education sciences

MDPI

Article

Bridging Mathematical Modelling and Education for Sustainable Development in Pre-Service Primary Teacher Education

Neslihan Bulut * and Rita Borromeo Ferri

Department of Mathematics and Natural Sciences, University of Kassel, 34131 Kassel, Germany; borromeo@mathematik.uni-kassel.de

* Correspondence: nbulut@mathematik.uni-kassel.de

Abstract: This study examined the impact of a teacher training programme combining Education for Sustainable Development (ESD) and Mathematical Modelling (MM) on pre-service primary mathematics teachers' (PSTs) understanding of sustainability and its integration into mathematics education. Using a mixed-methods approach, data were gathered through pre- and post-test questionnaires and qualitative reflections. The results showed a significant improvement in PSTs' knowledge of sustainability after the training. Key themes included the development of mathematical modelling competence and an increased understanding of sustainability topics and the importance of critical thinking. Participants also emphasized the importance of lifelong learning, openness to change, and acquiring the necessary didactic skills for creating ESD–modelling tasks. Additionally, the study found that PSTs' personal behaviours shifted toward sustainability, with a focus on responsible consumption, water conservation, and climate action, aligning with various Sustainable Development Goals (SDGs). The seminar addressed all 17 SDGs, however, in the post-test questionnaire, participants most frequently provided examples related to SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). It recommended a stronger emphasis on interdisciplinary approaches, targeting underrepresented SDGs, and challenging existing beliefs that restrict sustainability integration in subjects like mathematics. Mathematical modelling activities were highlighted as a key tool for integrating sustainability concepts into mathematics lessons.

Keywords: mathematical modelling; sustainability; education for sustainable development; mathematics education; SDGs

Academic Editors: Kittisak Jermsittiparsert, Ismail Suardi Wekke, Oytun Sozudogru and Jamaluddin Ahmad

Received: 16 December 2024
Revised: 13 February 2025
Accepted: 14 February 2025
Published: 16 February 2025

Citation: Bulut, N., & Borromeo Ferri, R. (2025). Bridging Mathematical Modelling and Education for Sustainable Development in Pre-Service Primary Teacher Education. *Education Sciences*, *15*(2), 248. https://doi.org/10.3390/educsci15020248

1. Introduction

Sustainability has become a central concern across various fields, including education, as global challenges like climate change, hunger, resource scarcity, and social inequities intensify. Integrating sustainability into educational systems aims to equip learners with the knowledge, skills, and values necessary to address these pressing issues effectively (Tilbury, 2011; UNESCO, 2020). The international commitment to sustainability was formalized in 2015 when 193 nations adopted the 2030 Agenda for Sustainable Development, which established 17 Sustainable Development Goals (SDGs) (United Nations,

2015). Among these, goal 4.7 specifically emphasizes Education for Sustainable Development (ESD), underscoring the role of education in fostering an understanding of sustainability and empowering individuals to take responsible action.

ESD is not merely about imparting knowledge; it also seeks to develop essential competencies such as critical thinking, ethical decision-making, and collaborative problem-solving. These skills enable learners to approach complex sustainability challenges with a systems perspective and actively contribute to sustainable development (UNESCO, 2017; Wiek et al., 2011). To this end, educational institutions are encouraged to incorporate participatory teaching and learning methods that inspire students to reflect on their behaviours and adopt sustainable practises. This approach ensures that learners acquire the ability to analyze current issues, imagine future scenarios, and make cooperative decisions to achieve sustainability goals (UNESCO, 2017; Wiegand & Borromeo Ferri, 2023).

The importance of ESD has been reinforced through international initiatives, including the UN Decade of ESD (2005–2015) and the World Action Programs (WAP). These initiatives highlight the commitment to ensuring that all learners acquire the knowledge and skills necessary to promote sustainable development by 2030. Such programmes reflect the need to integrate sustainability education across all levels of schooling and higher education (UNESCO, 2002, 2017). The process requires educators to play a transformative role as "powerful agents of change", with their knowledge and skills being critical to rethinking educational structures and methods in pursuit of sustainability (UNESCO, 2017).

The SDGs, structured around economic, social, and environmental dimensions, provide a framework for assessing and advancing sustainability within education. Through ESD, students develop competencies—encompassing skills, knowledge, and attitudes—that support sustainability at all levels of education. This holistic approach ensures that education systems prepare learners to navigate and contribute meaningfully to a sustainable future (Robles Moral, 2021; Vesterinen & Ratinen, 2023). Recognizing that sub-goal 4.7, Education for Sustainable Development (ESD), states that schools must also provide education about sustainability, researchers and practitioners from mathematics education are interested in how this can be carried out concretely in school and teacher education. Although the ESD framework is a well-known concept, there is a lack of research and a lack of practical examples for schools in the field of mathematics education in contrast to other fields, e.g., ethics or environmental biology (Holst et al., 2024). Encompassing research into pre-service secondary mathematics teachers' learning process in an ESD–modelling university seminar, the goal of this research was to bridge mathematical modelling and ESD, and to improve pre-service primary mathematics teachers' professionalism.

Mathematics education should not just be seen as something good for individuals or society, and the current global challenges of sustainability, etc., make us question its current role. As a result, mathematics and its teaching need to address social and political aspects of life (ICMI, 2025).

2. Theoretical Framework

2.1. Mathematics Teacher Education and Eduation for Sustainable Development

Education for Sustainable Development plays a critical role in equipping students with the knowledge and skills needed to address global challenges. Integrating sustainability concepts into the curriculum fosters awareness of the SDGs and prepares students to become responsible citizens capable of tackling pressing environmental and social issues (Dahl, 2019; Firth & Winter, 2007). To achieve this, educators must adopt authentic learning approaches that connect academic content to real-world challenges, enabling students to engage deeply with the subject matter (Hallström & Schönborn, 2019). In Germany, the Ministry of Education (KMK) developed a Framework for Global Development Education in the context of Education for Sustainable Development (KMK, 2016). Within

this framework, all school subjects, including mathematics, are given guidelines on how to teach ESD within that specific subject.

Teachers play a key role in helping the next generation address and solve problems that arise within the scope of sustainability. They influence how students perceive and respond to these challenges, making teacher training a cornerstone of educational reform (Dlouhá et al., 2019; Valderrama-Hernández et al., 2020). However, evidence suggests a gap in teachers' competencies in sustainability education, with many educators lacking in-depth knowledge of the SDGs and strategies for integrating these concepts into their teaching practises (Alsina & Silva-Hormazábal, 2023; García-Alonso et al., 2023). Addressing this gap requires effective teacher education programmes in order to prepare educators to integrate ESD into their classrooms with regard to specific subjects. Studies highlight the importance of grounding teacher training in evidence-based practises that keep up with the needs of today's education (Alsina & Mulà, 2019; Honey et al., 2014). Research has also shown that well-designed training programmes can significantly enhance teachers' understanding of sustainability in the context of mathematics education, improve their attitudes toward teaching sustainability, and increase the frequency with which they include these concepts in their lessons (Murphy et al., 2020; Vásquez et al., 2023, Wiegand & Borromeo Ferri, 2023).

For instance, initiatives focusing on STEAM education and contextualized projects based on real-life situations have proven successful in building teachers' competencies and confidence in teaching ESD (Alsina & Silva-Hormazábal, 2023; Vásquez & García-Alonso, 2020; Wiegand & Borromeo Ferri, 2023). These programmes not only help educators to develop practical skills but also foster a deeper understanding of the interdisciplinary nature of sustainability education.

Recent studies have increasingly emphasized the importance of integrating sustainability into teacher education, particularly in the context of mathematics education. Wiegand and Borromeo Ferri (2024) highlight the benefits of using mathematical modelling as a tool to teach Education for Sustainable Development (ESD), arguing that an integrative teaching approach not only fosters a deeper understanding of sustainability concepts but also strengthens the connection between mathematical thinking and real-world problems. Similarly, Borromeo Ferri and Wiegand (2023) identify both challenges and successes in preparing pre-service mathematics teachers to engage with sustainability through teacher training programmes, underlining the need for a multidisciplinary approach that encourages critical thinking and reflection. Furthermore, Alsina and Silva-Hormazábal (2023) advocate for the use of a STEAM approach to promote sustainability in mathematics teacher education, suggesting that the combination of science, technology, engineering, arts, and mathematics can help develop the necessary skills and mindset for addressing global sustainability issues. These studies reinforce the notion that teacher education programmes must go beyond traditional subject content to prepare teachers for the socio-ecological challenges of the 21st century, making sustainability a central theme in their professional development.

Despite progress, challenges remain in integrating sustainability into teacher education. Many educators struggle with limited resources, varying interpretations of sustainability, and a lack of structured training programmes regarding ESD (Biasutti, 2015). To overcome these obstacles, teacher training needs to emphasize both scientific content knowledge and pedagogical strategies that can be effectively transferred to the classroom (Garello & Rinaudo, 2013). Moreover, teacher beliefs, prior knowledge, and attitudes must be considered when designing these programmes, as they significantly influence the success of educational reforms (Eilks, 2015).

In many studies, sustainability topics have predominantly been addressed within the scope of science education (Eilks, 2015; Robles Moral, 2021). Examples of applied practises

in teacher education programmes also primarily focus on topics within science and social science courses (Guo et al., 2020). However, mathematics offers significant opportunities for addressing sustainability topics in classrooms by fostering skills such as problem-solving, critical thinking, systematic reasoning, and analytical thinking (Borromeo Ferri & Wiegand, 2023; Alsina & Vásquez, 2024). In this context, it is particularly important to develop applied examples in mathematics education within teacher training programmes.

On the other hand, research shows that introducing sustainability topics at an early age, including in preschool and primary school settings, significantly enhances children's understanding of sustainability and helps instil lifelong awareness and responsibility (Alsina & Silva-Hormazábal, 2023; Vásquez & García-Alonso, 2020). Early exposure to these concepts is crucial for developing foundational competencies aligned with the SDGs.

2.2. Mathematics Education and Mathematical Modelling in Terms of ESD

Mathematical modelling is a key tool for connecting real-world problems with mathematical concepts. It involves simplifying real-life situations, converting them into mathematical terms, solving them, and interpreting the results (Niss & Blum, 2020). Modelling competencies, such as problem understanding, identifying variables, simplifying, mathematizing real-world situations, and interpreting and validating solutions, are essential for addressing global challenges (Borromeo Ferri, 2006; Niss et al., 2007).

As a core element of mathematics education, modelling fosters real-world problem-solving skills and aligns with global curricula (Cevikbas et al., 2022). It also bridges mathematics and interdisciplinary goals like ESD. Wiegand and Borromeo Ferri (2023) developed a model (Figure 1) emphasizing mathematical modelling as the central component connecting ESD and STEAM education.

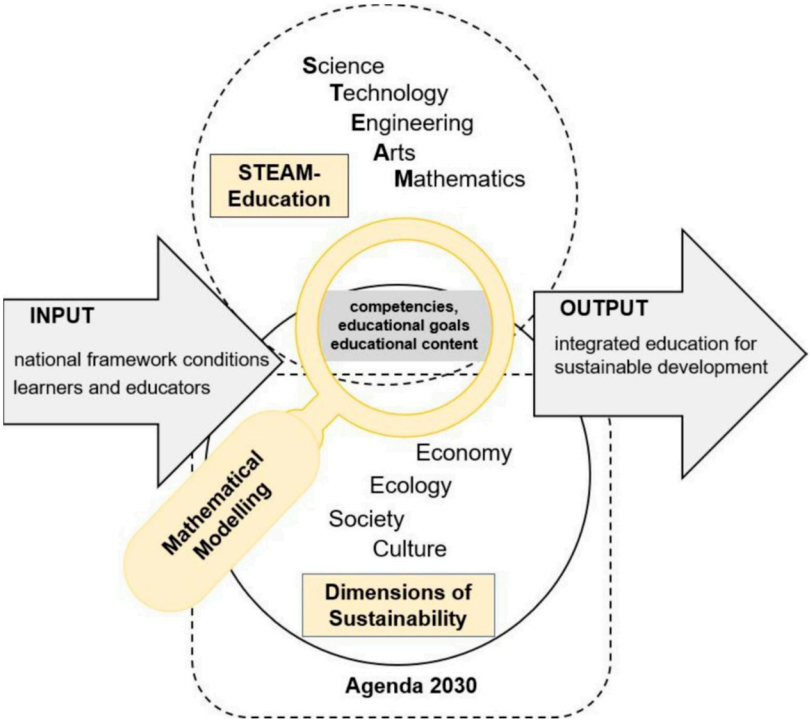

Figure 1. Mathematical modelling in the context of STEAM and ESD (Wiegand & Borromeo Ferri, 2023).

This framework highlights the need to train teachers in modelling to effectively incorporate sustainability into their lessons.

Integrating sustainability into mathematics education supports the SDGs and promotes a sustainable future (Alsina & Mulà, 2019; UNESCO, 2017; Wiegand & Borromeo Ferri, 2024). While challenges like limited time and knowledge expansion remain, many teachers acknowledge the value of this integration (Vásquez et al., 2021).

A research study conducted by the second author on the impact of attending an ESD–modelling seminar at university on pre-service secondary mathematics teachers showed that the knowledge of teachers regarding ESD and the SDGs increased over the course of a semester due to the use of mathematical modelling (Borromeo Ferri & Wiegand, 2023).

Therefore, equipping primary school teachers and pre-service teachers with the skills and knowledge necessary to enable them to integrate sustainability as a key practice in mathematics lessons, using mathematical modelling to do so, seems to be essential. This approach will enable them to fully leverage the potential of mathematics education in cultivating sustainability competencies in their students, preparing them for the challenges of the 21st century.

2.3. Research Questions

This study offers a detailed exploration of pre-service primary mathematics teachers' perception and understanding of Education for Sustainable Development (ESD), the Sustainable Development Goals (SDGs), and their application in mathematics lessons through mathematical modelling within the context of ESD. The university seminar aimed to integrate sustainability education with mathematical modelling education. The study specifically examines how pre-service teachers' (PSTs) perceptions of ESD concepts develop after participating in an ESD–modelling seminar at university over 5 months.

This research is guided by the following research questions:

(1) How does seminar participation influence pre-service mathematics teachers' understanding of sustainable development concepts and their perception to integrate ESD into mathematics teaching?
(2) How do pre-service teachers' perceptions of the core competencies needed to teach sustainability through mathematics change between the pre-test and post-test questionnaires?
(3) How do pre-service teachers describe the personal influence of the seminar and their specific project work on their perspectives and behaviours toward sustainability, and what concrete examples do they provide?

3. Materials and Methods

3.1. Research Design

This research employs a mixed-methods approach (Buchholtz, 2019) integrating quantitative and qualitative techniques for data collection. Quantitative data were collected using a Likert-scale survey to evaluate participants' perceptions and skills before and after the intervention. Meanwhile, qualitative data were gathered through open-ended questions, providing rich insights into participants' experiences, reflections, and thought processes. Both types of data were collected at two key stages: as a pre-test questionnaire conducted at the beginning of the seminar and as a post-test questionnaire administered at the end of the intervention.

3.2. Participants

The participants of this study were 20 pre-service primary school teachers (PSTs) enrolled in a seven-semester teacher education programme at a public university in Germany. For statistical analyses, a minimum sample size of 20 subjects (Porst, 2000) to 30

subjects (Bortz, 1993) is recommended. These participants were in their 5th or 6th semesters of the programme during the study and were taking part in the seminar "Education for Sustainable Development in Primary Mathematics School Education", which formed the context for this research. The seminar was part of a teacher education programme offered by the university, specifically designed to enhance pre-service teachers' understanding and integration of mathematical modelling and ESD. The university provided the framework, content, and instructional guidance for the seminar, while the pre-service teachers were participants who engaged in both theoretical and practical components of the programme.

The primary mathematics teachers had minimal prior exposure to mathematical modelling, typically limited to a single lecture during their first semester. This course aimed to deepen and enhance their understanding of mathematical modelling while integrating it with ESD. To assess their baseline familiarity with sustainability concepts, the following questions were included in the pre-test:

1. Could you please estimate your level of familiarity with sustainable development?
2. How familiar are you with Education for Sustainable Development (ESD)?
3. How familiar are you with the 17 Sustainable Development Goals (SDGs)?
4. To what extent are you familiar with the dimensions of sustainable development (economic, social, environmental)?
5. To what extent are you familiar with the 2030 Agenda?

The pre-test results revealed that most participants had limited prior knowledge of sustainability. For question 1, nearly half of the participants (n = 13) reported having little to no knowledge, while seven participants indicated a moderate level of familiarity. For question 2, 18 participants stated that they had little to no knowledge of ESD. Similarly, for question 3, 15 participants reported having almost no familiarity with the 17 SDGs. Regarding question 4, half of the participants (n = 10) reported no familiarity with the dimensions of sustainable development, while eight indicated a moderate level of knowledge. Lastly, for question 5, 19 participants stated that they had no prior knowledge of the 2030 Agenda. These findings suggest that participants' previous experience and familiarity with sustainability-related concepts were generally very limited.

Additionally, the seminar was part of the teacher education curriculum and conducted throughout the semester by the second author of this study.

All participants volunteered to take part in the study and were informed about the research objectives and procedures prior to their consent. To maintain confidentiality, participants were instructed to create and use a unique code instead of providing their names on the survey instruments.

3.3. Intervention

The study was conducted within the context of an ESD–modelling university seminar for primary mathematics school education, which lasted 14 weeks and included weekly 90 min sessions. The ESD–modelling seminar, based on previous courses run for pre-service secondary mathematics teachers (see in detail Wiegand & Borromeo Ferri, 2023), aimed to equip participants with knowledge and skills related to mathematical modelling and its applications in primary education, particularly in the context of sustainable development. During the seminar, the participants received training on mathematical modelling, the SDGs, and the 2030 Agenda framework.

Figure 2 provides an overview of the 14-week intervention, grouped into 3- to 4-week segments, detailing the content of the training, including topics on mathematical modelling the SDGs and ESD.

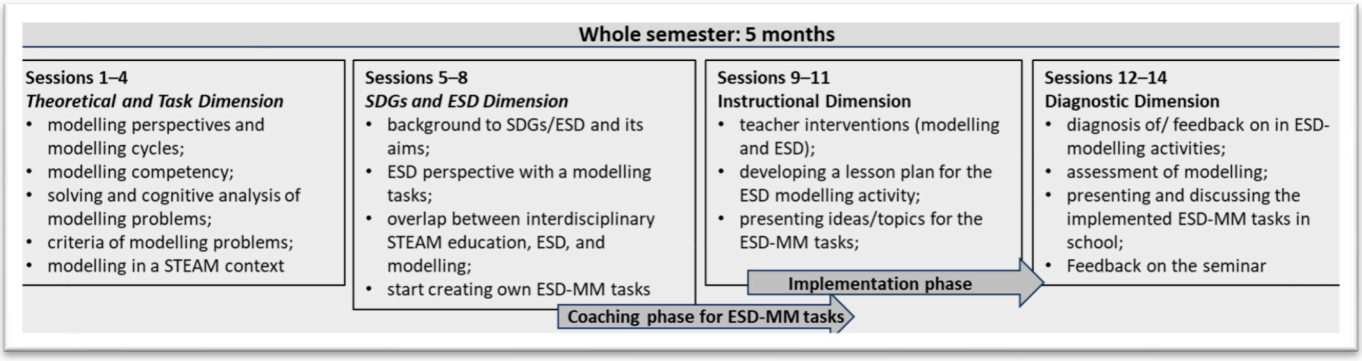

Figure 2. Overview of 14-week intervention.

The main part of the seminar involved the pre-service teachers developing, in pairs, an ESD–modelling task for primary school-aged learners, with the aim of teaching this task in primary school classrooms during the semester. An ESD–modelling task is, according to Wiegand and Borromeo Ferri (2023), a task combining the criteria of the ESD framework and the criteria of a modelling problem (realistic, authentic, open, problem-based, and modelling phases must be passed; see Maaß, 2010). They engaged in various activities designed to foster their understanding of these topics and their relevance to primary education. The responsibilities of the teacher candidates are outlined in the table below (Table 1).

Table 1. The tasks of the PSTs.

Task No	Task Description
1	Attending the ESD–modelling seminar, where mathematical modelling, sustainable development, and ESD concepts were discussed.
2	Developing ESD–modelling activities.
3	Presenting the activities in the seminar.
4	Receiving feedback from participants of the seminar and the lecturer.
5	Revising the activities based on the feedback received.
6	Implementing ESD–modelling activities in a primary school setting.
7	Organizing the results and presenting them in the seminar in the last session.

The ESD–modelling activities were developed in stages, with participants sharing their initial designs with other teacher candidates in the seminar and the professor leading the seminar for feedback, then improving them based on the input received. Finally, the developed activities were implemented in real primary classroom settings, with each pair of pre-service teachers conducting their sessions with learners from grades 2, 3, or 4 in primary schools approximately over two class periods. The number of students in the schools where the implementation was carried out ranged between 20 and 30.

3.4. Data Collection and Analysis

Quantitative and qualitative data were collected and analyzed using a mixed-methods approach to provide a comprehensive understanding of the research objectives.

Quantitative data were gathered through a structured 31-item Likert-type scale designed to assess participants' perspectives, knowledge, and perceptions related to mathematical modelling and sustainable development. This scale explored teacher candidate**s'** awareness, interpretations, and perceptions regarding the core concepts of Education for Sustainable Development (ESD) as well as its teaching and education dimensions. These data were coded and analyzed using SPSS 29.

The 31-item Likert-type scale used in this study was not newly developed; instead, it was constructed by selecting items from previously validated instruments in the literature that aligned with this study's objectives. Example items from the 31-item Likert-type scale are provided in Appendix A. Specifically, items were adapted from the following studies: Álvarez-Vanegas et al. (2024), García-González et al. (2020), Gericke et al. (2019), Uitto and Saloranta (2017), and Vásquez et al. (2020). These sources were carefully reviewed to ensure their relevance to the context of mathematics education and mathematical modelling. The selected items were then reviewed by two doctoral-level experts in mathematics education and mathematical modelling, who are independent of the authors of this study, to confirm their suitability and relevance for the study.

To further support the validity and reliability of the data, open-ended questions were included alongside the Likert-type items. This approach allowed for the triangulation of data and provided richer insights into participants' perceptions. The scale was divided into sub-scales based on thematic groupings derived from the reviewed literature and the study's conceptual framework. These sub-scales align with the research questions and provide a clear structure for analyzing participants' responses.

While no separate pilot study was conducted for this scale, the selection and refinement process—including expert reviews—served to enhance its validity. Although factor analysis was not performed due to the scale's reliance on established instruments and the relatively small sample size, the grouping of items into sub-scales was informed by theoretical foundations and prior research findings.

Qualitative data were collected through open-ended questions included in the pre- and post-test questionnaires. The open-ended questions used to collect qualitative data were constructed by selecting relevant questions from the literature. These questions were reviewed by an expert in mathematics education, independent of the study authors, to ensure their validity and relevance to the research context. The final set of open-ended questions, informed by expert feedback, is presented in Appendix B. No separate pilot study was conducted for the open-ended questions, as their validity was supported by expert review and alignment with the established literature. Responses were systematically coded and analyzed using content analysis. The qualitative data, derived from pre-service teachers' responses to the open-ended questions, were analyzed using thematic coding. At the beginning, the pre- and post-test responses were reviewed to identify recurring keywords and phrases that represent participants' understanding of the concept. These were then categorized into themes using inductive coding to capture the scope of their conceptualizations. The first author categorized the data to identify emerging themes and patterns, while the second author independently coded a random sample of 25% of the responses (five pre-test and five post-test responses) to ensure reliability. Interrater reliability was calculated using Cronbach's alpha, resulting in a high agreement score of 0.98 (Creswell, 2013).

By integrating qualitative and quantitative data, the study achieved a robust, multi-faceted analysis. The mixed-methods approach also facilitated triangulation, enhancing the validity and reliability of the findings. Combining qualitative and quantitative data made the analysis stronger and more comprehensive. The mixed-methods approach also improved the accuracy and reliability of the results.

4. Results

4.1. Influence of ESD–Modelling Seminar on Pre-Service Teachers' Familiarity with Sustainable Development Concepts (Such as ESD, the SDGs, the Dimensions of Sustainable Development, and the 2030 Agenda), Their Perceptions of the Potential of Mathematics Education to Address Sustainability Challenges, and Their Preparedness to Incorporate ESD into Mathematics Teaching, as Measured Through Pre- and Post-Test Questionnaires

We conducted statistical analyses on the dataset, which comprised the responses to the first section of the survey, in order to test the influence of the seminar on pre-service teachers' self-perceived familiarity with sustainable development, Education for Sustainable Development (ESD), the Sustainable Development Goals (SDGs), the dimensions of sustainable development, and the 2030 Agenda, as measured through pre- and post-test responses.

The study involved 20 pre-service primary school teachers who completed a set of five questions in both pre and post-test questionnaires to assess their self-perceived familiarity with the following concepts:

1. Sustainable development.
2. Education for Sustainable Development.
3. The 17 Sustainable Development Goals.
4. The dimensions of sustainable development (economic, social, and environmental).
5. The 2030 Agenda.

Due to the non-normal distribution of the data (Table 2) and the small sample size (n = 20), the Wilcoxon signed-rank test was chosen as the most appropriate statistical test for comparing the pre- and post-test scores. This test is particularly useful for analyzing paired data when the assumptions of normality are not met, making it a suitable choice for our dataset (Field, 2014). The Wilcoxon signed-rank test evaluates whether there is a significant difference between two related samples, in this case, the pre-test and post-test scores.

Table 2. Test of normality for the first set of questions**.**

Tests of Normality			
	Shapiro–Wilk		
	Statistic	**df**	**Sig.**
Diff_Q1	0.856	20	0.007
Diff_Q2	0.793	20	<0.001
Diff_Q3	0.907	20	0.056
Diff_Q4	0.865	20	0.010
Diff_Q5	0.856	20	0.007

The analysis revealed statistically significant differences in participants' pre- and post-test responses for all five questions included in the survey. Specifically, the p-values for each of the items were less than 0.01 (Table 3), indicating that the observed differences were not due to random chance and that the training programme had a substantial impact on the participants' knowledge and perceptions. The low p-values suggest a high degree of confidence in the results, supporting the conclusion that the training led to meaningful changes in participants' understanding of ESD.

Table 3. Wilcoxon signed-rank test for the first research question.

Related-Samples Wilcoxon Signed-Rank Test Summary					
	Q1	**Q2**	**Q3**	**Q4**	**Q5**
Total N	20	20	20	20	20
Test Statistic	153,000	210,000	171,000	105,000	190,000
Standard Error	20,588	26,062	22,625	15,516	24,431
Standardized Test Statistic	3716	4029	3779	3384	3888
Asymptotic Sig.(2-sided test)	<0.001	<0.001	<0.001	<0.001	<0.001

These findings suggest that participation in the seminar had a substantial influence on the pre-service teachers' self-perceived familiarity with the topics of sustainable development, ESD, the SDGs, and the 2030 Agenda. Specifically, the pre-service teachers demonstrated a significant increase in their understanding and awareness of these sustainability-related concepts after completing the seminar. The *p*-values less than 0.01 indicate that the observed changes were highly significant, reinforcing the effectiveness of the seminar in enhancing the participants' knowledge in these areas.

In summary, the ESD–modelling seminar had a significant positive impact on pre-service teachers' self-assessed familiarity with key concepts related to sustainability and global development frameworks. This finding suggests that, integrating the framework of Education for Sustainable Development into teacher training programmes is effective in increasing teachers' knowledge and preparedness to address sustainability issues in their future teaching practises.

For pre-service teachers to effectively incorporate ESD into mathematics education, a solid understanding of key sustainability concepts, including the SDGs and Agenda 2030, seems to be necessary. Without this foundational knowledge, it would not be possible to design lessons that contribute to solving sustainability challenges. The findings of this study also highlight that mathematical modelling can offer valuable opportunities for addressing ESD topics, but only if teachers are equipped with the necessary conceptual framework.

The analyses draw on data from five Likert-type items, supplemented by open-ended questions aimed at gaining deeper insights. In the following sections, we examine how pre-service teachers conceptualized sustainability-related terms in their pre- and post-test responses. These open-ended responses also served to validate the Likert-scale findings and provided an opportunity to explore the extent to which participants connected these concepts to mathematics education and mathematical modelling through their examples.

4.1.1. Findings from Open-Ended Question 1: What Do You Understand by the Concept of Sustainable Development? Could You Please Provide Some Examples?

In order to analyze the qualitative data gathered from the first open-ended question, the responses of the participants were systematically coded based on their contents, like "preserving resources", "developing awareness", and "counteracting climate change", which reflected the key ideas therein. This generated a set of initial codes, such as environmental awareness, resource preservation**,** social responsibility, systemic thinking, and action orientation. These codes were then grouped into four overarching themes. The environmental responsibility theme included responses focusing on resource conservation, environmental protection, and minimizing waste. The social and economic dimensions theme comprised concepts such as social equity, economic sustainability, and addressing global inequalities. The action orientation theme encompassed the responses emphasizing change, raising awareness, and future-focused actions. Finally, the mathematical applications theme covered educational approaches, particularly the integration of sustainability

into mathematics teaching. Themes were compared across pre- and post-test responses to identify changes in scope and depth.

The qualitative analysis revealed a significant progression in pre-service teachers' understanding of sustainable development after participating in the seminar. Responses to the pre-test questionnaire predominantly emphasized environmental responsibility and were based on resource preservation and reducing waste. While these responses reflected a basic awareness of sustainability concepts, they were limited in scope and often lacked a systemic perspective. For instance, participants primarily mentioned ideas such as "preserving resources in the long term" and "creating environmental awareness", with minimal attention to the economic and social dimensions of sustainability.

In contrast, post-test questionnaire responses displayed a broader and more integrated understanding of sustainability. Themes such as social equity, economic sustainability, and interconnectedness emerged more prominently, indicating a shift toward a multidimensional perspective. Additionally, participants adopted a more action-oriented tone, using phrases like "changing behaviour", "considering concrete options for action", and "counteracting climate change". They increasingly highlighted the importance of future generations and systemic solutions, moving beyond descriptive accounts to practical implications. While mentions of mathematical applications remained limited, there was some evidence of growth in recognizing the role of mathematics in addressing real-world sustainability challenges like addressing real-world issues in the classroom through mathematical modelling.

Overall, the findings suggest that the seminar effectively deepened participants' understanding of sustainable development by broadening their perspectives, enhancing their ability to link sustainability to education, and fostering a proactive mindset. This progression aligns with the seminar's objectives of improving pre-service teachers' familiarity with ESD and the SDGs and equipping them to address sustainability challenges through mathematics teaching.

4.1.2. Findings from Open-Ended Question 2: What Do You Understand by the Concept of Education for Sustainable Development (ESD)?

The participants' answers to the second open-ended question showed a progression in pre-service teachers' understanding between the pre- and post-test questionnaires. Their pre-test responses focused on general themes such as raising awareness among students, explaining sustainable living, and emphasizing cross-disciplinary connections (e.g., linking sustainability to mathematics or economics). While participants recognized the importance of critical thinking and reflection, their ideas were mostly abstract, with limited focus on specific strategies or practical implementation.

The post-test responses indicated a shift toward a more action-oriented and practical perspective. The participants highlighted the need to sensitize students to sustainability issues, teach actionable options, and integrate sustainability as a school-wide, interdisciplinary concept. Responses increasingly emphasized early education and fostering lifelong behaviours, with comments like "the earlier children begin, the more likely they will act sustainably". This progression demonstrates a growing awareness of ESD as a tool for empowering students to take meaningful action rather than simply gaining knowledge.

4.1.3. Findings from Open-Ended Question 3: Do You Know the 2030 Agenda? If So, Could You Explain It?

The responses to the third open-ended question highlight a significant shift in participants' understanding between the pre- and post-test questionnaires. In the pre-test questionnaire, the majority of participants (n = 16) did not provide an answer, while the remaining four participants answered with incomplete responses, such as "goals to be

achieved by 2030" or "no poverty". In the post-test questionnaire, participants showed a much clearer and detailed understanding of the 2030 Agenda. Many of them correctly identified the 17 Sustainable Development Goals (SDGs) as its core, emphasizing goals such as "ensuring dignity for all" and "global collaboration to achieve sustainability by 2030". This improvement reflects enhanced awareness and knowledge, likely resulting from educational interventions. However, some participants still left the question unanswered (n = 5), indicating room for further improvement in comprehending global sustainability frameworks.

Furthermore, the participants' awareness of Agenda 2030 led them to recognize and mention the responsibilities that schools and classrooms, also including mathematics education, must undertake to achieve these goals.

4.1.4. Findings from Open-Ended Question 4: What Are the Goals of Sustainable Development? Please Name Some of Them

This question reveals a noticeable improvement in participants' understanding between the pre- and post-test questionnaire. The pre-test responses were limited, with eight participants providing no answer and the remainder focusing primarily on environmental aspects, such as "reducing CO_2 emissions", "using renewable resources", and "environmental protection". A few responses referenced broad goals like "no poverty", but overall, there was a lack of detailed knowledge or diversity in the answers, indicating a limited familiarity with the full scope of the Sustainable Development Goals (SDGs).

In the post-test questionnaire, nearly all participants (n = 19) provided detailed and diverse responses, reflecting a broader understanding of the SDGs. Key themes included goals such as "no poverty", "zero hunger", "gender equality", "clean water", and "sustainable cities". Participants also mentioned social aspects like "social justice" and "protecting children", alongside environmental priorities like "protecting life underwater", "reducing waste", and "promoting sustainable consumption". This shift highlights a more comprehensive grasp of the SDGs, encompassing environmental, social, and economic dimensions. The improvement suggests that the seminar content effectively enhanced participants' awareness and understanding of the interconnectedness of the Sustainable Development Goals. As participants' knowledge of the SDGs increased, they were able to provide concrete examples of how mathematics lessons could be used in the context of ESD to achieve these goals. In Sections 4.3 and 4.4, participants who were unable to offer specific examples of mathematical modelling in the ESD context during the pre-test, were able to explain and provide examples of how mathematical modelling could be applied in the context of various SDGs in the post-test. However, the continued emphasis on certain themes (e.g., poverty and environmental protection) suggests that further emphasis could be placed on the integration of less-mentioned goals like quality education and partnerships.

4.1.5. Findings from Open-Ended Question 5: Do You Have Knowledge About the Dimensions of Sustainability (Economic, Environmental, and Social)? If Yes, Could You Please Explain?

The evaluation of the pre- and post-test responses to this question highlights a clear improvement in participants' awareness following the seminar. In the pre-test questionnaire, 17 participants provided no response, and the answers from the remaining three participants were weak, focusing on general concepts like "climate protection", "fighting poverty and hunger", and "sustainable economy". These responses lacked clarity and a comprehensive understanding of the three interconnected dimensions of sustainability.

In the post-test questionnaire, while four participants still did not respond, the remaining answers showed significant progress. Most participants correctly identified the

three dimensions—economic, ecology, and social—and described their interconnectivity. For instance, responses mentioned "fair wages and sustainable infrastructure" within the economic aspect, "environmental protection and climate-friendly energy" within the environmental aspect, and "social equality and stopping unjust treatment of people from different cultures" within the social aspect. Several participants noted the interplay between the dimensions, emphasizing that sustainability requires addressing all three areas holistically. Although explanations remained somewhat surface-level and lacked in-depth elaboration, the shift from vague or absent responses in the pre-test questionnaire to clearer identification and some examples in the post-test questionnaire indicates a marked improvement in participants' understanding and awareness of the dimensions of sustainability.

Although mathematics lessons and mathematical modelling have the potential to offer solutions to problems across various areas, particularly within the economic dimension of ESD, participants focused more on examples related to the environmental dimension in the post-test. This may be due to environmental issues being more frequently encountered in everyday life.

4.2. Changes in Teachers' Perceptions of Mathematical Modelling and Mathematics Instruction for Addressing Sustainability Challenges

To explore how the pre- and post-test responses revealed changes in teachers' perceptions of the potential of mathematical modelling and mathematics instruction to enhance students' awareness and competence in addressing sustainability challenges, a Wilcoxon signed-rank test was conducted for each of the 13 items in the second part of the survey. This non-parametric test was used due to the non-normal distribution of the data and the sample size (Table 4).

Table 4. Test of normality for the second research question.

Tests of Normality			
	Shapiro–Wilk		
	Statistic	**df**	**Sig.**
Diff_Q1	0.760	20	<0.001
Diff_Q2	0.816	20	0.002
Diff_Q3	0.760	20	<0.001
Diff_Q4	0.843	20	0.004
Diff_Q5	0.869	20	0.011
Diff_Q6	0.817	20	0.002
Diff_Q7	0.723	20	<0.001
Diff_Q8	0.906	20	0.053
Diff_Q9	0.838	20	0.003
Diff_Q10	0.868	20	0.011
Diff_Q11	0.855	20	0.006
Diff_Q12	0.779	20	<0.001
Diff_Q13	0.798	20	<0.001

After conducting the Wilcoxon signed-rank test, the results revealed that nine out of thirteen items showed a statistically significant change ($p < 0.05$) between pre- and post-test scores (Table 5).

Table 5. Wilcoxon signed-rank test for the second research question.

Related-Samples Wilcoxon Signed-Rank Test Summary					
	Total N	**Test Statistic**	**Standard Error**	**Standardized Test Statistic**	**Asymptotic Sig. (2-Sided Test)**
Q1	20	55,000	9253	2972	0.003
Q2	20	45,000	9014	1941	0.052
Q3	20	49,500	10,290	1604	0.109
Q4	20	171,000	22,296	3835	<0.001
Q5	20	120,000	17,103	3508	<0.001
Q6	20	84,500	13,000	3000	0.003
Q7	20	45,000	7794	2887	0.004
Q8	20	88,500	16,771	1699	0.089
Q9	20	30,000	9014	0.277	0.782
Q10	20	73,000	12,124	2804	0.005
Q11	20	61,000	10,553	2653	0.008
Q12	20	91,000	13,565	3354	<0.001
Q13	20	72,000	11,619	2840	0.005

These items include perceptions related to the following:

- The relevance of the SDGs for mathematical modelling.
- The integration of ESD into elementary and mathematics curricula.
- The role of mathematics in developing students' awareness and action competence regarding sustainability.
- The importance of sustainability-related content in mathematics instruction.
- The potential of mathematical modelling to analyze sustainability challenges and raise awareness.

These findings suggest that the seminar or intervention positively influenced pre-service teachers' perceptions regarding the integration of sustainability into mathematics instruction and the role of mathematical modelling in addressing sustainability challenges. Participants increasingly recognized the potential of mathematics and mathematical modelling as tools to promote sustainability awareness and action competence among students.

However, four items (namely items 2, 3, 8, and 9) did not show significant differences between pre- and post-test responses ($p > 0.05$). These items pertain to the following concepts:

- The perceived importance of sustainability topics relative to other mathematics curriculum priorities (item 2).
- The relevance of sustainability and the SDGs within the specific school context (item 3).
- The treatment of topics like poverty and hunger separately from mathematics instruction (item 8).
- The sufficiency of natural sciences and technology in addressing sustainability challenges (item 9).

The lack of significant changes in these areas may indicate that pre-service teachers' perceptions in these domains were either well-established prior to the intervention or were less directly influenced by the seminar content. For instance, the view that sustainability is more pertinent to natural sciences (item 9) and that topics like poverty should be treated separately from mathematics (item 8) might reflect deep-seated beliefs or systemic perspectives on subject boundaries.

In summary, the results demonstrate that the intervention was effective in shifting teachers' perceptions of the role of mathematics and mathematical modelling in fostering

sustainability awareness and competencies. However, the findings also highlight areas where further emphasis or targeted discussion may be needed to challenge pre-existing perceptions and to expand teachers' understanding of interdisciplinary approaches to sustainability education.

4.3. Pre-Service Teachers' Preparedness to Incorporate ESD and the SDGs into Mathematics Teaching

The data obtained from the third section of the Likert-type scale were used to examine how pre-service teachers' perceptions of their preparedness to incorporate Education for Sustainable Development (ESD) and the SDGs into mathematics teaching changed between pre- and post-test questionnaires, and what factors contributed to their confidence levels. A Wilcoxon signed-rank test was conducted for each of the 13 survey items. This analysis was selected due to the non-normal distribution of the data and the small sample size (n = 20) (Table 6).

Table 6. Test of normality for the third research question.

Tests of Normality			
	Shapiro–Wilk		
	Statistic	**df**	**Sig.**
Diff_Q1	0.871	19	0.015
Diff_Q2	0.854	19	0.008
Diff_Q3	0.907	19	0.065
Diff_Q4	0.928	19	0.162
Diff_Q5	0.910	19	0.074
Diff_Q6	0.890	19	0.032
Diff_Q7	0.733	19	<0.001
Diff_Q8	0.814	19	0.002
Diff_Q9	0.765	19	<0.001
Diff_Q10	0.874	19	0.017
Diff_Q11	0.814	19	0.002
Diff_Q12	0.814	19	0.002
Diff_Q13	0.863	19	0.011

The results indicated statistically significant changes in seven out of the thirteen items, suggesting that participation in the programme positively influenced pre-service teachers' self-perceived preparedness for and perceptions of integrating ESD and the SDGs into mathematics teaching (Table 7).

Table 7. Wilcoxon signed-rank test for the third research question.

Related-Samples Wilcoxon Signed-Rank Test Summary					
	Total N	**Test Statistic**	**Standard Error**	**Standardized Test Statistic**	**Asymptotic Sig. (2-Sided Test)**
Q1	20	190,000	24,254	3917	<0.001
Q2	20	50,500	9253	2486	0.013
Q3	20	171,000	22,567	3789	<0.001
Q4	20	109,000	16,974	2887	0.004
Q5	20	136,000	19,174	3547	<0.001
Q6	20	37,500	12,278	−0.122	0.903
Q7	20	45,000	7794	2887	0.004
Q8	20	42,000	9950	0.905	0.366
Q9	20	20,000	5292	1134	0.257
Q10	20	49,500	10,290	1604	0.109

Q11	20	30,000	9014	0.277	0.782
Q12	20	33,000	8696	0.632	0.527
Q13	20	56,000	10,559	2178	0.029

These items include the following concepts:

1. Preparedness to integrate ESD into teaching (item 1): participants felt more confident about their skills and knowledge to include ESD after the training.
2. The role of mathematical modelling in ESD (items 4, 5): there was increased recognition of the potential for mathematical modelling to convey sustainability concepts and address real-world challenges.
3. Interdisciplinary collaboration for ESD (item 6): teachers increasingly acknowledged the importance of collaboration among different subject teachers to achieve SDG goals.
4. Sustainability in mathematical modelling activities (item 7): post-test responses showed greater emphasis on including sustainability criteria when evaluating student projects.
5. Willingness to incorporate modelling activities (item 12): participants expressed a stronger readiness to integrate modelling activities related to sustainability and ESD into their teaching.
6. Illustrating sustainability challenges through modelling (item 13): teachers increasingly recognized the value of using modelling to illustrate real-world sustainability challenges for students.

These findings indicate that the ESD–modelling seminar effectively enhanced pre-service teachers' confidence and awareness regarding the integration of ESD and the SDGs in mathematics instruction.

For six items (namely items 2, 3, 8, 9, 10, and 11), no statistically significant differences were observed between pre- and post-test responses. These items focus on the following concepts:

- The inclusion of ESD in mathematics curricula (items 2, 3): Participants' perceptions about the importance of including ESD and the SDGs in the mathematics curriculum did not change significantly. This may suggest that their initial awareness and agreement on the topic were already high before the programme.
- The primary role of elementary teachers in promoting sustainability (item 8): teachers consistently recognized the importance of their role in fostering sustainability principles, indicating a stable belief throughout the training.
- Prioritization of sustainability in mathematics (item 9): no change was observed in perceptions of whether sustainability should be a high priority in mathematics instruction.
- Training needs in mathematical modelling (item 10): teachers' views on the importance of being trained in mathematical modelling for sustainability challenges were consistent before and after the programme.
- Responsibility of primary school teachers for fostering sustainability awareness (item 11): perceptions of this responsibility were already strong and did not significantly shift.

The lack of significant change in these items could indicate pre-existing high levels of agreement or a need for more explicit emphasis on these topics during the training programme.

The results demonstrate that the ESD–modelling seminar successfully enhanced pre-service teachers' self-perceived preparedness for and awareness of the potential for math-

ematics instruction and mathematical modelling to address sustainability challenges. Significant improvements were observed in their confidence to incorporate ESD and the SDGs into mathematics teaching and their understanding of mathematical modelling's role in illustrating and addressing sustainability challenges.

For items where no significant change was observed, the data suggest that participants entered the programme with a high level of awareness or belief in these areas, indicating a potential ceiling effect. Future training could focus on deepening engagement with these topics and providing more hands-on strategies to further strengthen their implementation in teaching practises.

These findings provide important insights into the impact of professional development on integrating sustainability education into mathematics instruction, highlighting both the successes and areas for further development.

4.4. Findings Regarding Pre-Service Teachers' Perceptions of Core Competencies for Teaching Sustainability in Mathematics

The analysis of responses from pre-service teachers showed an increase in their understanding of core competencies required for integrating sustainability into mathematics education. In the pre-test, 30% of participants did not respond, indicating limited awareness of the topic. Among those who did respond, the most common themes were "raising awareness of sustainability" (15%) and "mathematical modelling" (15%). Other competencies, such as "knowing sustainability goals" (10%), "problem-solving and strategy development" (10%), and "reflective thinking" (10%), were mentioned less frequently. These responses reflected a surface-level understanding of sustainability and its connection to mathematics, with less emphasis on practical implementation or interdisciplinary approaches.

In contrast, the post-test results indicated significant growth in participants' competencies and awareness. Only 20% of participants left the question unanswered, suggesting increased engagement. The most frequently cited theme was "mathematical modelling and related skills" (25%), followed by "subject knowledge and understanding sustainability topics" (20%). Participants also highlighted "reflective thinking and self-assessment" (15%) and "communication and teamwork" (10%). New themes emerged, including "didactic skills for creating suitable tasks" (10%) and "openness to change and lifelong learning" (10%), demonstrating some shift toward practical and actionable competencies. These findings suggest that participants gained a deeper understanding of sustainability in mathematics and how to implement it effectively in their teaching practises.

4.5. Findings Regarding Pre-Service Teachers' Reflections on Personal Influence of the Seminar

Data for this research problem were collected through an open-ended question included in the post-test questionnaire, which specifically asked primary school pre-service teachers to reflect on how the seminar and their project work influenced their personal behaviours and perspectives toward sustainability. Participants were encouraged to provide concrete examples to illustrate their responses. Unlike for the other research questions, no pre-test data were available for comparison, as the question was only posed after the seminar. The qualitative responses were analyzed and grouped into themes, with a focus on identifying connections to specific Sustainable Development Goals (SDGs) and changes in personal attitudes and actions. The analysis of responses revealed that the seminar significantly influenced participants' personal perspectives and behaviours toward sustainability, with many aligning their actions to specific Sustainable Development Goals (SDGs). The most frequently referenced SDGs included SDG 12: Responsible Consumption and Production; SDG 6: Clean Water and Sanitation; and SDG 13: Climate Action.

Under SDG 12, 40% of participants described changes in their consumption habits, such as reducing plastic use, second-hand shopping, and minimizing waste. For example, one participant reflected: "I have become more aware of my consumption habits, questioning the necessity of purchasing new clothes. I now prefer second-hand options and share clothes I no longer use with friends". Another noted, "The seminar made me more conscious of avoiding waste by reducing the use of laminating materials in teaching and buying less plastic". These responses illustrate a shift toward mindful consumption.

For SDG 6, 35% of participants mentioned adopting water-saving habits. Examples include shorter showers and being cautious about water use during daily activities. One participant shared her idea as follows: "I've started paying attention to my water consumption, such as turning off the tap while shampooing, and I've reduced my shower time". This indicates that the seminar raised awareness about the personal impact of water conservation.

Finally, SDG 13 was highlighted by 25% of participants, who reported integrating sustainability into their teaching practises and fostering environmental awareness. One participant commented: "The seminar demonstrated how sustainability topics can be effectively linked to mathematics. I am now motivated to teach these themes in a way that encourages children to take small but impactful actions". Others noted their commitment to reducing environmental impact by minimizing plastic waste and improving waste separation.

Initially, in the pre-test, the background knowledge of the teacher candidates regarding sustainability, mathematical modelling, and ESD was found to be low. Consequently, their perceptions of how these concepts could be applied in mathematics education were also limited. However, following the intervention, the post-test results showed a significant increase in their knowledge in these areas, which in turn led to a noticeable improvement in their perceptions. This shift highlights the influence of enhanced background knowledge on the development of more informed and holistic views on ESD, the SDGs, and their integration into mathematics education.

These findings underscore the seminar's success in inspiring concrete changes aligned with key SDGs and equipping pre-service teachers with practical ideas to implement sustainability in their personal lives and future classrooms. It not only broadened their understanding but also fostered a sense of responsibility as educators to promote sustainable behaviours among students.

5. Discussion

This study offers a detailed exploration of pre-service teachers' perceptions and understanding of ESD, the SDGs, and their application in mathematics lessons through mathematical modelling within the context of ESD in primary mathematics education. The ESD–Modelling seminar aimed to integrate sustainability education with mathematics teaching and specifically examined how pre-service teachers' perceptions of ESD concepts developed after participating in a training programme focused on ESD. By addressing these aspects, the research highlights both the transformative potential of teacher education programmes and also the challenges that remain in preparing future educators to tackle global sustainability challenges.

The pre-test results revealed that pre-service teachers lacked sufficient background knowledge in sustainability and education for sustainable development. Regarding mathematical modelling, they had only been exposed to a single one-hour session during their first semester, indicating a limited level of preparedness. Additionally, their responses to open-ended questions suggested that they perceived mathematical modelling and mathematics education as separate from sustainability topics.

As the intervention progressed, the training, content development, feedback received during the seminar, and their classroom implementation experiences helped participants realize the significant potential of mathematical modelling to address sustainable development in schools. The post-test responses reflected a notable increase in their personal awareness of sustainability and ESD, with participants providing more concrete examples to illustrate their understanding.

The analysis of quantitative data showed significant improvements in participants' self-assessed familiarity with sustainability concepts. The Wilcoxon signed-rank test results consistently showed p-values < 0.01 for all items, indicating substantial gains in knowledge about SD, ESD, the SDGs, and the 2030 Agenda. These findings align with previous research emphasizing the transformative potential of targeted interventions in sustainability education (Alsina & Vásquez, 2024; Vesterinen, 2024; Wiegand & Borromeo Ferri, 2023). As teachers are pivotal in disseminating sustainability concepts, these results underscore the value of integrating sustainability into teacher training programmes to enhance their readiness to address global challenges.

The content analysis of open-ended responses highlighted a shift in participants' understanding of sustainability. Pre-test responses primarily focused on environmental dimensions, reflecting a basic and somewhat fragmented awareness of sustainability. However, post-test responses exhibited a more holistic understanding, encompassing social equity, economic sustainability, and the interplay between these dimensions. Participants also increasingly demonstrated an action-oriented perspective, emphasizing behavioural change and systemic solutions.

This progression aligns with findings by Murphy et al. (2020), who noted that sustainability education fosters critical thinking and promotes multidimensional perspectives. Notably, themes such as mathematical applications emerged, albeit to a limited extent, indicating the potential to further integrate mathematics into sustainability education.

The study also demonstrated an enhancement in participants' competencies for teaching sustainability in mathematics classrooms. Pre-test responses showed a surface-level understanding, mainly focusing on "raising awareness" and "mathematical modelling". However, post-test responses demonstrated deeper engagement, with participants highlighting competencies such as didactic skills, reflective thinking, and interdisciplinary collaboration.

These findings align with the framework proposed by Zandvliet and Fisher (2007), which highlights the importance of giving teachers practical skills to integrate sustainability into their teaching. The emerging focus on lifelong learning and openness to change further reinforces the notion that sustainability education is a continuous process requiring adaptability and innovation.

The study also explored pre-service teachers' perceptions of mathematics as a tool to address sustainability challenges. Statistically significant improvements were observed in nine of thirteen items related to the topic, demonstrating a growing recognition of the potential for mathematical modelling to promote sustainability awareness and action competence. The findings of Alsina and Vásquez (2024) highlight the importance of mathematical modelling in promoting systemic thinking among students, in order to fulfil the Sustainable Development Goals. This approach supports the creation of mathematically meaningful learning experiences, allowing students to apply mathematical knowledge to solve real-world problems. Drawing from research conducted at UniLaSalle, integrating sustainability into teacher education through interdisciplinary approaches can significantly enhance pre-service teachers' ability to connect mathematical modelling with broader sustainability challenges, fostering a more holistic understanding of global sus-

tainability issues (Fourati-Jamoussi et al., 2019). However, certain items showed no significant change, particularly those addressing the relative importance of sustainability topics in mathematics curricula and the perceived sufficiency of natural sciences for addressing sustainability challenges. This finding may be related to the fact that some participants still view sustainability topics as falling within the scope of other lessons such as science, which could serve as a barrier to fully integrating sustainability into mathematics instruction.

Qualitative data regarding the personal gains of the participants from post-test reflections indicated that the seminar influenced participants' personal behaviours and attitudes toward sustainability, with many aligning their actions to specific SDGs such as SDG 12 (Responsible Consumption and Production), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). For example, participants reported adopting mindful consumption habits, water-saving behaviours, and incorporating sustainability themes into their teaching practises. These findings highlight the seminar's success in fostering not only professional growth but also personal commitment to sustainability, as evidenced by the alignment of actions with global goals.

Although the study aimed to address all 17 SDGs, the participants primarily focused on SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) when developing activities and providing examples during the intervention. This emphasis on these specific goals may be attributed to the direct and tangible nature of these issues, which allowed the participants to more easily connect sustainability concepts with mathematical modelling tasks. SDG 6, for instance, is highly relevant to issues such as water management, which can be effectively analyzed using mathematical models. Similarly, SDG 12's focus on responsible consumption and SDG 13's focus on climate action are pressing global challenges that participants were able to relate to through mathematical applications.

This trend may reflect the participants' perceived relevance and urgency of these goals in the context of primary education, as well as their accessibility to mathematical modelling. While all the SDGs were part of the training programme, future interventions might further encourage pre-service teachers to explore the interconnections among different goals and broaden the scope of sustainability-related activities they design, thereby ensuring that all the SDGs receive equal attention in the classroom.

Mathematical modelling, as described by Blum and Borromeo Ferri (2009), is a structured process of translating real-world problems into mathematical representations. This process is particularly relevant to sustainable development, as it allows for the systematic analysis of complex environmental, social, and economic issues.

A group of pre-service teachers from the 10 groups participating in this study designed and implemented a mathematical modelling task related to SDG 12: Responsible Consumption and Production in a grade four classroom of 12 students. The process began with constructing, where they identified the problem of plastic waste in schools and defined key variables such as the amount of plastic waste produced per week. They then moved to simplifying, ensuring the problem was manageable by focusing on a single classroom's waste as a representative sample. In the mathematising step, they translated real-world observations into a mathematical model by estimating the volume of total plastic waste generated by all primary schools in their city using proportional reasoning and multiplication. Following to this, the students performed calculations, analyzed the collected data, and made predictions based on their model. They then proceeded to interpreting, where they examined the implications of their results, considering the environmental impact of plastic waste accumulation on a larger scale. They reflected on the accuracy and realism of their estimations, comparing them with available data on plastic waste production and adjusting their model if necessary. Finally, they discussed their findings

as a class, explored the potential long-term effects of plastic waste accumulation, and brainstormed actionable solutions such as reducing plastic use, promoting recycling, and encouraging sustainable alternatives. Through this structured modelling process, students not only developed their mathematical skills but also deepened their understanding of sustainability and responsible consumption. This example demonstrates how mathematics contributes to ESD by enabling students to quantify environmental issues, identify variables, analyze patterns, and make data-driven predictions. Through mathematical modelling, they can assess the long-term impact of plastic waste and explore effective solutions, fostering critical thinking and responsible decision-making. By integrating real-world sustainability challenges into mathematical tasks, students develop both mathematical competence and environmental awareness, empowering them to contribute to a more sustainable future.

6. Conclusions

This study highlights the significant impact of integrating sustainability into teacher and thus higher education training programmes, demonstrating how such initiatives like an ESD–modelling seminar can enhance pre-service teachers' preparedness to tackle sustainability challenges. The findings underscore the importance of fostering a holistic, interdisciplinary, and action-oriented mindset in future educators, enabling them to drive positive change within their classrooms and communities. By aligning teacher education and training with global frameworks like the SDGs, educational institutions can play a pivotal role in promoting sustainable development both locally and globally.

For primary school teacher candidates, it is crucial that sustainability education is not limited to subjects like science or social studies but is integrated across all subjects, including mathematics. This approach offers an opportunity to develop and implement sustainability-themed content in mathematics lessons, utilizing mathematical modelling activities to address real-world sustainability issues. These activities present a unique chance to engage students in problem-solving and critical thinking while connecting mathematics to global sustainability goals. Therefore, teacher training programmes should place emphasis on equipping pre-service teachers with the skills and knowledge to incorporate sustainability into their mathematics teaching practises, ensuring that they are prepared to foster sustainable development through their future teaching practises.

Mathematical modelling activities offer a valuable way to help pre-service teachers bring ESD into primary school classrooms. These activities make it easier to connect abstract mathematical ideas with real-world sustainability challenges, giving PSTs the tools to create lessons that are both engaging and practical. Through modelling tasks, PSTs not only strengthen their skills in problem-solving and systems thinking but also learn how to approach teaching in a way that cuts across different subject areas. These activities show how mathematics can play a key role in addressing important issues, such as managing resources or tackling climate change. Including mathematical modelling in teacher training programmes can help future teachers see the potential of mathematics as more than just numbers—it is a way to encourage critical thinking and meaningful learning. Similarly to the findings of Vesterinen (2024), this approach not only helps PSTs prepare to integrate sustainability into their lessons but also equips them to inspire students to think about the world's challenges in a creative and solution-oriented way.

The mathematical modelling approach presented in this study can be adapted to different countries by focusing on their most pressing challenges. For example, in India, where water scarcity is a critical issue due to climate change and over-extraction, students could develop models to estimate water consumption and explore conservation strategies. In Ethiopia, where food insecurity remains a major concern, mathematical models could help analyze agricultural productivity, food waste, and efficient resource allocation.

Meanwhile, in Bangladesh, where the textile industry generates a significant amount of waste, students could investigate the environmental impact of fast fashion and propose sustainable alternatives. In the United States, where high levels of consumption result in significant electronic waste, mathematical modelling could be used to monitor e-waste accumulation and assess recycling efficiency. While these challenges vary by region, they are all interconnected and affect global sustainability. Addressing them requires collective responsibility, and incorporating these issues into mathematics curricula from primary school not only enriches students' mathematical abilities but also empowers them to take an active role in creating sustainable solutions, fostering a sense of responsibility toward a more sustainable future for all. In addition to revising curricula, it is also important to incorporate ESD topics into the training programmes for mathematics and primary school teachers, ensuring that educators are equipped to teach these critical issues effectively.

7. Recommendations and Limitations

In addition to these findings, there are several key areas that require further attention in future research, as follows:

- Strengthen interdisciplinary links: while there has been progress in connecting mathematics to sustainability, more effort is needed to blend different subjects and move beyond traditional boundaries.
- Focus on overlooked SDGs: it is important to give more attention to the less-discussed SDGs, like partnerships for the goals and quality education, to provide a well-rounded view of sustainability.
- Address limiting beliefs: training programmes should actively challenge the idea that sustainability topics only belong in subjects like science, showing how they can fit seamlessly into mathematics lessons too.
- Small sample size: This study's relatively small sample size (n = 20) limits the generalizability of the findings. Future research should aim to include a larger, more diverse group of participants to provide more robust conclusions and better applicability across various educational contexts.
- Bias from self-reported data: As the study relied on self-reported questionnaires, there is a potential bias in the responses, such as social desirability or participants' tendency to align with expected answers. Future studies should consider using more objective data collection methods, such as classroom observations or longitudinal studies, to complement self-reports and provide a more comprehensive picture.
- Factor analysis not conducted: While the study adapted a validated scale, factor analysis was not conducted with the current sample. This could impact the reliability and validity of the findings. Future research could benefit from performing a factor analysis to ensure the accuracy of the measurement tools and their alignment with the study's objectives.

Author Contributions: Conceptualization, N.B. and R.B.F.; methodology, N.B. and R.B.F.; software, N.B.; validation, N.B. and R.B.F.; formal analysis, N.B.; investigation, N.B. and R.B.F.; resources, N.B. and R.B.F.; data curation, N.B. and R.B.F.; writing—original draft preparation, N.B.; writing—review and editing, R.B.F.; visualization, N.B. and R.B.F.; supervision, R.B.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded by the Alexander von Humboldt Foundation.

Institutional Review Board Statement: According to the ethics committee of the authors' affiliation, ethical review was not required for this study by its regulation.

Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available from the author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Sample Questions from the Questionnaire (Likert-Type Items)

1	Can you estimate your level of familiarity with sustainable development?
2	How familiar are you with education for sustainable development (ESD)?
3	To what extent are you familiar with the 2030 Agenda?
4	The mathematics curriculum contains more important, subject-specific topics than sustainability topics.
5	I am familiar with the key competencies in the field of sustainability that students can develop through education for sustainable development.
6	ESD should be integrated into the curriculum of primary schools.
7	ESD should be integrated into the mathematics curriculum in general.
8	Topics such as poverty, hunger and social inclusion should be treated separately from mathematics teaching and mathematical modelling.
9	Teachers should incorporate sustainability education and the SDGs into their mathematics teaching.
10	In my lessons, I can develop mathematical modelling activities for sustainable development.
11	It is important that primary school teachers are trained in mathematical modelling techniques to address sustainability challenges.
12	I believe that primary school teachers have a responsibility to foster sustainability awareness in their students.

Appendix B. Open-Ended Questions from the Questionnaire

1	What do you understand by the concept of sustainable development? Could you please give some examples?
2	What do you understand by the concept of education for sustainable development?
3	Are you familiar with the 2030 Agenda? If so, could you please explain it?
4	What are the Sustainable Development Goals? Please name some of them?
5	Are you familiar with the dimensions of sustainability (economic, environmental, social)? If yes, please explain.
6	What could be the core competences of primary school teachers to teach sustainability through mathematics? Please name and explain 3 competences.
7	Briefly explain how the seminar and the topic you worked on influenced you personally to act sustainably. Give a concrete example.

References

Alsina, Á., & Mulà, I. (2019). Advancing towards a transformational professional competence model through reflective learning and sustainability: The case of mathematics teacher education. *Sustainability*, *11*, 4039. https://doi.org/10.3390/su11154039.

Alsina, Á., & Silva-Hormazábal, M. (2023). Promoting mathematics teacher education for sustainability through a STEAM approach. *Avances de Investigación en Educación Matemática*, *23*, 105–125. https://doi.org/10.35763/aiem23.5402.

Alsina, Á., & Vásquez, C. (2024). Professional development and teacher agency in mathematics teacher education for sustainability. *Mathematics Education Research Journal*, *36*, 1–24. https://doi.org/10.1007/s13394-024-00488-y.

Álvarez-Vanegas, A., Rieckmann, M., Lopera Pérez, M., & Aguirre, P. M. (2024). Teaching with a rounder sense of purpose: A survey study on education for sustainable development competences in Latin America. *Frontiers in Education*, *8*, 1205478. https://doi.org/10.3389/feduc.2023.1205478.

Biasutti, M. (2015). An intensive programme on education for sustainable development: The participants' experience. *Environmental Education Research*, *21*, 734–752.

Blum, W., & Borromeo Ferri, R. (2009). Mathematical modelling: Can it be taught and learnt? *Journal of Mathematical Modelling and Application*, *1*(1), 45–58.

Borromeo Ferri, R. (2006). Theoretical and empirical differentiations of phases in the modelling process. *ZDM-International Journal on Mathematics Education*, *38*, 86–95.

Borromeo Ferri, R., & Wiegand, S. (2023). Teaching Education for Sustainable Development—Challenges and Successes of pre-service mathematics teachers. In M. Ayalon, B. Koichu, R. Leikin, L. Rubel, & M. Tabach (Eds.), *Proceedings of the 46th conference of the international group for the psychology of mathematics education* (PME 46; Vol. 2, pp. 131–138). University of Haifa.

Bortz, J. (1993) *Statistik: Für sozialwissenschaftler (Vierte, vollständig überarbeitete Auflage)*. Springer. https://doi.org/10.1007/978-3-662-10034-9.

Buchholtz, N. (2019). Planning and conducting mixed methods studies in mathematics educational research. In G. Kaiser, & N. Presmeg (Eds.), *ICME-13 Monographs. Compendium for early career researchers in mathematics education* (pp. 131–152). Springer International Publishing.

Cevikbas, M., Kaiser, G., & Schukajlow, S. (2022). A systematic literature review of the current discussion on mathematical modelling competencies: State-of-the-art developments in conceptualizing, measuring, and fostering. *Educational Studies in Mathematics*, *109*, 205–236.

Creswell, J. W. (2013). *Qualitative inquiry and research design: Choosing among five approaches*. Sage.

Dahl, T. (2019). Prepared to teach for sustainable development? Student teachers' beliefs in their ability to teach for sustainable development. *Sustainability*, *11*, 1993. https://doi.org/10.3390/su11071993.

Dlouhá, J., Heras, R., Mulà, I., Salgado, F. P., & Henderson, L. (2019). Competences to address SDGs in higher education—A reflection on the equilibrium between systemic and personal approaches to achieve transformative action. *Sustainability*, *11*, 3664.

Eilks, I. (2015). Science education and education for sustainable development—Justifications, models, practices and perspectives. *Eurasia Journal of Mathematics, Science and Technology Education*, *11*, 149–158.

Field, A. (2014). *Discovering statistics using IBM SPSS statistics*. Sage.

Firth, R., & Winter, C. (2007). Constructing education for sustainable development: The secondary school geography curriculum and initial teacher training. *Environmental Education Research*, *13*, 599–619. https://doi.org/10.1080/13504620701659079.

Fourati-Jamoussi, F., Dubois, M. J., Agnès, M., Leroux, V., & Sauvée, L. (2019). Sustainable development as a driver for educational innovation in engineering school: The case of UniLaSalle. *European Journal of Engineering Education*, *44*, 570–588. https://doi.org/10.1080/03043797.2018.1501348.

García-Alonso, I., Sosa-Martín, D., & Trujillo-González, R. (2023). Assessing sustainability competencies present in class proposals developed by prospective mathematics teachers. *Avances de Investigación en Educación Matemática*, *23*, 61–83. https://doi.org/10.35763/aiem23.5419.

García-González, E., Jiménez-Fontana, R., & Azcárate, P. (2020). Education for sustainability and the sustainable development goals: Pre-service teachers' perceptions and knowledge. *Sustainability*, *12*, 7741. https://doi.org/10.3390/su12187741.

Garello, M. V., & Rinaudo, M. C. (2013). Autorregulación del aprendizaje, feedback y transferencia de conocimiento. *Revista Electrónica de Investigación Educativa*, *15*, 131–147. Available online: http://redie.uabc.mx/vol15no2/contenido-garellorinaudo.html (accessed on 23 November 2024).

Gericke, N., Boeve-de Pauw, J., Berglund, T., & Olsson, D. (2019). The sustainability consciousness questionnaire: The theoretical development and empirical validation of an evaluation instrument for stakeholders working with sustainable development. *Sustainable Development*, *27*, 35–49. https://doi.org/10.1002/sd.1859.

Guo, M., Su, H., & Yue, L. (2020). Ecology-focused aesthetic music education as a foundation of the sustainable development culture. *Interdisciplinary Science Reviews*, *45*, 564–580.

Hallström, J., & Schönborn, K. J. (2019). Models and modelling for authentic STEM education: Reinforcing the argument. *International Journal of STEM Education*, *6*, 22. https://doi.org/10.1186/s40594-019-0178-z.

Holst, J., Singer-Brodowski, M., Brock, A., & de Haan, G. (2024). Monitoring SDG 4.7: Assessing Education for Sustainable Development in policies, curricula, training of educators and student assessment (input-indicator). *Sustainable Development*, *advance online publication*. https://doi.org/10.1002/sd.2865.

Honey, M., Pearson, G., & Schweingruber, A. (2014). *Stem integration in K-12 education: Status, prospects, and an agenda for research*. The National Academies Press.

International Commission on Mathematical Instruction (ICMI). (2025). *The 27th ICMI study: Mathematics education and the socio-ecological discussion document*. ICMI.

KMK. (2016). *Orientierungsrahmen für den lernbereich globale entwicklung. Im rahmen einer bildung für nachhaltige entwicklung. Ein beitrag zum weltaktionsprogramm "bildung für nachhaltige entwicklung"* (2nd ed.). Cornelsen. Available online: https://www.kmk.org/fileadmin/Dateien/veroeffentlichungen_beschluesse/2015/2015_06_00-Orientierungsrahmen-Globale-Entwicklung.pdf (accessed on 15 December 2024).

Maaß, K. (2010). Classification Scheme for Modelling Tasks. *Journal für Mathematik-Didaktik*, *31*, 285–311. https://doi.org/10.1007/s13138-010-0010-2.

Murphy, C., Smith, G., Mallon, B., & Redman, E. (2020). Teaching about sustainability through inquiry-based science in Irish primary classrooms. *Environmental Education Research*, *26*, 1112–1136.

Niss, M., & Blum, W. (2020). *The learning and teaching of mathematical modelling*. Routledge.

Niss, M., Blum, W., & Galbraith, P. (2007). Introduction. In W. Blum, P. L. Galbraith, H. W. Henn, & M. Niss (Eds.), *Modelling and applications in mathematics education. The 14th ICMI study* (pp. 3–32). Springer.

Porst, R. (2000). *Praxis der umfrageforschung (2., überarb. aufl.). Teubner-studienskripten studienskripten zur soziologie*: *Bd. 126*. Teubner. vs. Verlag für Sozialwissenschaften.

Robles Moral, F. J. (2021). Learning about sustainability and SDG with future primary education teachers in initial training. *Social Sciences*, *10*, 409. https://doi.org/10.3390/socsci10110409.

Tilbury, D. (2011). *Education for sustainable development: An expert review of processes and learning*. UNESCO. Available online: http://unesdoc.unesco.org/images/0019/001914/191442e.pdf (accessed on 11 November 2024).

Uitto, A., & Saloranta, S. (2017). Subject teachers as educators for sustainability: A survey study. *Education Sciences*, *7*, 8. https://doi.org/10.3390/educsci7010008.

UNESCO. (2002). *Education, public awareness and training for sustainability: Input to the report of the secretary general to the second preparatory session for the world summit on sustainable development*. UNESCO.

UNESCO. (2017). *Education for sustainable development goals: Learning objectives*. UNESCO. Available online: https://www.unesco.org/en/articles/education-sustainable-development-goals-learning-objectives (accessed on 11 November 2024).

UNESCO. (2020). *Education for sustainable development: A roadmap*. UNESCO Publishing. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000374802 (accessed on 23 November 2024).

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations. Available online: https://sdgs.un.org/2030agenda (accessed on 4 December 2024).

Valderrama-Hernández, R., Sánchez-Carracedo, F., Alcántara Rubio, L., & Limón-Domínguez, D. (2020). Methodology to analyze the effectiveness of ESD in a higher degree in education. *Sustainability*, *12*, 222.

Vásquez, C., & García-Alonso, I. (2020). La educación estadística para el desarrollo sostenible en la formación del profesorado. *Profesorado*, *24*(3), 125–147.

Vásquez, C., Alsina, Á., Seckel, M. J., & García-Alonso, I. (2023). Integrating sustainability in mathematics education and statistics education: A systematic review. *Eurasia Journal of Mathematics, Science and Technology Education*, *19*, em2357.

Vásquez, C., García-Alonso, I., Seckel, M. J., & Alsina, Á. (2021). Education for Sustainable Development in Primary Education textbooks—An educational approach from statistical and probabilistic literacy. *Sustainability*, *13*, 3115. https://doi.org/10.3390/su13063115.

Vásquez, C., Seckel, M. J., & Alsina, Á. (2020). Belief system of future teachers on education for sustainable development in math classes. *Uniciencia*, *34*, 1–15.

Vesterinen, M. (2024). Sustainability competences in environmental education: Research on guidebooks for teachers at Finnish primary schools. *Cogent Education*, *11*, 2286120.

Vesterinen, M., & Ratinen, I. (2023). Sustainability competences in primary school education—A systematic literature review. *Environmental Education Research*, *30*, 56–67.

Wiegand, S., & Borromeo Ferri, R. (2023). Promoting pre-service teachers' professionalism in steam education and education for sustainable development through mathematical modelling activities. *ZDM–Mathematics Education*, *55*, 1269–1282.

Wiegand, S., & Borromeo Ferri, R. (2024). Teaching and learning of education for sustainable development through modelling activities with an integrative teaching approach. In H.-S. Siller, G. Kaiser, & V. Geiger (Eds.), *Researching mathematical modelling education in disruptive/challenging times (ICTMA 20)* (pp. 665–675). Springer.

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*, 203–218. https://doi.org/10.1007/s11625-011-0132-6.

Zandvliet, D. B., & Fisher, D. L. (2007). *Sustainable communities, sustainable environments: The contribution of science and technology Education*. BRILL.