2011 and Sjöström and Talanquer, 2014) that is deemed practical, relevant, and responsive to recent trends, developments, and realities of context and time, thus, contributing to the sustainable development goals (Canlas and Karpudewan, 2022). It highlights what should be taught in the science education curriculum that aims for critical and transformative impact on the top of scientific knowledge and processes developed. To realize this level of critical scientific literacy, understanding the nature of science and the interaction of Science-Technology-Society (STS) must be strengthened, and one of the most cited ways to attain it is through an SSI-based approach (Canlas and Karpudewan, 2020). Over the past two decades, SSI has gained popularity in scientific investigations spread across different areas of science to examine its effectiveness in promoting conceptual understanding and scientific literacy, such as in biology (Anisa et al., 2020), chemistry (Dishadewi et al., 2020), and physics (Hariapsari et al., 2018); disaster risk reduction (Canlas and Karpudewan, 2022); and biotechnology (Anisa et al., 2020). All these works of literature about SSI claimed to have a positive impact on the overall learning process, specifically, in improving reasoning and argumentative skills, increasing interest and attitude toward science and learning, promoting motivation and self-efficacy, along with their sense of civic responsibility (Canlas and Karpudewan, 2022). The severity of human-caused climate change affects societal and cultural perspectives and goes beyond scientific domains (Sharma, 2012). As such, teachers need to do more than impart knowledge; they also must develop in their learners an attitude and a practice of initiative (Morgan, 2012; Cotton, 2006). Different approaches to teaching about climate change aim to stimulate learners' behavior changes, attitude changes, and sense of empowerment (Rooney-Varga et al., 2014; Stapleton, 2015; Alexandar and Poyyamoli, 2021; Flora et al., 2014; Pruneau et al., 2006; Liu et al., 2015). A thorough review that uses various indicators and assessment metrics is necessary to determine the effectiveness of these strategies (Hallar et al., 2011; Howell and Allen, 2019; McNeal et al., 2014; Ignell et al., 2019; Kunkle and Monroe, 2019).

With this context in mind, the current study aims to perform a meta-analysis by examining the effectiveness of SSI-based approaches in climate change teaching. Through the compilation of global research from 2017 to 2021, this meta-analysis aims to clarify the relative influence of these methods on learners' learning outcomes. In particular, critical questions regarding the methods used in SSI-based climate change education, the overall effects on learners' understanding, attitudes toward the environment, and pro-environmental behaviors were addressed, along with possible variations based on publication year, research location, design, educational level, and field of study.

Statement of the Study

This meta-analysis examined the impact of the SSI-based approach in teaching learners about climate change. Specifically, it sought to answer critical issues on the effectiveness of using the SSI-based approach in climate change education and the different key teaching strategies for implementing it in the discipline. Subgroup, moderator, and publication analyses were done to evaluate the current literature on the SSI-based approach in climate change education.

METHODOLOGY

Research Design

Using a systematic literature review methodology, particularly the meta-analysis technique for quantitative studies, this research evaluated the effectiveness of the SSI-based approach in teaching climate change. With direction from the Borenstein et al. (2009) and Picardal and Sanchez (2022) meta-analytical procedure, the study assembled a corpus of published empirical research studies relevant to the topic. The study's first phase comprised a thorough compilation of these empirical investigations, guaranteeing a wide range of understandings and viewpoints. After that, a thorough coding procedure was used to classify and define the unique features that each of the chosen studies possessed. This careful coding methodology guaranteed that the research remained consistent and methodical throughout, allowing for an organized analysis.

After the coding stage, the main analytical task was determining the effect sizes corresponding to the outcome measures in each study. The several outcome indicators were standardized through this quantification procedure onto a similar scale, allowing for a comparative evaluation of the SSI approach's efficacy across numerous studies. Combining these effect sizes, the research sought broad generalizations about how the teaching style affected learners' conceptual understanding, environmental attitudes, and pro-environmental behaviors connected to climate change. In addition, adhering to the meta-analytical protocols, the investigation probed the moderating effects that might be exerted by specific attributes inherent to individual research studies. The research aimed to clarify how different characteristics or factors related to individual studies might affect or vary the observed outcome measures, taking cues from the work of Merchant et al. (2014).

Study Search Procedure

A systematic search was carried out, focusing on publications from 2017 to 2021 that examined the effects of the SSI-based approach in teaching climate change on learner results to guarantee an exhaustive and organized method of finding pertinent research articles. The first step in the search was to access several well-known databases for their scientific publications. Important sites visited were Crossref and Google Scholar, known for their extensive collections of scholarly literature. Specialized keywords and phrases were used in combination to maximize search precision. Keywords such as "socio-scientific approach" and "socio-scientific issue-based approach" were used. These primary keywords were deliberately paired with terms that complemented them, such as "behavior," "understanding," "quasi-experiment," "climate change education," and "attitude." These chosen terms were used in the meta-search engines in an alternating and random fashion to carry out the search strategy.

The first search, conducted using specialized software called "Publish or Perish," produced many academic publications. More specifically, 1824 possible studies were found during this search phase. Another manual search was done, resulting in an addition of 348 studies. This large body of literature made a foundational dataset available, which paved the way for the following stages of screening and review to identify the most relevant and rigorous studies to be included in the meta-analysis (Figure 1).

Inclusion and Exclusion Criteria

Inclusion criteria were established to guarantee methodological rigor and consistency in the synthesis. Peer-reviewed journals from 2017 to 2021 provided the research for this study, which ensured data reliability and captured current trends in climate change education. The SSI-based approach was the focus, especially on climate change. It was necessary to compare groups that employed this approach with those that received conventional equivalents. A pre-test and post-test framework was also necessary to assess the impact of the intervention and provide data for analysis. Furthermore, studies must have crucial statistical data, such as mean, SD, t-value, F-value, or p-value, to guarantee a consistent assessment of the influence of the SSI-based approach. The exclusion of studies from 2022 onward was done to provide a comprehensive peer review procedure and gather adequate data for subsequent examination.

On the other hand, stringent exclusion criteria were used. Research that did not provide thorough statistical reporting was disregarded, particularly those that only provided a portion of the experimental groups' data without complete group comparisons. Papers written in languages other than English were also not included to maintain uniformity and clarity in interpretation.

Research Quality Assessment

A thorough strategy was taken to guarantee the methodological rigor and dependability of the possible research to be included in the meta-analysis. To ensure professional inspection and verification, only papers published in peer-reviewed publications were considered. Following Gegenfurtner et al. (2014), a *post hoc* evaluation procedure was used to analyze the selected paper's quality further. Using the Medical Education Research Study Quality Instrument (MERSQI) was essential to this evaluation. This instrument, well known for its extensive evaluation abilities, assesses: study design, sampling techniques, data validity, equipment dependability, and analytical methodologies.

Jensen and Konradsen (2018) have remarked that although the MERSQI was initially created for medical education, its application was more comprehensive than just that field. It was also adopted in others, such as social science. Every chosen study was carefully assessed using the domains of MERSQI as a reference. Methodological strength determined the results, and mean scores and standard deviations were computed to

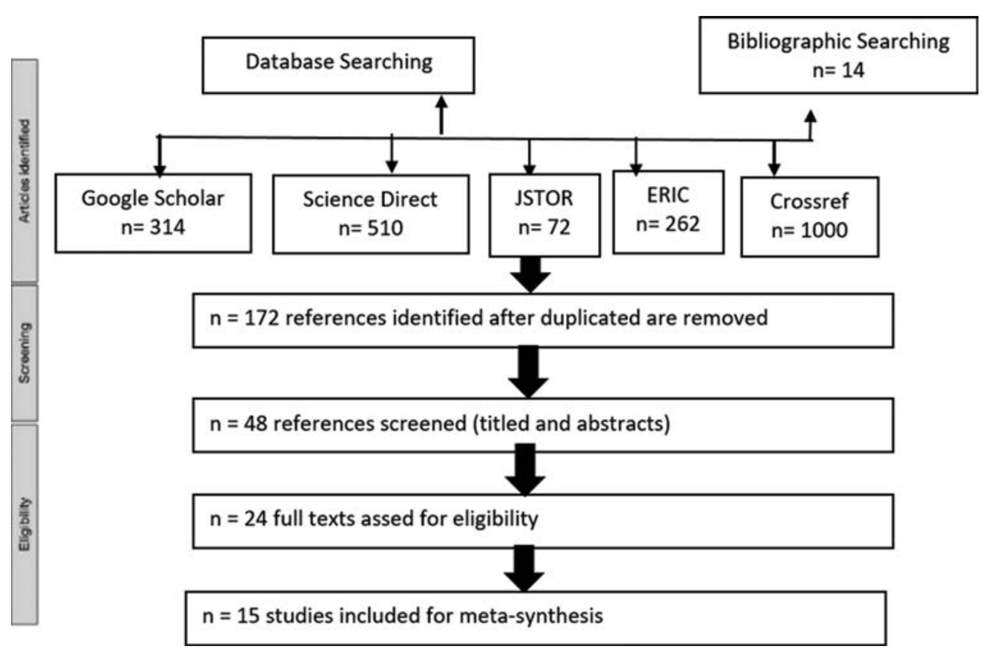

Figure 1: PRISMA table of the meta-analysis

provide a thorough comparison analysis. Using a quantitative approach guaranteed the validity of the meta-analysis and furnished stakeholders with a refined comprehension of the research landscape's advantages and disadvantages.

Coding Procedure

A structured coding approach was employed to analyze the eligible journal articles in this meta-analysis systematically. Each article was uniquely identified by combining its publication year and author's last name. This coding captured essential details such as study location, educational level (spanning kindergarten to college), and specific science disciplines, such as biology, chemistry, STS, environmental science, and physics. Key databases such as Google Scholar, Web of Science, and ERIC were referenced to trace article sources.

The coding also provided information about the study's comparison condition, which pitted the SSI-based approach against conventional teaching methods. The details of the outcome measures, such as sample size, means, and standard deviations, were also recorded for clarity. All the researchers coded independently to guarantee compatibility. Any differences were resolved through cooperative conversations, guaranteeing the methodological accuracy, and trustworthiness of the meta-analysis.

Analysis Procedures

The meta-analysis used a methodical strategy to assess and interpret the data carefully. Effect sizes were calculated for each study using the comprehensive meta-analysis (CMA) version 3 software, considering parameters such as sample size, means, standard deviations, and statistical tests. Hedges's g was chosen because it is more appropriate for smaller sample sizes than Cohen's d (Borenstein et al., 2010). Outliers were identified by analyzing variances of more than three standard deviations from the mean. Considering the research design's diversity, the random effects model calculated an overall impact size. Using Cohen's standards, effect sizes were classified as small, medium, or big.

A funnel plot was created to identify publication biases, and Egger's test was applied to analyze asymmetry. Using the Q-statistic and I^2 metric, a homogeneity analysis evaluated consistency between research, with levels of heterogeneity indicated by thresholds derived from Higgins and Thompson (2002). A mixed-effect analysis was used to investigate potential moderators influencing effect sizes because of the heterogeneity.

RESULTS AND DISCUSSION

A total of 2582 secondary (including junior and senior high) and post-secondary learners took part in the quantitative research that fulfilled the inclusion criteria for the meta-analysis. Table 1 summarizes this research by outlining particular characteristics, including the geographic location, learners' educational level, and the scientific field, in which the SSI-based approach was used to investigate the incorporation of concepts related to climate change.

Table 1: General characteristics of studies about the SSI-based approach in climate change education

Attributes	Characteristics	Frequency	Percentage
Locale	Eurasia	10	67
	Americas	5	33
Educational Level	Junior High School	9	60
	Senior High School	2	13
	University Level	5	33
Science Domain	Biology	4	27
	Chemistry	2	13
	Environmental science	7	48
	Geography	1	6
	Agricultural Science	1	6
Total		15	

SSI: Socio-scientific issues

The data in Table 1 indicate that a noteworthy majority of the studies (67%) were conducted in the Eurasian region, highlighting its prominence in this field of study. On the other hand, the remaining studies (33%) were conducted in the Americas, suggesting that there is also a significant amount of research from this continent. Junior high school learners were the most commonly investigated group regarding educational stages, making up most of the research. Learners in higher education followed, with 33% of the sample, and seniors in high school made up 13%. In addition, the bulk of the studies, 48% of the total, examined the science domains in which the SSI-based approach was applied, which were focused on environmental science. Biological sciences accounted for 27% of the studies after this. Chemistry was a noteworthy focus area examined in 13% of the studies. Furthermore, 6% of the papers were in specialist fields such as geography and agriculture, indicating their small but noteworthy inclusion in the meta-analysis.

Conceptual Understanding

Conceptual understanding is crucial in climate change education as it examines the learners' comprehension of complex environmental concepts (Celades et al., 2021). This section presents and discusses the forest plot, subgroup and moderator analyses, and publication bias.

Forest plot

Figure 2 presents the effect sizes of the studies concerning conceptual understanding brought about by the SSI-based approach.

The forest plot in Figure 2 provides insights into the effectiveness of the SSI-based approach for teaching about climate change by displaying effect sizes from several researches. Smith and Rayfield's (2017) research stood out with noticeably high effect sizes between 1.903 and 3.193, while studies like those by Villarin and Fowler (2019) and Vogelzang et al. (2020) revealed small effect sizes (ranging from 0.017 to

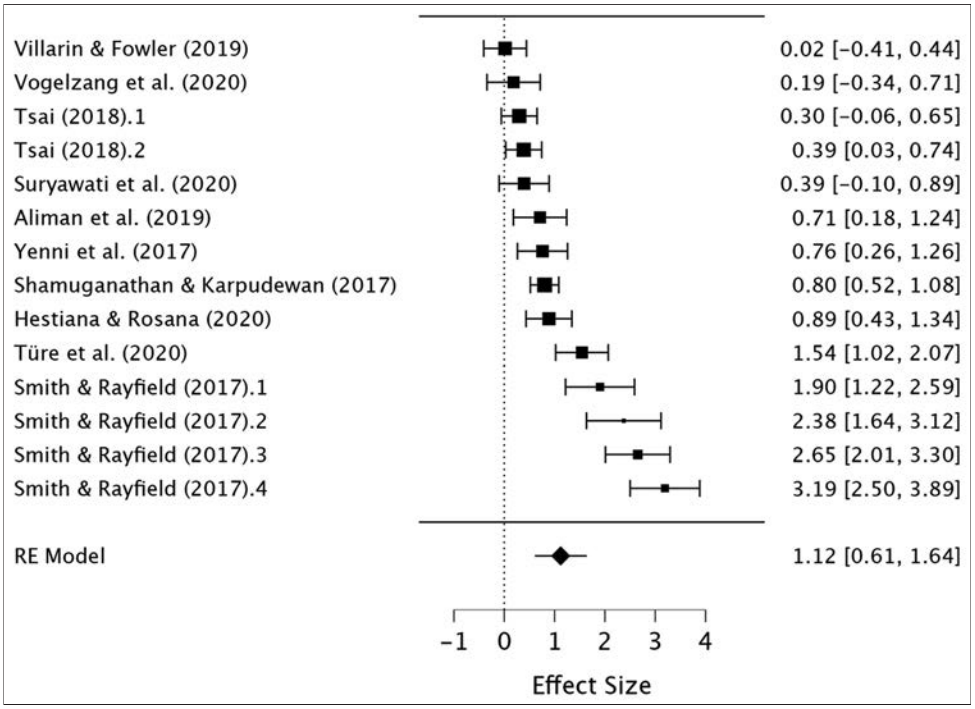

Figure 2: Effect sizes for conceptual understanding

0.888), showing different effects on understanding. Smith and Rayfield highlighted customized experiential learning based on each learner's interests, demonstrating how personalized learning approaches can significantly improve learner learning outcomes.

However, a more nuanced picture becomes apparent in research like those by Vogelzang et al. (2020) and Villarin and Fowler (2019). Their findings highlight that although the SSI-based approach can improve subject knowledge, its efficacy differs depending on instructional context, methodology, and learner demographics. For example, Villarin and Fowler (2019) discovered differences in socio-scientific reasoning according to learner performance, indicating contextual factors influencing the effectiveness of the SSI-based. Similarly, Vogelzang et al.'s (2020) investigation highlighted the complex interactions between different instructional components and underscored that attaining substantial scientific literacy necessitates more than just particular approaches. Essentially, even while customized experiential approaches, like those of Smith and Rayfield (2017), are helpful, a comprehensive comprehension necessitates considering the various contextual aspects that influence the effectiveness of the SSI-based approach.

When taken as a whole, the average effect size of all the studies was 1.12, indicating a significant improvement in conceptual understanding across the literature, with the SSI approach working well to improve learners' learning about climate change. Because the SSI-based approach incorporates real-world concerns into teaching, learners' comprehension of climate change is considerably improved. In contrast to conventional approaches, the SSI-based approach emphasizes climate change's scientific, societal, and ethical aspects while encouraging learners to go beyond the surface level of knowledge. Across a comprehensive approach, learners can comprehend the broader consequences of climate change, encompassing scientific principles and socio-economic and ethical aspects. A thorough approach like this gives learners the critical thinking and moral reasoning skills they need to successfully tackle the environmental issues of the modern world. The SSI-based approach's ability to enhance conceptual comprehension ultimately highlights how important it is in raising environmentally conscious people who are equipped to address global sustainability concerns.

Subgroup analysis

The results of the subgroup analysis of the SSI-based approach toward conceptual understanding are reflected in Table 2.

The subgroup analysis, as demonstrated by Hedge's g values and I^2 heterogeneity measures, reveals the variation in the influence of the SSI-based approach on conceptual understanding. Even with a high 93.11% heterogeneity in 2017, the effect size of 1.92 is noteworthy, highlighting its noteworthy impact; nevertheless, studies from 2018 show a minor impact with an effect size of 0.34 and no heterogeneity. Effect values of 0.35 and 0.75 indicate moderate-to-high heterogeneity for 2019 and 2020.

Geographically, American studies show 94.54% heterogeneity but a more significant effect size of 1.68, suggesting more consistent yet significant results in America, whereas Eurasian research shows 32.10% heterogeneity and an effect size of 0.60. Regarding research design, studies with quasi-experimental and mixed designs show similar improvement in conceptual comprehension, with effect sizes of about 1.11–1.14, respectively, and heterogeneities of 83.35% and 92.09%, respectively. Regarding education levels, studies from junior high school learners find a substantial effect size of 1.36 with 92.73% heterogeneity. In contrast, studies from senior high school learners show a lessened impact. Finally, across scientific disciplines, "Other Science" studies exhibit notable heterogeneity of 94.82% and the highest impact size of 1.79, indicating strong effectiveness in this sector. Overall, Hedge's g consistently indicates the favorable impact of the SSI technique on conceptual understanding in various scenarios despite varying degrees of variability.

Moderator analysis

The moderators were analyzed using Egger regression, and the summary of the results is presented in Table 3.

Several essential conclusions from the moderator analysis of conceptual comprehension provide insight into the variables affecting the research's effect size. The year is a significant moderator, accounting for 27.79% of the variation in results. In particular, there is a discernible decrease with time, with a significant p-value of.018 and a Z-value of −2.37, suggesting that more recent research might be less successful or have a smaller effect size than previous ones. In addition, the location is crucial, explaining 29.70% of the variation. Studies carried out outside of a typical context have a more substantial impact on conceptual understanding than those carried out inside a typical setting (Z-value of 2.55 and p = 0.011).

The science domain also demonstrates significance, accounting for 22.49% of the variation. This indicates that some science domains may be more favorable to fostering conceptual comprehension than others, with a Z-value of 2.04 and a p = 0.041. On the other hand, non-significant p-values indicate that educational level and design have less of an impact, with just 16.05% and 0.04% of the variation explained, respectively. These findings highlight the complex interactions among variables and the necessity of specialized methods for improving conceptual comprehension in the context of the interventions under study.

Publication bias

Publication bias was included to evaluate whether there is bias in publishing studies about the SSI-based approach to conceptual understanding. The funnel plot is presented in Figure 3.

Several tests revealed important issues with publication bias analysis for conceptualizing the SSI-based approach in

Table 2: Subgroup analysis of studies in SSI-based approach toward conceptual understanding

Category	Subgroup	n	Test for Heterogeneity			Test for Effect	
			I^2 (%)	Q-stat	p-value	Hedges' g	95% CI
Year	2017	6	93.11	72.61	0.000	1.92	1.11, 2.72
	2018	2	0.00	0.12	0.730	0.34	0.25, 0.43
	2019	2	75.15	4.02	0.004	0.35	−0.34, 1.03
	2020	4	80.73	15.57	0.000	0.75	0.16, 1.34
Locale	Eurasia	7	32.10	8.84	0.183	0.60	0.42, 0.78
	America	7	94.54	109.94	0.000	1.68	0.78, 2.58
Design	Quasi-experimental	2	83.35	6.00	0.014	1.14	0.41, 1.87
	Mixed	12	92.09	139.06	0.000	1.11	0.50, 1.72
Educational Level	Junior HS	10	92.73	123.88	0.000	1.36	0.68, 2.05
	Senior HS	2	0.00	0.09	0.768	0.78	0.71, 0.86
	Senior HS/College	2	0.00	0.12	0.728	0.34	0.25, 0.43
Science Domain	Chemistry	2	75.29	4.05	0.044	0.54	−0.06, 1.14
	Environmental Science	4	70.29	10.10	0.018	0.89	0.43, 1.36
	General Science	2	0.00	0.12	0.728	0.34	0.25, 0.43
	Other Science	6	94.82	96.47	0.000	1.79	0.81, 2.77

SSI: Socio-scientific issues

Table 3: Results of the moderator analysis on conceptual understanding

Moderator	R^2 (%)	ES	SE	T^2	95% CIs		B	Z-value	p-value
					Lower	Upper			
Year	27.79	1.11	0.17	0.56	−0.76	−0.03	−0.40	−2.37	0.018
Locale	29.70	1.10	0.41	0.51	0.16	1.92	1.04	2.55	0.011
Design	0.04	1.11	0.66	0.69	−1.36	1.47	0.05	0.08	0.935
Educ. Level	16.05	1.11	0.28	0.55	−1.13	0.10	−0.51	−1.82	0.069
Science Domain	22.49	1.11	0.20	0.62	−0.02	0.83	0.40	2.04	0.041

climate change education. A funnel plot asymmetry is shown by the rank correlation test's Kendall's τ value of 0.538 and the low $p = 0.007$, which suggest that some of the included studies may have biases. With a z-value of 4.227 and an even lower p-value of 2.373e-5, Egger's test further supported this finding and suggested that smaller studies with adverse or null outcomes might not exist. Rosenthal's fail-safe N, which was noticeably high at 1136.000, further highlighted this bias by showing that many unpublished investigations with null results would be required to refute the observed significance level of 1.503e-50. As a result, even while the results point to the potential effects of the SSI-based approach on conceptual understanding, the clear publication bias emphasizes the need for caution because the results might not accurately reflect the entirety of the literature.

Environmental Attitudes

Environmental attitudes emerge as a pivotal dimension in climate change education. They refer to the learners' perceptions, beliefs, and feelings about environmental issues

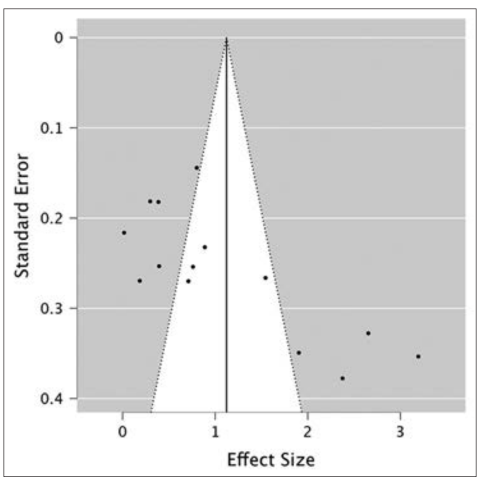

Figure 3: Funnel plot of publication bias of socio-scientific issues-based approach in terms of conceptual understanding

(Sanchez et al., 2022). Like the previous section, forest plots, subgroup and moderator analyses, and publication bias are shown and elaborated here.

Forest plot

This meta-analysis also investigated the change in environmental attitudes. Figure 4 shows the effect sizes and forest plots on these attitudes.

In the context of teaching about climate change, Figure 3 illustrates the various effects of the SSI-based approach on learners' environmental viewpoints. As shown by Tsai (2017), early research suggested challenges in the digital application of SSI. However, later studies, including Wallace and Bodzin (2017), Türe et al. (2020), Liu (2018), and Aliman et al. (2019), demonstrated increasingly positive effect sizes. Hewitt et al. (2019) recorded an impressive 9.61 effect size, highlighting the potential of the SSI-based approach to increase motivation among undergraduate biology learners significantly. Tsai's research, however, revealed flaws in the online SSI-based approach, underlining the need for more sophisticated approaches and the complex difficulties in incorporating the approach into various educational contexts.

The different effect sizes shown in different research highlight the complexity of the SSI-based approach and call for customized implementation techniques that consider particular educational environments, goals, and desired results. The SSI-based approach has the potential to significantly increase learner motivation and engagement, as some studies (Hewitt et al., 2019) have shown. However, other studies (Tsai, 2017) highlight areas that need further refinement, highlighting the necessity for researchers and teachers to critically assess and optimize the SSI-based approach within unique pedagogical frameworks.

The average effect size is 1.72, which indicates that the SSI-based approach has a consistently favorable and significant effect on improving environmental attitudes in climate change

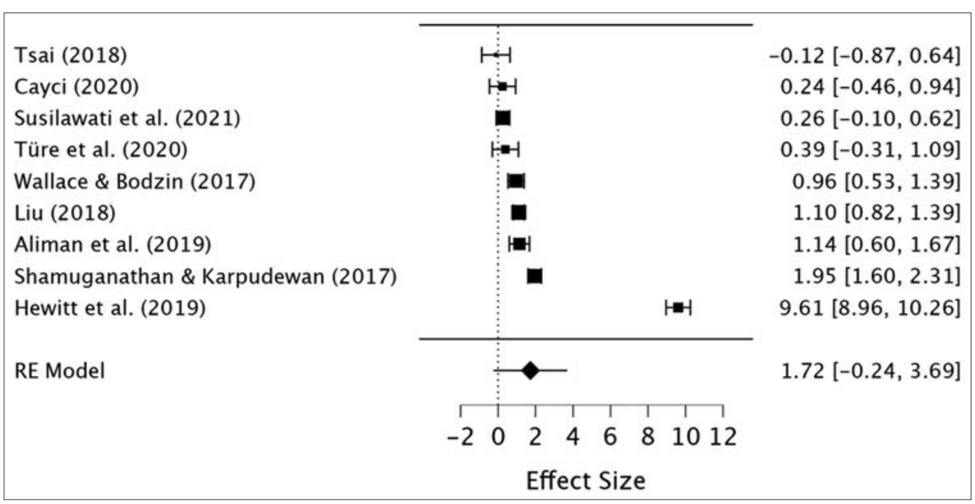

Figure 4: Effect sizes for environmental attitudes

education. The approach is crucial in educating learners about climate change by efficiently linking scientific principles with practical societal challenges. Learners thoroughly comprehend the complex interplay between human activities and environmental consequences by exploring subjects such as biodiversity and climate change strategies. Learners who engage with the SSI-based approach become engaged participants encouraged to think critically and reflect ethically. This methodology fosters consciousness and compassion and equips learners to confront climate-related issues with well-informed decision-making abilities. Consequently, the steady beneficial influence of the approach gives upcoming leaders the skills and perspective required for ethical and sustainable environmental management.

Subgroup analysis

Like conceptual understanding, the I^2, z-, and p-values of the studies regarding environmental attitudes due to the SSI-based approach are high and significant. A subgroup analysis was performed, and the results are showcased in Table 4.

The SSI-based approach's subgroup analysis shows clear trends in how it affects learners' environmental attitudes in climate change education. Studies from 2017 and 2019 show notable variability at 99.08% and 96.30%, respectively, but the effect sizes differ, with 2017 showing a significantly greater effect size of 5.27 compared to 1.05. Comparing Eurasian studies geographically, their American counterparts show 97.93% heterogeneity and a more prominent effect size of 2.31, while Eurasian studies indicate 84.89% heterogeneity and an effect size of 0.89. The research design is also crucial; whereas mixed-method and quasi-experimental designs show notable levels of heterogeneity, mixed designs have a higher significant effect size of 2.51 compared to 0.41 for quasi-experimental studies.

Looking more closely at studies conducted in education and science, senior high school studies stand out as being especially significant. They have an incredible 99.20% heterogeneity and a remarkable 4.85 impact size. On the other hand, the "Other Science" categories have an impressive impact size of 1.47, which suggests that it works well in this field. When taken as a whole, these results demonstrate the complex and varied ways the SSI-based approach influences attitudes toward the environment. They also highlight the critical roles that timeframes, geographic locations, research methodologies, and particular educational and scientific contexts play in climate change education's larger context.

Moderator analysis

The moderators were analyzed using Egger regression, and the summary of the results is presented in Table 5.

Several moderator factors shed light on the subtleties of the impact of environmental attitudes on effect size in the research that focuses on these attitudes. First, the variable "Year" is responsible for 12.87% of the variability related to the element of time. The significant p = 0.014 and the negative Z-value of −2.46 indicate that the influence of prior studies on environmental views is reducing with time. This is an important finding. "Educational Level" is identified as a significant moderator, accounting for 22.68% of the variance when looking at the educational characteristics. The Z-value of −3.24 and the very significant p = 0.001, which show that the influence on environmental views decreases noticeably with increasing educational attainment, highlight this even more.

A noteworthy aspect of the study is its design, which accounts for 15.46% of the variance and has a significant p = 0.005 and a Z-value of −2.79. This suggests that some research designs have a lower impact on environmental attitudes. On the other hand, although "Locale" and "Science Domain" account for some of the variance explained (6.21% and 6.09%, respectively), their p-values suggest that the significance is lower. Overall, these moderator analyses highlight the complex

Table 4: Subgroup analysis of studies in SSI-based approach toward environmental attitudes

Category	Subgroup	n	Test for heterogeneity			Test for effect	
			I^2 (%)	Q-stat	p-value	Hedges' g	95% CI
Year	2017	2	99.08	108.53	0.000	5.27	−3.01, 13.55
	2018	2	31.17	1.45	0.228	0.19	−0.29, 0.67
	2019	2	96.30	27.02	0.000	1.05	−0.60, 2.71
	2020/21	3	74.60	7.87	0.020	0.78	0.26, 1.30
Locale	Eurasia	5	84.89	26.48	0.000	0.89	0.23, 1.55
	Americas	4	97.93	144.68	0.000	2.31	−1.82, 6.43
Design	Quasi-experimental	4	89.98	29.93	0.000	0.41	−0.10, 0.91
	Mixed	5	96.87	127.67	0.000	2.51	−0.62, 5.65
Educational Level	Junior HS	4	87.63	24.24	0.000	0.57	0.01, 1.12
	Senior HS	2	99.20	125.04	0.000	4.85	−4.29, 14.00
	College	3	86.85	15.21	0.000	1.11	0.26, 1.96
Science Domain	Biology	2	99.26	135.48	0.000	4.84	−4.26, 13.95
	Environmental science	3	82.64	11.52	0.003	0.45	−0.28, 1.17
	General Science	2	68.57	3.18	0.074	0.68	0.13, 1.24
	Other Science	2	82.12	5.59	0.018	1.47	0.65, 2.28

SSI: Socio-scientific issues

Table 5: Results of the moderator analysis on environmental attitudes

Moderator	R^2 (%)	ES	SE	T^2	95% CIs		B	Z-value	p-value
					Lower	Upper			
Year	12.87	1.39	0.27	0.99	−1.28	−0.04	−0.66	−2.46	0.014
Locale	6.21	1.41	0.74	1.12	−0.49	2.93	1.22	1.64	0.101
Design	15.46	1.36	0.66	0.89	−3.38	−0.32	−1.84	−2.79	0.005
Education Level	22.68	1.39	0.46	1.01	−2.56	−0.43	−1.49	−3.24	0.001
Science Domain	6.09	1.42	0.36	1.18	−1.40	0.26	−0.57	−1.59	0.111

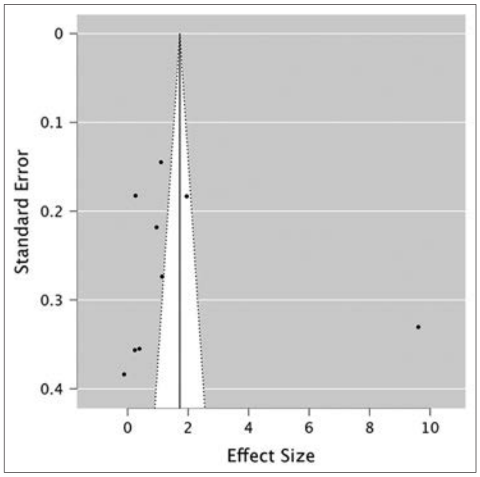

Figure 5: Funnel plot of publication bias of socio-scientific issues-based approach in terms of environmental attitudes

interactions between various elements that influence people's attitudes toward the environment, indicating the necessity for various approaches in educational interventions.

Publication bias

Figure 5 presents the funnel plot to check the publication bias of SSI-based approach studies regarding environmental attitudes.

Several statistical tests were used to examine publication bias connected to environmental views within the SSI approach in climate change education. The rank correlation test yielded Kendall's τ value of −0.167 with a p = 0.612, demonstrating negligible publication bias and no discernible funnel plot asymmetry. Egger's test further supported the idea of modest publication bias, which revealed a z-value of 0.308 and a p = 0.758. Furthermore, a sizable number of non-significant or negative investigations would be required to alter the existing significance level of 8.250e-86, according to the high Rosenthal's fail-safe N of 1269.000. Thus, the overall evaluation raises the likelihood that the meta-analysis on environmental attitudes in this educational context resists publishing biases, enhancing its credibility.

Pro-environmental Behavior

The third dimension in the meta-analysis is the pro-environmental behavior. This set of behaviors is observable actions and choice learners demonstrate to commit to environmental conservation and sustainability (Yaun et al., 2021). The extent of the changes due to the SSI approach as education intervention is embedded in the forest plot, subgroup and moderator analyses, and publication bias.

Forest plot

The effect sizes and forest plots of the effect sizes of the studies about pro-environment behavior are gleaned in Figure 6.

Figure 4 shows the differing effect sizes of the SSI-based approach on pro-environmental behavior in climate change education. While highlighting increases in areas such as cooperative learning and communication, Susilawati et al. (2021) identified a little negative impact of −0.12, suggesting the limited usefulness of the SSI-based approach in boosting learner's environmental awareness and skills. On the other hand, Shamuganathan and Karpudewan (2017) showed a more substantial beneficial impact of 1.10, while Aliman et al. (2019) identified a minor positive effect size of 0.39, suggesting some benefits. With an astonishingly high effect size of 9.61, Liu's (2018) study demonstrated the significant impact of using films to encourage learners' environmental behavior and critical thinking.

Although Susilawati et al. (2021) emphasized the potential advantages of the SSI-based approach, a noticeably small negative effect size limited the approach's overall influence. It may indicate methodological flaws in the study or other contextual issues. Liu (2018), on the other hand, highlighted the effectiveness of media-rich approaches, such as documentaries, significantly improving learners' environmental attitudes and behaviors. These wide ranges of impact sizes highlight the complex ways the SSI approach works, and they call for a more thorough comprehension of the study-specific factors that influence its results. Even if the results of the individual investigations varied, the impact size of 2.75 obtained by combining all the studies highlights that the SSI-based approach has a noteworthy positive role in fostering pro-environmental behavior. This suggests the approach integrates science education with societal issues such as climate change, promoting critical thinking and in-depth comprehension. Learners gain an understanding of environmental complexity and cultivate a sense of responsibility by tackling real-world challenges. In addition, the SSI-based approach improves teamwork and communication abilities, enabling learners to become proactive environmental champions. The approach is essential for developing efficient climate change education and encouraging sustainable practices.

Subgroup analysis

Pro-environmental behavior was also analyzed further for subgroup analysis due to its heterogeneity but only for specific subgroups due to the number of studies included in this learning outcome. The results are presented in Table 6.

The meta-analysis reveals significant trends in pro-environmental behavior in several subgroup categories. Geographically, studies conducted in the Eurasian region show a moderate variability of 80.74% and an effect size of 0.93, suggesting a noticeable but limited impact of the SSI-based approach. A noteworthy finding emerges from comparing research designs: quasi-experimental methods, which have a heterogeneity of 77.35%, produce a moderate effect size of 0.46, whereas mixed-method approaches, which have a heterogeneity of 29.66%, provide a more significant effect size of 1.40. This implies that mixing techniques may increase the effectiveness of treatments meant to improve environmentally friendly behavior.

Furthermore, interesting differences emerge when examining educational levels and scientific disciplines. Research at the Senior High School and College levels shows heterogeneities of 88.07% and 85.41%, respectively, with effect sizes of 0.64 and 1.19. Comparable degrees of heterogeneity are also seen in the "Other Science" and Environmental Science categories, with similar effect sizes of 1.19 and 85–88%, respectively. Even if the SSI strategy consistently affects pro-environmental behavior in various domains, the effect sizes vary, highlighting the complexity of treatments and the significance of contextual subtleties.

Moderator analysis

The moderators were analyzed using Egger regression, and the summary of the results is presented in Table 7.

The moderator analysis provides essential insights into the analysis of pro-environmental behavior. "Year" is the variable that accounts for 23.44% of the variability, starting with the temporal factor. Interestingly, a Z-value of 0.86 and a $p = 0.391$ indicate that pro-environmental behavior is not significantly influenced by time or the year of study, suggesting that the results remain stable regardless of the study's timing.

However, the study design is a significant moderator, accounting for 68.76% of the variance. The study's design significantly impacts pro-environmental behavior outcomes,

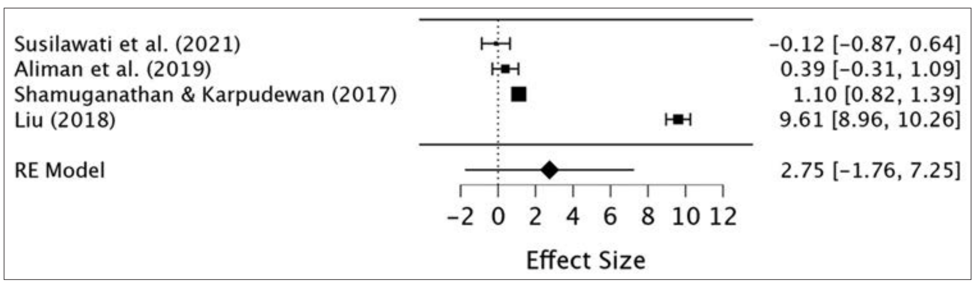

Figure 6: Effect sizes for pro-environmental behavior

Table 6: Subgroup analysis of studies in SSI-based approach toward pro-environmental behavior

Category	Subgroup	n	Test for heterogeneity			Test for effect	
			I^2 (%)	Q-stat	p-value	Hedges' g	95% CI
Locale	Eurasia	4	80.74	15.58	0.001	0.93	0.28, 1.59
Design	Quasi-Exp.	2	77.35	4.42	0.036	0.46	−0.28, 1.21
	Mixed	2	29.66	1.42	0.233	1.40	0.95, 1.85
Educational Level	Senior HS	2	88.07	8.38	0.004	0.64	−0.54, 1.81
	College	2	85.41	6.85	0.009	1.19	0.32, 2.05
Science Domain	Environmental science	2	88.07	8.38	0.004	0.64	−0.54, 1.81
	Other science	2	85.41	6.85	0.009	1.19	0.32, 2.05

SSI: Socio-scientific issues

Table 7: Results of the moderator analysis on pro-environmental behavior

Moderator	R^2 (%)	ES	SE	T^2	95% CIs		B	Z-value	p-value
					Lower	Upper			
Year	23.44	0.93	0.22	0.37	−0.51	0.88	0.19	0.86	0.391
Design	68.76	0.94	0.45	0.13	−2.35	0.49	−0.93	−2.08	0.038
Education Level	21.87	0.93	0.72	0.45	−2.84	1.74	−0.55	−0.77	0.444
Science Domain	21.87	0.93	0.72	0.45	−2.84	1.74	−0.55	−0.77	0.444

as indicated by the Z-value of −2.08 and the significant p = 0.038. This suggests that some research designs or methodologies encourage pro-environmental behaviors more successfully than others. Conversely, "Science Domain" and "Educational Level" each account for 21.87% of the variance. Based on the current study, the impact of educational level and science domain on pro-environmental behavior appears less conclusive, with a Z-value of −0.77 and a p = 0.444 for both variables. Although specific variables such as research design are crucial, the findings point to a complex environment in which several factors interact to influence the outcomes of pro-environmental behavior.

Publication bias

The funnel plot about publication bias of SSI-based approach studies in terms of pro-environmental behavior is presented in Figure 7.

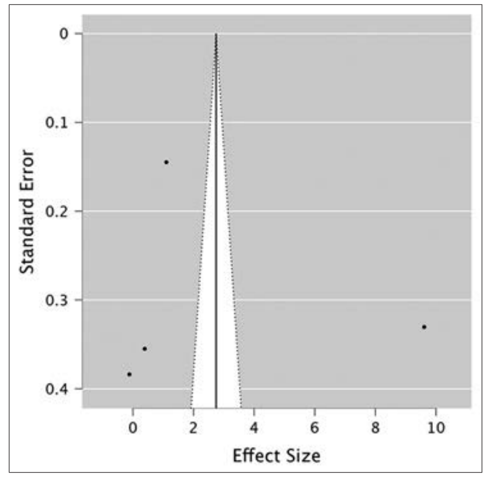

Figure 7: Funnel plot of publication bias of socio-scientific issues-based approach in terms of pro-environmental behavior

Several statistical analyses were conducted to investigate the possibility of publication bias about pro-environmental behavior while using the SSI approach in climate change education. With a p = 1.000 and Kendall's τ value of 0.000 for the rank correlation test, there was no noticeable funnel plot asymmetry. Egger's test, which showed a z-value of 0.091 and a high p = 0.927, indicating a low possibility of publication bias, highlighted this lack of substantial asymmetry even more. Rosenthal's fail-safe N was also 516.000, which suggests that many negative or non-significant studies would be required to change the 1.181e-78 observed significance level to a non-significant value (p > 0.050). These thorough results suggest that the meta-analysis on pro-environmental behavior in this educational setting resists publication biases, supporting the findings' validity and dependability.

Table 8: Strategies for using SSI-based approach in climate change education

Strategy	Frequency	Percentage
Argumentation	4	27
Case/controversy oriented	4	27
Problem/project-based	3	20
Model-based	2	13
Mobile/online learning	2	13
Film/role-play	2	13
Curriculum-based	2	13
Integrated materials	2	13
Heuristics	1	7

SSI: Socio-scientific issues

Strategies for Implementing the SSI Approach

The present study also examines the strategies used by the researchers to implement SSI in their respective studies. A summary of their strategies is shown in Table 8 below.

It is clear from looking more closely at the methods used in climate change education studies using the SSI-based approach that teachers and researchers use various pedagogical strategies to engage learners successfully. The importance of argumentation, seen in 27% of the studies, indicates a change in pedagogy toward encouraging critical thinking. Teachers strongly emphasize argumentation to ensure that learners can communicate and defend their ideas. This develops learners' capacity to assess, evaluate, and build reasoned arguments concerning complex socio-scientific problems relevant to climate change. Similarly, the relevance of contextualizing learning within real-world concerns is demonstrated by the popularity of a case or controversy-oriented approach in another 27% of the research. This kind of instruction immerses learners in real-world problems, inspiring them to investigate several angles of a problem, comprehend opposing points of view, and recognize the challenges in tackling climate change. This approach fosters empathy, perspective-taking, ethical reasoning, and improving topic understanding.

Moreover, 20% of the studies included problem- or project-based learning, emphasizing an immersive, hands-on approach to teaching. Across the provision of concrete difficulties associated with climate change, teachers facilitate collaborative problem-solving, foster innovation, and enable the application of theoretical knowledge in real-world scenarios. With the knowledge and self-assurance to tackle environmental issues in the real world, this approach enables learners to become proactive change agents. Furthermore, the variety of approaches used in 13% of the research illustrates the SSI-based approach's multidimensionality. Teachers are creatively adapting their teaching tactics to fit various learner preferences and settings using digital platforms, cinematic narratives, organized curricula, integrated learning resources, model-based simulations, and more. The approach's flexibility ensures adaptability, relevance, and effectiveness across various educational settings.

In general, the strategies in the SSI-based approach for teaching about climate change provide a well-balanced combination of innovative and flexible pedagogy. They result from a deliberate attempt to mold a knowledgeable, involved, and empowered generation to navigate and confront the complex socioscientific problems of today.

IMPLICATIONS FOR TEACHER EDUCATION

The findings of the meta-analysis on the SSI-based approach in climate change education have important implications for teacher education. The approach's significant favorable influence on learners' conceptual knowledge of climate change highlights the need for teacher preparation programs to incorporate thorough instruction on SSI-based strategies. By relating scientific ideas to societal effects, these methods involve presenting climate change topics in a way that makes learning more relevant and exciting for learners. Teachers who want to apply the SSI-based approach successfully must be skilled in creating and leading activities that promote debate, critical thinking, and problem-solving. As a result, courses covering both theoretical information and sound teaching practices for the approach must be included in teacher preparation programs. This will give teachers the tools to use experiential and individualized learning strategies, which will help learners understand concepts more deeply. Furthermore, given the variation in efficacy throughout studies, teacher preparation programs should equip teachers to customize SSI-based strategies to particular classroom environments, accounting for variables including learner demographics, past learning, and learning environments. Regardless of their background or learning environment, all learners will be able to profit from this approach with the support of customized strategies.

Furthermore, the subgroup analysis reveals notable variations in the effectiveness of SSI-based strategies according to science domains, educational attainment, and geographic locations. For example, specific geographic areas may have particular climate-related issues that can be immediately resolved with localized SSI-based strategies. To ensure that teachers can modify these strategies to fit their specific contexts, teacher preparation programs must consider these contextual and geographical variations. This can entail preparing teachers to integrate community-specific challenges, local case studies, and regional statistics into their curricula. Furthermore, the data show that the SSI-based approach significantly affects junior high school learners. Early interventions should be emphasized in teacher education when this approach promotes comprehension and involvement with climate issues. To provide a solid basis for ongoing environmental education, training programs should concentrate on helping teachers create age-appropriate SSI-based strategies that connect with younger learners.

The beneficial effects of the SSI-based approach on environmental attitudes and behaviors highlight how crucial it is to incorporate these strategies into teacher preparation to foster positive environmental attitudes and motivate learners to act in ways that are beneficial to the environment. This indicates that developing an ethical and effective bond with environmental issues should be a significant component of teacher preparation programs and teaching scientific information. Programs ought to provide techniques for applying the SSI-based approach successfully in various contexts and resolving particular issues, like those found in the approach's digital applications. Teachers should be trained in digital literacy and how to use online platforms to involve learners in SSI-based activities, mainly because technology is becoming increasingly integrated into the classroom. Programs should encourage blended learning so teachers can use various resources to improve learner learning. Since the approach significantly impacts higher education, teachers should be ready to use SSI-based strategies to help learners develop durable habits and critical thinking as they advance through their academic careers.

In climate change education, teacher education programs should incorporate SSIs to improve learners' conceptual understanding, environmental attitudes, and pro-environmental behaviors. Teachers will be better able to teach their learners to tackle issues related to global sustainability by doing this. A more knowledgeable and ecologically conscious generation of learners will result from teachers being able to provide practical, pertinent, and engaging climate change education thanks to this all-encompassing approach to teacher preparation. Future teachers will be better positioned to motivate and encourage their learners to take significant steps to address climate change and contribute to a more sustainable future due to training in an SSI-based approach.

CONCLUSION, LIMITATIONS, AND FUTURE DIRECTIONS

According to a CMA, the SSIs-based approach considerably impacts climate change education. This study emphasizes that the approach is critical in helping learners develop their environmental attitudes and improve their conceptual understanding of climate change. Learners exposed to the approach are more likely to turn awareness of environmental issues into practical action. Examining a wide range of academic and geographic backgrounds demonstrates how the approach fosters critical thinking, ethical reasoning, and a thorough understanding of the socioeconomic effects of climate change. The SSI-based approach is an essential educational tool for producing environmentally conscious citizens who can bring about meaningful change because it gives learners the information, attitudes, and abilities to address environmental challenges proactively.

Teachers should use a multimodal approach that effectively engages learners and satisfies contemporary pedagogical objectives to improve climate change education. It is imperative to employ the SSI-based approach, which centers on real-world climate change issues. Teachers can help learners better grasp and appreciate ecological concerns and solutions by basing teachings in pertinent environmental contexts. Customizing the strategies to the unique educational contexts, institutional objectives, and intended learning results is essential. In addition, teachers should prioritize strategies such as problem-based learning, real-world case studies, and reasoned argumentation that promote critical thinking and active engagement. To be relevant and effective in an educational environment that is changing quickly, teachers must constantly evaluate and modify their approaches to ensure learners have the knowledge and abilities they need to confront the problems posed by climate change.

While the study on the SSI-based approach in climate change education shows some potential benefits, a careful analysis is necessary due to many limitations. Because published studies might not accurately reflect the entirety of knowledge, publication bias presents a serious risk to the accuracy of the results. The differences in study methodologies, geographical locations, and educational attainment further complicate the generalization of results. The variety in results is increased by moderating factors, including study year, location, and educational attainment, indicating the necessity to evaluate the approach in various circumstances carefully. These restrictions show the difficulty of assessing the approach's influence on climate change education, even though the study provides insightful information. Future research should address publication bias, concentrate on context-specific studies, investigate innovative pedagogical approaches, and include longitudinal studies to evaluate the long-term impacts and scalability of the SSI-based approach to maximize educational outcomes and improve comprehension.

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