

## Fostering education for sustainable development through mathematics education: A systematic review study

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### Abstract

This systematic review analyzed 68 studies indexed in the Web of Science and Scopus databases to investigate how education for sustainable development is integrated into mathematics education across different contexts and levels. The analysis focused on study characteristics, methodologies, alignment with sustainable development goals (SDGs), and research gaps. Results show a growing interest in the field, especially in the past five years, though further development is needed. Most studies were conducted in European countries which have relatively high environmental performance index scores. Many adopted qualitative methods and included in-service and pre-service teachers as participants, while studies involving students were comparatively limited. Over half of the studies did not explicitly reference specific SDGs. Findings highlight the transformative potential of mathematics education for sustainability: participants showed greater understanding of real-world issues and stronger engagement. This review offers valuable insights for educators and policymakers to strengthen mathematics education's role in achieving the SDGs globally.

**Keywords:** sustainable development, mathematics education, systematic review, SDG, Education for Sustainable Development

### INTRODUCTION

In response to growing concerns about environmental degradation and social inequalities resulting from rapid industrialization and economic expansion, the concept of sustainability emerged in the second half of the 20<sup>th</sup> century and has become increasingly important in contemporary society. Agenda 2030 has been recognized by all 193 United Nations (UN) member states since 2015 and consists of 17 sustainable development goals (SDGs) to be fulfilled. SDGs can be related to mathematics education, as they provide contexts in which critical reasoning, data analysis, and mathematical modelling can be meaningfully applied. For example, SDG 13 (climate action) may be addressed through the analysis and modelling of climate-related data, SDG 12 (responsible consumption and production) through the examination of resource use and efficiency, and SDG 10 (reduced inequalities) through the statistical exploration of social and economic disparities. Within this framework, SDG 4 (quality education) plays a

central role, as it emphasizes inclusive and equitable quality education and lifelong learning as the foundation for achieving all other SDGs (UN, 2015). Sub-goal 4.7, education for sustainable development (ESD), states that schools must also provide education about sustainability. With the ESD framework as defined by the UN (2015), certain goals are also set regarding practical implementation in the classroom in terms of the fulfilment of ESD competencies. This means that it is clear how ESD is characterized; how ESD activities should be designed, based on the proposed criteria; and which ESD competencies should be promoted (UN, 2015). If researchers in mathematics education investigate ESD, then the framework of ESD and its objectives should be considered as comprehensive as possible. Therefore, ESD must also be seen as the theoretical framework on which studies are based. We emphasize this because ESD is a keyword for the search algorithm in our review study.

Research in mathematics education increasingly addressing how issues of sustainability can be taken up

### Contribution to the literature

- This systematic review provides a comprehensive synthesis of 68 studies on education for sustainable development (ESD) in mathematics education across all educational levels, offering an up-to-date overview of a rapidly emerging research field.
- The review reveals that ESD in mathematics education is often addressed implicitly, with limited explicit alignment to the SDG framework, highlighting a critical gap between global sustainability agendas and mathematics education research.
- By synthesizing evidence on learning outcomes, pedagogical practices, and classroom dynamics, the study identifies key research gaps—particularly in curriculum integration, assessment, teacher professional development, and long-term impact—thereby outlining clear directions for future research.

in relation to curriculum, teaching practices, and student learning. Studies point out that engaging with sustainable futures in mathematics education involves how teachers design classroom activities, how students work with real-world contexts, and how mathematical practices such as modelling or data analysis are used to make sense of socio-ecological issues. Recent discussions in the field also stress the importance of reflecting on the roles and responsibilities of different actors in mathematics education when addressing sustainability (Makramalla et al., 2025). Mathematics plays a crucial role in ESD, as many sustainability-related challenges—such as climate change, resource management, population growth, and social inequality—require the interpretation of data, mathematical modelling, reasoning, and critical evaluation of evidence. Through mathematics education, learners can develop competencies necessary to understand complex systems, analyze socio-ecological relationships and make decisions about sustainable futures. Therefore, mathematics is not only a subject that can incorporate sustainability-related contexts, but also a key discipline for fostering ESD competencies. In the literature on mathematics education, however, there are already many theoretical, philosophical, and partly empirical studies that take an ecological and social perspective, as well as focusing on sustainability issues. For instance, Barwell (2013) explored how mathematics can be taught in a way that promotes environmental awareness and sustainability. By integrating ecological concepts into mathematical problems and examples, educators can help students understand the relevance of mathematics to real-world environmental issues. Coles and Helliwell (2023) extended this discussion by examining practical strategies for mathematics teacher education. Similarly, Skovsmose (2023) provided insights into how mathematics teaching practices can be adapted to address socioecological challenges. The aim of these studies and the currently published proceedings of the ICMI-study 27 on mathematics education and the socio-ecological (le Roux et al., 2025) as well as the thoughts of Makramalla et al. (2025) is to shed light on the socio-ecological aspects of doing mathematics.

The present study aims to provide a comprehensive and up to date systematic review of research on ESD in mathematics education. By synthesizing journal articles and conference proceedings across different educational levels, this study seeks to identify dominant research trends, conceptualizations of sustainability, and existing research gaps. In doing so, the study contributes to mathematics education research by offering an overarching framework for understanding how ESD has been addressed in mathematics education and by outlining directions for future research. In this review study, the ESD framework is particularly focused on the learning and teaching of mathematics.

## THEORETICAL BACKGROUND AND RESEARCH QUESTIONS

### SDGs, Education, and Sustainable Development Relationship

According to Kuhlman and Farrington (2010), sustainability is the maintenance of well-being over an indefinite or very long period of time. Although environmental issues are part of this process, 'environment' and 'sustainability' are not synonymous. Sustainability encompasses many economic and social phenomena in addition to the environmental dimension.

The guiding principle of sustainability is to achieve a balance between the three dimensions of sustainability (ecological, economic, and social) as well as intra- and intergenerational justice, according to the UN (2015). Teaching and learning about sustainability, ESD (subgoal 4.7) is the result of political will. It is the responsibility of the education ministries of the countries, educational experts, teacher educators, and teachers to structurally integrate ESD into the school subjects, including mathematics lessons, and also to develop practical examples (Wiegand & Borromeo Ferri, 2023). According to the UN (2015), ESD is characterized as follows:

- (1) Key topics of sustainable development should be included in teaching and learning (e.g., climate change and poverty reduction), which also incorporate the three dimensions of sustainability.

- (2) ESD demands participatory teaching and learning methods that motivate and empower learners to reflect on their behavior and act on (non)sustainable issues.
- (3) ESD should promote competencies such as critical thinking, imagining future scenarios, and making decisions cooperatively.

Moreover, the three core competencies of ESD, recognizing, evaluating, and acting, should also be focused on (de Haan, 2002; Schreiber & Siege, 2016; Vorhölter et al., 2025). In addition to the definition and competencies to be promoted, the following ESD criteria (e.g., de Haan, 2002) form an excellent basis for the development of “ESD-mathematical tasks.” ESD-oriented teaching should meet certain ESD criteria to convey (non)sustainable thinking and action. Thus, an ESD topic or activity must be a central, local, and/or global topic for sustainable development processes with long-term significance, an interdisciplinary approach, and potential for action. The aim is to develop visions and provide creative solutions while demanding participatory, inter- and transdisciplinary teaching and school culture. During the ESD activity, learners must also be encouraged to adopt a “first-person perspective” to be able to formulate precisely these visions and options for action. To become more specific about what this means and to concretize the ESD definition, competencies, and criteria mentioned, the following ‘ESD-modelling task’ should be considered (Borromeo Ferri & Wiegand, 2023). This task was developed within an ESD-modelling seminar at university. In this task, learners model the energy consumption involved in transporting aluminum from the country where the raw material is extracted and processed, to the country where electric vehicles are manufactured. Using assumptions and data-based estimations, learners apply basic mathematical models to calculate the energy needed for transportation and related processes in this production chain. Through this example, pre-service teachers experience the relevance of mathematics in analyzing global supply chains and engaging in fact-based discussions about sustainability. Teacher competencies are crucial for developing students’ skills and knowledge, and these competencies must be acquired by teachers during teacher training. In this respect, the skills and dispositions of prospective teachers need to be analyzed to determine how they can acquire these skills and how teaching can be better designed to help students develop these skills (Häkkinen et al., 2020). Sustainability is becoming an increasingly important issue, and schools, as educational institutions, play a crucial role in the process of sustainable development (UNESCO, 2002). To effectively implement ESD in the future, it is important to equip educators and learners, particularly in mathematics classrooms, with both the requisite expertise and appropriate instruction (Wiegand & Borromeo Ferri, 2023).

## Mathematics Education and Sustainable Development

Mathematics plays a central role in everyday and professional lives, as well as in answering real, relevant questions that children and young people ask themselves, such as climate and environmental protection in ‘Fridays for future’ (<https://fridaysforfuture.org/>). Mathematics also involves solving real-world problems using mathematical models. This includes fostering and understanding the natural world and our interconnectedness with it, cultivating a critical perspective on progress and technological advancement, and tackling complex problems through systems thinking approaches (Borromeo Ferri, 2018). This was demonstrated using an ESD-modelling problem as an example in the previous section.

The SDGs, which provide a roadmap for addressing global challenges, emphasize science, technology, engineering, arts, and mathematics (STEAM) expertise, of which mathematics education is a part. STEAM education has gained importance with ESD, which emphasizes integrating sustainable development principles into teaching and learning. Mathematics education is an important part of STEAM education and provides powerful opportunities for problem solving, critical thinking, modelling, and realizing sustainability goals in education (Siller et. al, 2025; Wiegand & Borromeo Ferri, 2023).

Sustainability principles have been incorporated into various preservice teacher education disciplines, such as language and science education (Sleurs, 2008; Wals, 2014, 2020). However, education for sustainability studies in STEAM fields, especially in science, stand out (Eilks, 2015; Kumar et al., 2023; Kyle, 2020); there is a notable gap in the literature when it comes to exploring the intersection of mathematics education, sustainability, and ESD. A nationwide analysis in Germany conducted by Holst and Brock (2020) highlighted a significant trend: educational methods designed to tackle practical ESD tasks frequently originate from subjects such as biology, geography, ethics, and political science. These subjects have a rich history of engaging with environmental and global learning topics, allowing them to effectively integrate ESD principles into their curricula. This longstanding tradition contrasts with the relatively recent efforts to position mathematics within the ESD framework, thereby emphasizing the importance of promoting mathematics as a key discipline in this context. This phenomenon is, of course, not unique to Germany. Similar trends can be observed worldwide. For example, in the USA, education systems have traditionally focused on subjects such as science and social studies to deliver ESD content (Feinstein & Carlton, 2012). Although sustainability issues have predominantly been addressed in science courses (Vasconcelos & Orion, 2021;

**Table 1.** Truncated search terms

Database	Search Terms
WoS core collection	Math* (Topic) AND ((mathematics education OR mathematics teaching OR mathematics learning (All fields)) AND ((sustainable development OR education for sustainable development OR education for sustainability OR ESD (Topic)))
Scopus	(ABS OR TITLE OR KEYWORDS (mathematics education OR mathematics teaching OR mathematics learning) AND (sustainable development OR education for sustainable development OR education for sustainability OR ESD))

Zidny et al., 2020), mathematics courses offer unique opportunities for ESD, such as in mathematical modelling. Sustainable mathematics education transforms math teaching to prioritize environmental awareness and sustainable practices, making it a crucial and inevitable initiative (Renert, 2011). Yet there is a scarcity of research that delves into the pivotal role of mathematics education in empowering learners to devise innovative solutions to sustainable development challenges efficiently (Alsina & Mulà, 2019). The purpose of this study is to present the current state of the literature addressing sustainability goals in mathematics education.

### Aim of the Study and Research Questions

Expanding on the theoretical frameworks mentioned earlier to conceptualize sustainable development in mathematics education, we conducted a comprehensive review of the existing literature within the field of mathematics education. Although there have been some systematic reviews of sustainable development in various educational fields (González-Salamanca et al., 2020), only one study has specifically focused on sustainable development in mathematics education, concentrating on studies in mathematics teacher education (Su et al., 2023). Su et al. (2023) conducted an exclusive study on mathematics teacher education, analyzing 16 articles. However, the exclusion of conference papers may result in a limited perspective, particularly considering potential publication biases in journals. Therefore, it is crucial to incorporate conference proceedings into a systematic literature review to capture the most recent experimental work in the field. Currently, there is a lack of comprehensive reviews across all levels of mathematics ESD. Our systematic review includes 68 studies and aims to address this gap in the scientific literature, offering a comprehensive and updated perspective on the interplay between sustainable development and mathematics education. This effort is expected to contribute to the advancement of knowledge in this particular field of study. This systematic review addresses the following research questions:

1. What are the general characteristics of the reviewed studies (e.g., methodologies, participants, data collection tools, domains, publication years, citation scores, authors'

countries of origin, and digital tools used in the studies)?

2. What are the SDGs, content domains (economic, social, and ecological), and issues reported in the reviewed studies?
3. How does mathematics education for ESD influence learning content and outcomes, classroom dynamics, and pedagogical practices?
4. What are the research gaps in the context of ESD in mathematics education, as reported in the reviewed studies?

The following section describes the methodology used for the systematic review. The paper concludes with a comprehensive discussion of the research based on the current review and offers an outlook for future research trends using the ESD framework in mathematics education.

## METHODOLOGY

### Search Strategies

To address the research questions and achieve the main aim of the study, a systematic approach to reviewing the literature according to the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines was used (Moher et al., 2009). The associated search was conducted on 28 February 2025 using the Web of Science (WoS) and Scopus databases. We selected these electronic databases because of their

- (1) high-quality indexing standards,
- (2) excellent international reputations, and
- (3) inclusion of studies on mathematics education.

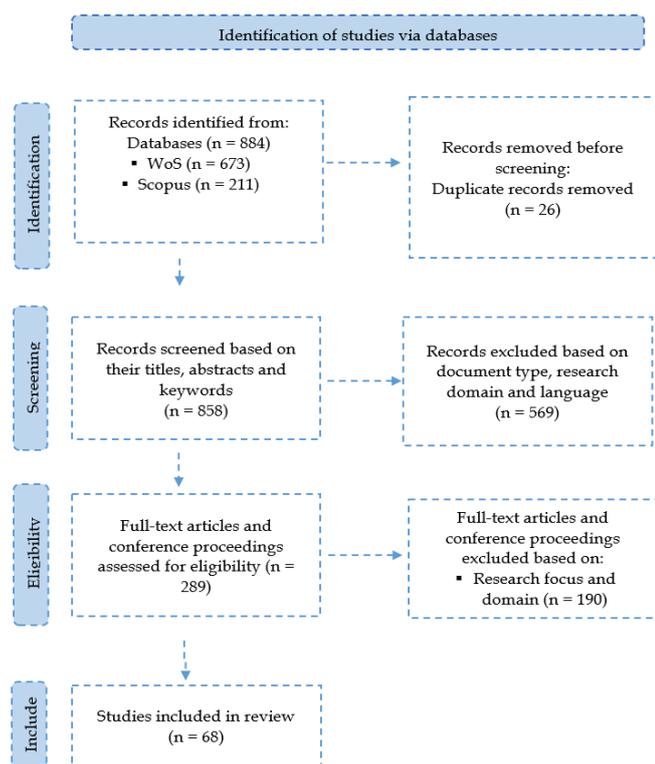
To capture as many potentially relevant mathematics education studies on ESD as possible, we developed diverse search strings to identify selected terms in the articles' titles, abstracts and keywords using the following truncated search terms (Table 1).

### Article Selection Procedure

We selected peer-reviewed research articles and conference proceedings on mathematics education published in English, focusing on ESD. The review focused on studies reporting original research data and excluded editorials, book chapters, books and review articles. This decision was made because such document

**Table 2.** Article selection criteria

Category	IC	EC
Domain	Studies conducted in the field of mathematics education	Studies conducted in a discipline other than mathematics education
Focus	Studies focusing on education for sustainable development and reporting original research data and results	No focus on education for sustainable development and studies not reporting original research data (e.g., books, review articles, editorials)
Publication year	All time periods	
Document type	Peer-reviewed research articles and conference proceedings (reporting original research data)	Papers other than peer-reviewed research articles and conference proceedings
Language	Articles written in English	Articles written in a language other than English
Database	WoS or Scopus	Studies indexed in a database other than WoS and Scopus



**Figure 1.** Search strategy flow diagram (Source: Authors' own elaboration)

types often do not report original research data or provide sufficient methodological detail regarding research setting and implementations, which may limit the depth and comparability of analysis. By focusing on primary research studies, we aimed to ensure a rigorous and transparent synthesis of data-based finding. Moreover, the review covered all publication years in order to capture the development of the field over time, as mathematics ESD is still an emerging research area.

The article selection process was based on the four main components of the PRISMA guidelines:

- (1) identification,
- (2) screening,
- (3) eligibility, and
- (4) inclusion (Moher et al., 2009).

First, the search strings in **Table 1** were used to search for related literature in the aforementioned two databases, and 884 articles were identified. Duplications (26 records) were removed using EndNote X9 bibliographic software before the screening phase. Six identified inclusion criteria (IC) and six exclusion criteria (EC) (**Table 2**) were used to frame the screening and eligibility phases.

First, the authors carefully examined 884 studies' titles, abstracts and keywords based on the pre-defined IC and EC and excluded 569 papers based on document type, research domain and language. The full-text analysis of 289 papers yielded 68 eligible papers. **Figure 1** shows the flow diagram for the article selection process and the list of studies included in this review represented in the references with an asterisk.

### Data Analysis

For the data analysis, the authors reviewed the full texts of 68 eligible articles and conference proceedings and then conducted a coding process based on qualitative content analysis (Miles & Huberman, 1994) by adopting the coding scheme developed by Cevikbas and Kaiser (2022). This coding scheme provides a structured approach to systematically arranging and classifying data extracted from research papers. It encompasses various sections, including the authors' names, publication year, countries of origin of the authors, details about the sample, research methodology and journal source. The coding scheme was also adopted for analyzing the sustainable development content, pedagogical content, learning outcomes and type of technologies used in the studies. The categories associated with research question 3 and research question 4 were developed inductively through open coding, as these aspects were not predefined, but rather emerged in response to patterns identified in the data. The second researcher coded each of the 68 studies separately, and the analysis employed the following four main categories that addressed the research questions:

- (1) the general characteristics of the studies,
- (2) SDGs, perspectives and issues reported in the studies,

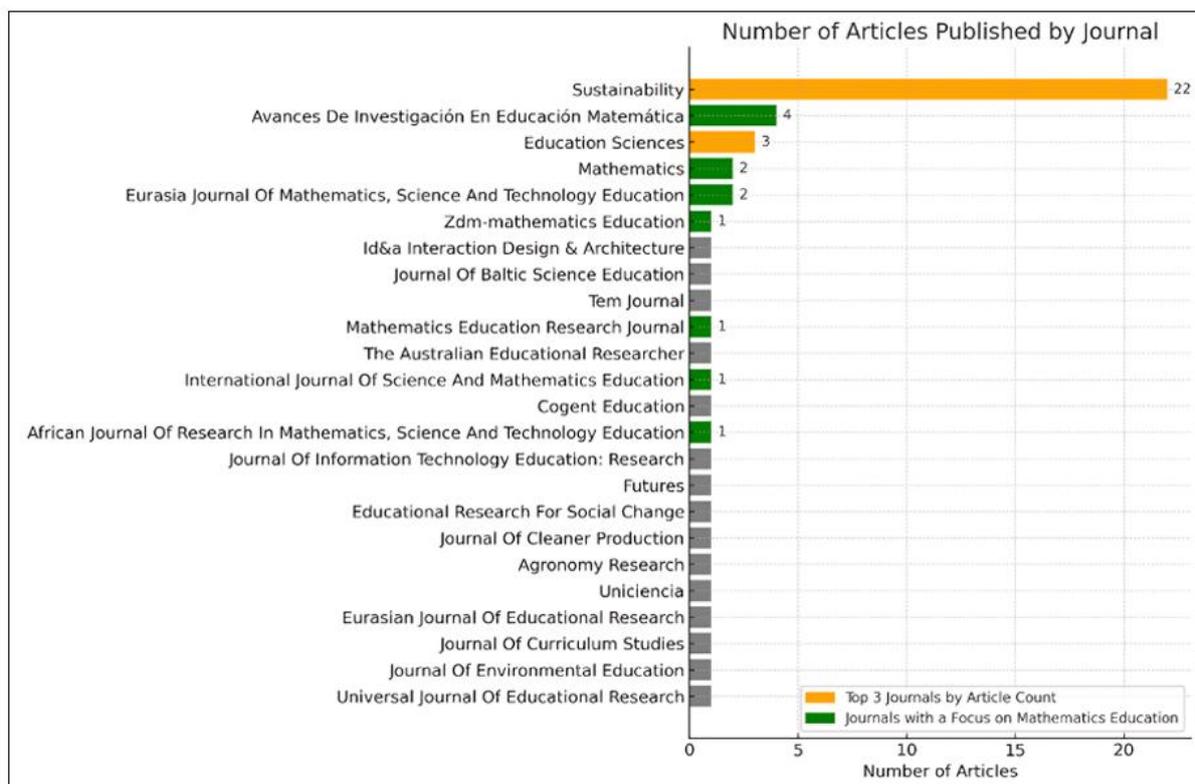


Figure 2. Source of publication (Source: Authors' own elaboration)

- (3) learning content, outcomes, classroom dynamics and pedagogical methods used in mathematics education for ESD, and
- (4) research gaps that are reported in the studies in the field of mathematics ESD.

Based on our key results, we discussed the potential of mathematics education for improving sustainable development. After completing the coding procedure, 15% of the studies ( $n = 10$ ) were randomly selected, and another researcher with a PhD in mathematics education evaluated the chosen studies using the same criteria. We calculated coding reliability based on Miles and Huberman's (1994) reliability formula by dividing the number of agreements by the total number of agreements plus disagreements. The calculations generated a satisfactory reliability rate of 0.91 (Creswell, 2013).

## RESULTS OF THE STUDY

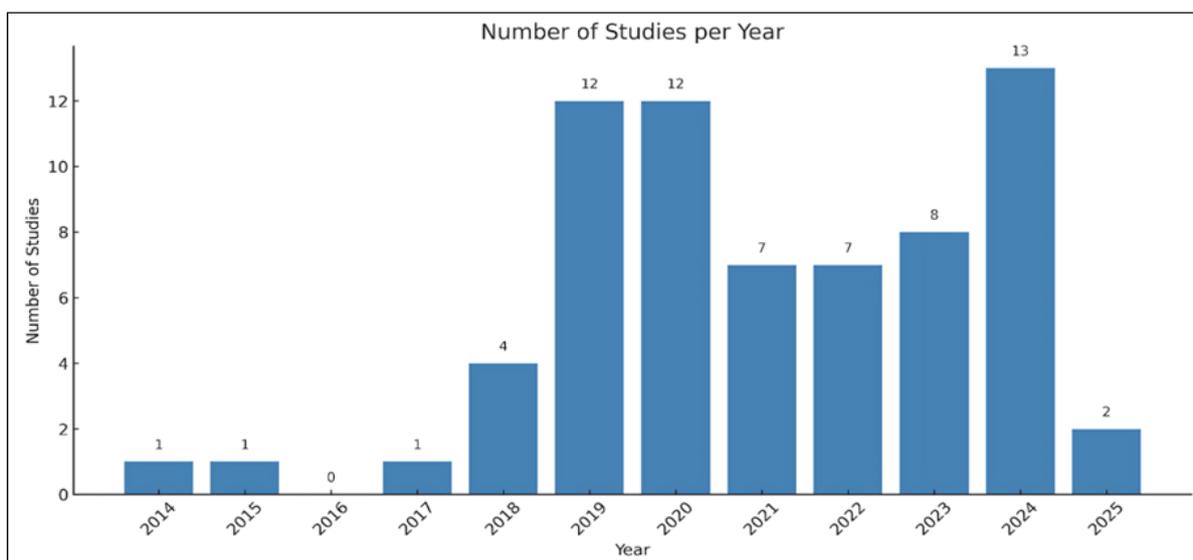
This section provides the answers to the research questions by reporting the findings of 68 studies published on sustainable development in mathematics education, including all times until March 2025. A structured summary initiates the overview by detailing the general characteristics of the included studies, the SDGs they address, the content domains they cover, and the issues they discuss. This is followed by a presentation of the key findings.

### General Characteristics of the Included Studies

To address research question 1, we summarize the general characteristics of the 68 included studies. These characteristics include publication type and year, geographical distribution, citation ranking, research method, data collection tool, digital tool and sample characteristics.

#### *Distribution of the studies: Document type, publication year and journal*

The 68 studies included in this study consisted of 52 articles (76%) and 16 (24%) conference papers. The eligible articles were published in 24 scientific journals, including 4 mathematics education journals; 1 mathematics and science education journal; 1 science journals, 14 interdisciplinary journals in the fields of science, technology, engineering, and mathematics (STEM) education and educational sciences, 1 journal in the field of engineering and 3 journals in the field of sustainability. The reviewed articles published in mathematics education journals constituted only 15% of all reviewed articles ( $n = 8$ ). In addition, 4 more articles were published in interdisciplinary journals with a particular focus on mathematics education. In total, 12 articles (24%) were published in journals that were published in the field of mathematics education. Regarding conference proceedings, almost all eligible papers came from engineering-focused conferences ( $n = 12$ ), 3 proceedings from physics conferences and one proceeding from e-learning conference, while no papers



**Figure 3.** Number of studies published by year (Source: Authors' own elaboration)

came from mathematics education conferences. The majority of articles were published in *Sustainability* ( $n = 22$ , 42%), which is an open access journal on humankind's environmental, cultural, economic and social sustainability, published online by MDPI (**Figure 2**).

In our study, the predominance of publications in the journal *Sustainability*, with its focus on sustainability, underscores the importance of disseminating research on ESD within mathematics education journals. This emphasis is crucial for reaching mathematics educators and teachers directly, fostering their interest and engagement in integrating sustainability into their teaching practices. The presence of only three mathematics education journals and totally 7 articles in these journals highlights the need for more concerted efforts to bridge sustainable development initiatives with mainstream mathematics education literature, ensuring broader visibility and impact among educational practitioners.

To determine how sustainable development content in mathematics education has developed over the years, all periods up to March 2025, the date of the research data collection, were included in the search. **Figure 3** shows the distribution of the reviewed studies according to their publication year. Although there is no year limit for the studies, there has been an increase in studies on sustainability in mathematics education since 2014. This may be due to the Rio+20 meeting in 2012, where it was agreed to focus on priority areas for sustainable development and to work on a process to set global SDGs for both developed and developing countries (IISD, 2012).

The 2030 agenda, agreed in 2015 and 2016, and the sustainability goals, which have gained popularity in mathematics education as in many other fields (Alvino et al., 2021), seem to be on a downward trend from the

end of 2020. On the one hand, this may be due to the impact of the COVID-19 pandemic, the war in Ukraine in Europe, which may have pushed sustainability concerns further down the list of priorities, or the increase in inflation and resulting financial hardships for citizens in various countries. The upward trend observed in 2023 continued into 2024, which recorded the highest number of studies to date. The apparent decline in 2025 is likely due to the data set covering only the first two months of the year. All eight studies published in journals specifically focused on mathematics education were produced within the last five years. This highlights an increasing effort to connect mathematics education with sustainability goals, showing that the field is gaining prominence in current educational discourse (Alvino et al., 2021; Ranjbari et al., 2021; Su et al., 2023). Although the number of studies has shown a marked increase, particularly in the past five years, it is also important to highlight that the field still requires further support and development.

### *Geographical distribution*

An analysis of the country affiliations of all 190 authors was carried out to assess the global perspective reflected in researchers' contributions to the topic of ESD in mathematics education. Our analysis revealed a wide range of contributors to this field, with authors representing 37 different countries (**Figure 4**). The values shown on the world map in **Figure 4** indicate the number of studies originating from each country. The reason why the total number of studies is more than 68 is that some studies were co-published by researchers from different countries and continents and, therefore, counted twice. Research on sustainable development in mathematics education was mostly conducted in European countries ( $n = 45$ , 51%), followed by Asia ( $n = 20$ , 23%), South America ( $n = 8$ , 9%), North America ( $n = 7$ , 8%), and Africa ( $n = 5$ , 6%). Three studies were

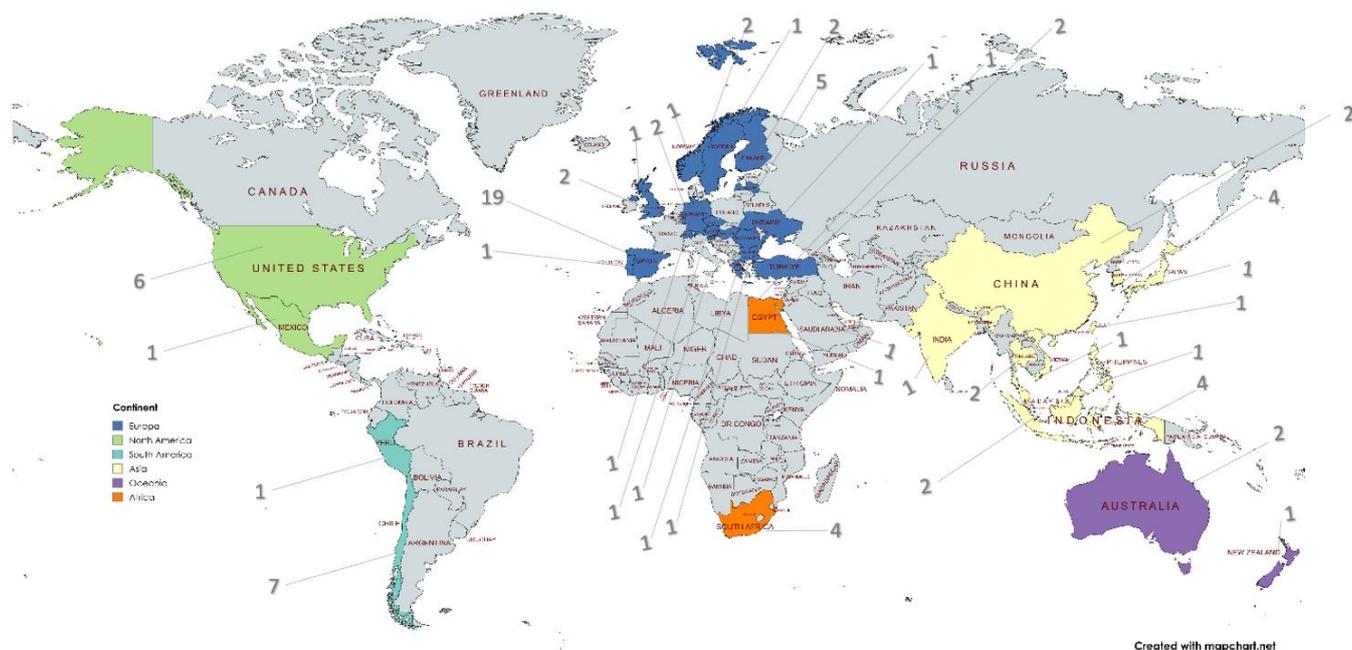


Figure 4. Geographical distribution of publications (Source: Authors' own elaboration)

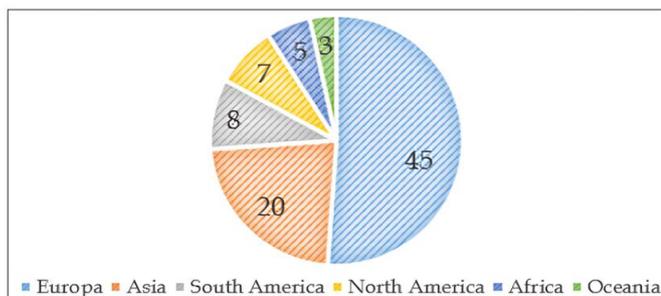


Figure 5. Number of studies within the continents (Source: Authors' own elaboration)

conducted in Oceania (3%). Spain was the leading country in Europe for publishing research related to sustainable development in mathematics education ( $n = 13$ ), followed by the USA ( $n = 7$ ) and Chile ( $n = 7$ ) and Latvia ( $n = 5$ ). Korea, Indonesia and South Africa contributed four studies each to the literature.

To assess the global perspective of the researchers' contributions to sustainable development in mathematics education, a study of all 190 authors' nation connections was conducted. The vast majority ( $n = 46$ , 24%) of the 190 authors associated with the studies were from Spain, followed by the USA ( $n = 19$ , 10%), Indonesia ( $n = 13$ , 7%), and Chile and Latvia ( $n = 10$ , 5%). Author affiliations show similar results to country affiliations.

The results on geographical distribution showed that researchers from different countries and continents have contributed to research on sustainability in mathematics education. The geographical distribution of studies is important, as it reflects research trends by continent and country. More than half ( $n = 45$ ) of the studies on sustainability in mathematics education were conducted in the European continent (Figure 5).

The countries that invest the most in the field of sustainability and have maximum number of studies in this field are in the European continent. Europe has the highest environmental performance index (EPI, 2022), which is also reflected in sustainability studies in the field of mathematics education. Similarly, most of the authors are of European origin, followed by Asia and America.

The distribution of research on sustainability in mathematics education shows varying regional priorities. Europe and Asia, where studies are more concentrated, are likely have educational systems that emphasize integrating sustainability into mathematics teaching. This regional focus suggests that educators in these areas may lead in incorporating environmental issues into curricula, potentially influencing global educational practices. However, the lack of research from other continents underscores a need for broader inclusivity and collaboration to promote sustainability in mathematics education worldwide.

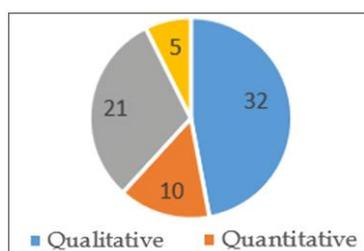
#### Citation ranking of the studies

In a systematic literature review, including citation rankings is essential because it offers a quantitative assessment of how widely a study has been referenced by other researchers. This not only helps evaluate the scholarly impact and relevance of the reviewed studies but also provides insights into the evolution of research trends and the enduring influence of seminal works within the field (Lin et al., 2025). To provide an overview of the impact of the articles analyzed within the scope of the research on subsequent scientific publications, the list of the 5 most cited articles is presented in Table 3. These articles received 660 citations in total.

**Table 3.** Citation rankings

No	Article	CS
1	Nguyen, T. P. L., Nguyen, T. H., & Tran, T. K. (2020). STEM education in secondary schools: Teachers' perspective towards sustainable development. <i>Sustainability</i> , 12(21), Article 8865.	171
2	Hsiao, P. W., & Su, C. H. (2021). A study on the impact of STEAM education for sustainable development courses and its effects on student motivation and learning. <i>Sustainability</i> , 13(7), Article 3772.	149
3	Manasia, L., Ianos, M. G., & Chicioreanu, T. D. (2019). Pre-service teacher preparedness for fostering education for sustainable development: An empirical analysis of central dimensions of teaching readiness. <i>Sustainability</i> , 12(1), Article 166.	146
4	Alsina, Á., & Mulà, I. (2019). Advancing towards a transformational professional competence model through reflective learning and sustainability: The case of mathematics teacher education. <i>Sustainability</i> , 11(15), Article 4039.	116
5	Zizka, L., McGunagle, D. M., & Clark, P. J. (2021). Sustainability in science, technology, engineering and mathematics (STEM) programs: Authentic engagement through a community-based approach. <i>Journal of Cleaner Production</i> , 279, Article 123715.	78

Note. CS: Citation score



**Figure 6.** Research methods of the studies (Source: Authors' own elaboration)

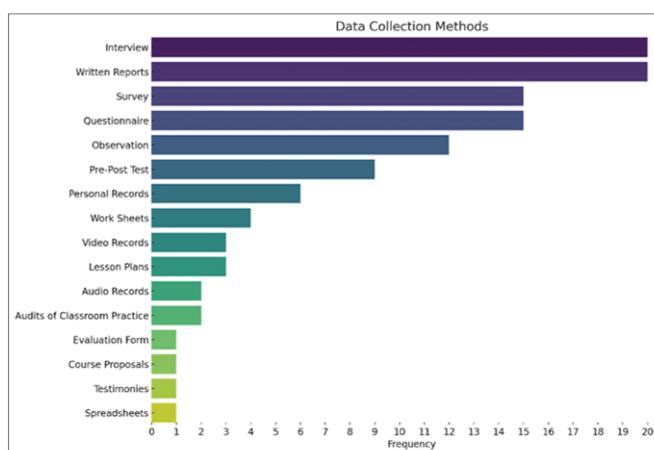
Four out of the five most cited articles are in the fields of STEAM and STEM, yet they also maintain a focus on mathematics education. Only one study among them is conducted exclusively within the domain of mathematics education. This trend may indicate that research on sustainability is particularly favored by scholars working in interdisciplinary areas, especially within the STEM fields.

### Research methods, data collection, and digital tools

Our analyses show that almost half of the studies (47%,  $n = 32$ ) used qualitative research methods (e.g., case study and content analysis). This was followed by mixed methods (31%,  $n = 21$ ), which involved both quantitative and qualitative research methods. Ten of the analyzed studies followed quantitative methods (e.g., experimental, quasi-experimental, survey, and correlational survey models) (15%). Among the eligible studies, 5 (7%) used design-based research (Figure 6).

Various data collection methods were used in the analyzed studies, with non-standardized test instruments being the most frequently used (Figure 7). Interviews and written reports were the most frequently used data collection tool (29%,  $n = 20$ ), followed by surveys and questionnaires (22%,  $n = 15$ ), observation (18%,  $n = 12$ ) and pre-post-tests (13%,  $n = 9$ ).

As technology develops rapidly, it also plays an important role in educational environments. Despite its potential to offer unique opportunities in the teaching of



**Figure 7.** Data collection methods (Source: Authors' own elaboration)

sustainability, innovative teaching technologies have not played a significant role in the reviewed research. Around two-thirds of the reviewed studies (65%,  $n = 44$ ) did not employ any form of digital tool in their design or implementation. In the studies where digital tools were used, learning management tools ( $n = 13$ ), mobile and smart devices ( $n = 5$ ) and multimedia content ( $n = 5$ ) were mostly utilized. Technological tools such as digital games, flipped or blended learning and GeoGebra or virtual environments were each used in three studies (Table 4). Across the reviewed studies, digital technologies were primarily used as supportive instructional tools rather than as central components for fostering ESD competencies. Most studies reported technology use in terms of facilitating content delivery, student engagement, or classroom management, while few explicitly examined how digital tools contributed to students' understanding of sustainability concepts or to the development of ESD-related competencies.

### Sample characteristics and course domain

In this review, to categorize the study participants, we considered the authors' reports on sample characteristics. The analysis indicated that a significant

**Table 4.** Digital tools

Digital tool category	Included tools	TF
Learning management tools	Web Portal, Edmodo, Padlet, Excel	13
Mobile and smart devices	Computers, Tablets, Smartphones, Robot Mouse Colby, M Bot, Makey Makey, Ozobot	5
Multimedia content	Social Media Content (Facebook, YouTube Videos), Videos	5
Game-based tools	Digital Games	3
Instructional models	Blended Learning, Flipped E-Learning	3
Interactive/simulated environments	GeoGebra, Virtual Environment	3

Note. TF: Total frequency

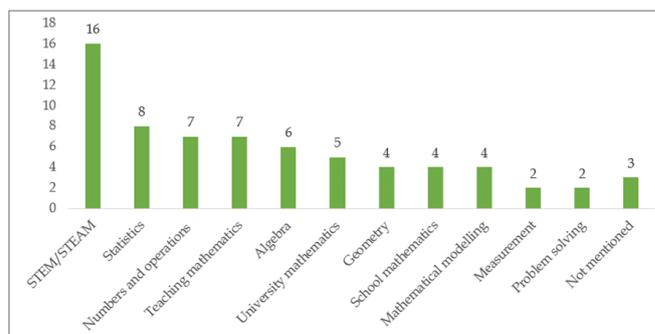
**Table 5.** Characteristics of participants

Category	Sub-category	n
Sample	Pre-service teachers	18
	In-service teachers	14
	Secondary school students	9
	Primary school students	5
	Undergraduate students (non-PST)	9
	Informal education and academics	3
	Non-human subjects (documents)	10
Sample size	1-100	38
	101-500	10
	501-1,000	4
	Not mentioned	6
	Document	10

portion of the examined studies (47%, n = 32) involved the recruitment of in-service and/or pre-service teachers.

Additionally, 13% (n = 9) utilized samples of undergraduates, including students from engineering, statistics, educational sciences. Approximately 13% (n = 9) of the studies concentrated on samples comprising secondary school students, while 7% (n = 5) focused on primary school students. This research defines primary education as corresponding to both pre and primary school levels. The remaining ten studies (15%) were not applicable to this categorization, as they did not involve participant-based data. However, we considered the analysis of mathematics curricula and textbooks in relation to sustainability concepts as valuable contributions to the research field. Therefore, these document analysis studies were also included in the review. The distribution of participants across the reviewed studies is illustrated in **Table 5**.

The higher emphasis on in-service and pre-service teachers as well as the lower incidence of studies involving primary school students aligns with earlier reviews (Su et al., 2023). Besides the importance of introducing sustainability at an early stage of education, the elementary school curriculum is already rich with a variety of topics in this area. Due to the scarcity of established methodologies and practical examples linking mathematical concepts directly to sustainability themes, there is a notable challenge in effectively integrating mathematics with sustainability goals at this level (Bulut & Borromeo Ferri, 2025). Most of the studies



**Figure 8.** Main content domains within mathematics education (Source: Authors' own elaboration)

involved a relatively small sample size, with fewer than 100 participants (56%, n = 38) (**Table 5**).

As expected, the STEM and STEAM fields emerged prominently in relation to sustainable development in mathematics education. Of the 68 articles analyzed, the most prevalent were those related to STEM/STEAM (24%, n = 16), followed by the statistics domain (12%, n = 8). The distribution included seven studies each in mathematics teaching and in numbers and operations. Furthermore, there were six studies in mathematical modelling, five in university mathematics and four in each of geometry, school mathematics and mathematical modelling. There are two studies for each of the measurement and problem-solving areas. Three studies did not mention any content domains. **Figure 8** provides an overview of the characteristics of the reviewed studies, which were conducted across 11 domains in mathematics education.

### SDGs, Content Domains, and Issues

Regarding research question 2, we report which SDGs, sustainability content domains (ecological, social, and economic), and sustainability-related issues are addressed across the reviewed studies. Even though all analyzed studies addressed sustainability, a majority (53%, n = 36) did not specify addressing any of the 17 sustainability goals. Only 32 studies (47%) identified sustainability goals, with 22 studies (32%) concentrating on SDG 4, 'ensure inclusive and equitable quality education and promote lifelong learning opportunities for all'. Following this, 16 studies (24%) focused on SDG 13, 'climate action'. There were 12 studies related to SDG

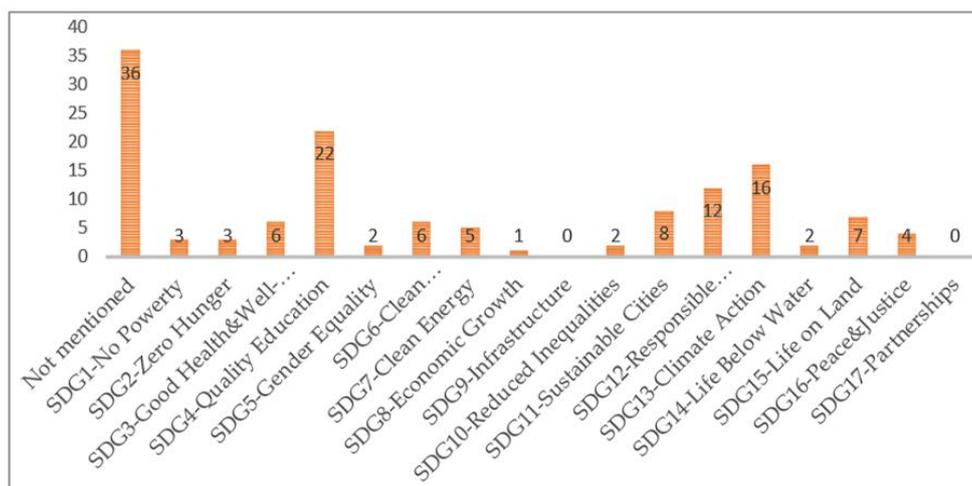


Figure 9. Targeted SDGs (Source: Authors' own elaboration)

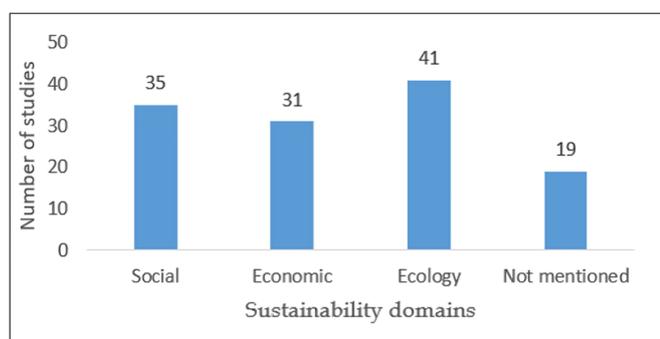


Figure 10. Targeted sustainability content domains (Source: Authors' own elaboration)

12 ‘responsible consumption and production’ and eight studies on SDG 11 ‘sustainable cities and communities’. A total number of 11 studies were representing SDG 6 “clean water and sanitation” and SDG 7 “affordable and clean energy”. Figure 9 represents the distribution of the targeted SDGs.

While most studies mentioned only one SDG, a few explored multiple goals simultaneously. In total, seven SDGs (SDG 1, 2, 5, 8, 10, 14, and 16) were each represented by a small number of studies ( $n < 5$ ). SDG 9 (industry, innovation, and infrastructure) and SDG 17 (partnerships for the goals) were not addressed in any of the analyzed studies. These findings are noteworthy, as most studies investigated ESD without explicitly referring to specific SDGs. However, the ESD framework naturally connects with the SDGs, especially in studies that aim to raise learners’ awareness and involvement in sustainability issues. The absence of explicit SDG references in more than half of the studies suggests that sustainability in mathematics education is often addressed implicitly through contextual themes rather than through direct alignment with individual SDGs. Moreover, although education is central to ESD, the limited explicit focus on SDG 4 indicates a gap between global policy frameworks and their explicit uptake in mathematics education research.

We evaluated the 68 studies in our research not only according to whether they stated sustainability goals but also according to sustainability content domains. Figure 10 shows the distribution of the analyzed studies according to the SDG content domains. Although 53% of the studies did not specify any sustainability goals, a lower percentage of the studies did not specify a sustainability domain (28%,  $n = 19$ ). Forty-one studies had an ecology domain (60%). This is followed by the social domain with 35 studies (51%), economic domain with 31 studies (46%). Although the total number of studies exceeds 68, this is because some studies address more than one sustainability domain and were therefore counted multiple times. Due to its strong connection with numerical reasoning and mathematical calculations, the economic domain could be expected to be the most closely related to mathematics. However, findings reveal that it is the least represented domain among the review studies. In contrast, the ecology domain is leading. This emphasis may stem from the fact that sustainability in education is often approached through environmental and ecological awareness.

Among the topics addressed in the studies, the prominent ones are as follows: waste management and recycling; litter and pollution; protection of nature and natural resources; efficient use of resources; climate; global supply chain; water, food and energy consumption; rainforests; water consumption; health; education and poverty.

### Findings Related to Learning, Teaching, and Pedagogical Practices

For research question 3, we synthesize how mathematics education for ESD is reflected in learning content and outcomes, classroom dynamics, and pedagogical approaches reported in the reviewed research. In the forthcoming section, we outline the primary findings from our analysis of 68 reviewed studies on promoting sustainable development through

mathematics education. Our examination leads to 6 subcategories.

### *Awareness of sustainability*

According to the literature, there is a significant lack of understanding of the term 'sustainability' among younger generations (Coutts et al., 2022; Isler Baykal & Karaarslan Semiz, 2020). Nevertheless, there is a perceived importance of sustainability, particularly among younger people (Coutts et al., 2022). In another study, pre-service mathematics teachers demonstrated awareness of the concept of sustainability, with challenges in providing a comprehensive definition (Isler Baykal & Karaarslan Semiz, 2020). ESD is crucial to ensure citizens' commitment to the SDGs in the 21<sup>st</sup> century. The primary responsibility for this lies with the teachers and trainers of future teachers. However, current curricula lack a focus on the comprehensive development of ESD (Vásquez et al., 2022).

Recent studies further emphasize that awareness of sustainability in mathematics education among teachers and students remains limited and largely implicit. For example, teachers who participated in statistical education programs recognized the importance of linking mathematics to real-life environmental and social issues, yet they demonstrated only a limited conceptual understanding of sustainability and the SDGs (Vásquez et al., 2023).

Similarly, in-service teachers in Chile recognized the potential of integrating sustainability with mathematical content such as ratios, geometry and statistics, but mostly associated sustainability with ecological awareness (Alsina & Vásquez, 2025). Despite this limited perspective, they demonstrated a significant interest in incorporating ESD principles into mathematics education and expressed a willingness to encourage their students to engage in contextualized problem-solving processes related to local sustainability issues such as water scarcity and waste reduction.

Another study of teachers showed that, although they believed that real-life contexts were the best way to connect to the SDGs, they still struggled to implement them in practice (Franco Seguí et al., 2024).

The findings underline a dual challenge: while the significance of sustainability is widely recognized by learners and educators, there is a significant gap in understanding and practical application of sustainability concepts in mathematics education.

### *Ethical and pedagogical approaches*

According to Wiegand and Borromeo Ferri (2023), mathematics tasks related to sustainability are engaging for students, aligning with their life experiences, prompting reflection on personal experiences, and supporting future-oriented sustainable perspectives. The study collected reflections from 14 pre-service math

teachers on the link between mathematical modelling and ESD through concrete lesson examples. Using a case study on Brazil's e-mobility and aluminum industry, they explored economic, ecological, and social impacts. The participants then created modelling tasks for secondary school students, using digital tools and internet resources to show how modelling promotes ESD by addressing real-world sustainability issues. The study reported increase in understanding, critical thinking, and practical application of mathematics to social issues.

Integrating sustainability into the curriculum provides concrete examples which can be applied in mathematics teaching. Recognizing that sustainable development issues provide authentic data for meaningful mathematical problems and that mathematical models can be used to describe, predict and communicate aspects of sustainability (Isler Baykal & Karaarslan Semiz, 2020) is important. The discussion underscores that many daily life problems and situations require some understanding of mathematics to be properly understood and solved (Kopeika & Zvirgzdina, 2020). The teaching methodology within ESD in mathematics education is an important tool for demonstrating the application of theoretical knowledge to concrete examples. According to Martín-Sánchez et al. (2022), teaching methodology and strategies play a significant role in acquiring curricular competencies and sustainability awareness.

Recent studies extend these insights by incorporating ethical, interdisciplinary and real-world perspectives into mathematics education. Some research directly links mathematics education and sustainable development, particularly addressing the ethical aspects of issues such as climate change and environmental sustainability (Hauge, 2024). These studies use real school projects involving sustainability topics in math lessons, such as sustainable clothing, traffic safety, and oil consumption. They emphasize the incorporation of ethical considerations, values and social responsibility in mathematical problem-solving. Students engage in authentic discussion and democratic decision-making processes, recognizing how values are embedded in mathematical reasoning.

Some studies have reported the benefits of technology as a means of teaching math for ESD (Karjanto & Acelajado, 2022; Román-Graván et al., 2020; Sharma & Ali, 2018). For example, students successfully applied their mathematical, creative and technological skills to analyze the social, economic and environmental aspects of sustainability through social media content (Saimon et al., 2023). Similarly, using gamified digital environments such as Minecraft enabled students to explore renewable energy concepts by applying area, perimeter and spatial reasoning to design and optimize wind farms and solar parks (Kersanszki et al., 2024). The flipped classroom pedagogy (FCP) is highlighted as an

active-learning, student-centered, flexible and multidimensional approach for promoting ESD in mathematics education (Karjanto & Acelajado, 2022). Compared to traditional paper-based methods, students showed better performance in learning about environmental protection, understanding a lean business plan and creating one when utilizing mobile devices, such as tablets and smartphones. This improvement was observed in terms of learning outcomes as well as in the intensity and duration of concentration (Pajk et al., 2021).

A successful implementation of ESD in school mathematics requires the reconstruction or reorientation of the mathematics curriculum (Kim & Pang, 2022). Focus on problem-solving using mathematical concepts offers students opportunities to recognize environmental issues and contemplate sustainable development. Challenges may arise in connecting certain aspects, such as human rights, gender equality and media literacy, when integrating sub-contents related to the social dimension into mathematics. Access to a curriculum focusing on meaningful learning is crucial for achieving high-quality education in mathematics (Hudson, 2019), enhancing engagement, motivation, enjoyment and fulfilment (Román-Graván et al., 2020).

Integrating mathematics and science in the context of ESD enhances students' understanding of air quality, weather and climate. It encourages pre-service primary teachers to think critically and propose solutions, fostering a connection between STEM topics and real-world situations. Students found the integrated mathematics and science project interesting but wanted more outdoor sessions. Pre-service primary teachers emphasized teaching environmental education, integrating ESD and increasing outdoor teaching, recognizing the link between STEM and sustainability topics. The results also highlight the significance of integrating technology with sustainability themes (Rico et al., 2021; Suh & Han, 2019).

Furthermore, mathematical modelling courses and engineering-based projects (Cibik & Boz-Yaman, 2025; Pinto et al., 2024; Tang et al., 2024) gave students the opportunity to address sustainability issues through calculus, quantitative reasoning and prototype design. These interdisciplinary activities combine real-world problem solving with authentic data analysis to help learners develop analytical and systems thinking skills.

Together, these approaches demonstrate that integrating sustainability into mathematics through ethical reflection, digital tools, and real-world modelling fosters the growth of critical, creative, and socially responsible learners.

### Curriculum and textbooks

Kim and Pang (2022) conducted a comprehensive study examining elementary mathematics textbooks from grades 3 to 6 in Japan, Korea, and Singapore. Analyzing 18 textbooks, they found that sustainability-related content is integrated across various domains such as numbers and operations, pattern and data, and possibilities. The study highlights the difficulties in integrating sustainability themes consistently across different mathematics content areas, while noting the progress in integrating environmental dimensions into textbooks and emphasizing the need for a more systematic approach to integrate all dimensions of ESD: ecology, social and economic. This will improve students' engagement with sustainability throughout their mathematics education in these countries.

Similarly, a study focusing on the Norwegian education system (Tesfamicael & Enge, 2024) revealed that while the core curriculum (LK20) explicitly includes sustainable development as a cross-curricular theme, the mathematics curriculum itself does not directly reference sustainability or ESD. Only indirect mentions of "nature" and "environment" serve as potential points for integrating sustainability into mathematics education. However, mathematics textbooks include specific sustainability-related activities such as waste management, local food production, energy use and sustainable consumption. These examples highlight that textbooks can play a key role in linking mathematics with real-world sustainability contexts, even when curricula remain abstract. Nevertheless, the study highlights a philosophical challenge: the perception of mathematics as a "value-free" discipline can hinder the integration of ethical and environmental considerations. Overcoming this requires a fundamental change to mathematics education, as well as more comprehensive professional development for teachers and textbook authors.

Additionally, Joutsenlahti and Perkkilä (2019) argue for a multi-semiotic approach in Finnish mathematics textbooks, which integrates natural, pictorial, and mathematical languages. This approach not only enhances comprehension of mathematical concepts but also promotes educational equity and lifelong learning skills crucial for sustainable development. By embedding sustainability themes into everyday mathematical tasks, textbooks can foster a deeper understanding of how mathematics can contribute to solving real-world sustainability challenges.

In another study, Vásquez et al. (2021) found in Chilean primary school textbooks a predominant focus on memorization in statistical and probability tasks, with minimal integration of sustainability contexts or alignment with SDGs. Their findings highlight a missed opportunity to engage students in critical thinking about social, economic, and environmental issues through

mathematics education. They stress the need for a revised educational approach that empowers students to apply mathematical skills to real-life sustainability challenges.

Further analysis of the curriculum (Said et al., 2024) revealed that mathematics standards tend to focus on abstract concepts, offering limited real-life applications or explicit connections to sustainability. Although SDG-related content is present in national education policies, references in mathematics curricula are often implicit or superficial. This is in contrast to science curricula, which are more directly aligned with sustainability goals. The findings suggest that incorporating authentic, real-world sustainability problems and modelling tasks into mathematics instruction could bridge this gap and enhance the relevance of learning.

These studies collectively underscore the importance of rethinking mathematics textbooks and curriculum to better align with sustainability goals. Mathematics textbooks play a crucial role in classrooms by providing structured resources that systematically present mathematical concepts, theories, and problem-solving techniques. They ensure consistency and coherence in curriculum delivery, serving as foundational tools for students' mathematical learning. By integrating sustainable development content with its all dimensions, these textbooks expand their relevance beyond mathematical theory, demonstrating how mathematical skills can be applied to analyze and address real-world sustainability challenges.

### *Teacher education*

Teacher training programs play a crucial role in supporting teacher education in tackling sustainable development challenges (Manasia et al., 2019; Suh & Han, 2019). Teacher job readiness involves key dimensions such as professional knowledge and practice, professional engagement and self-management, each encompassing various components related to adopting sustainable development practices. Engaging pre-service teachers in mathematical modelling activities can serve as a viable approach to attaining the targeted competencies of ESD. This method, being a suitable and fundamental skill in mathematics, can contribute to the promotion of ESD in schools (Wiegand & Borromeo Ferri, 2023).

Recent studies further emphasize the need for teacher education to move beyond technical knowledge and incorporate ethical, systemic and reflective competencies. A large-scale study of pre-service and in-service mathematics teachers (Moreno Pino et al., 2023) showed moderate overall development in sustainability competencies, with community participation being the weakest area. These results emphasize the importance of incorporating sustainability focused learning outcomes into mathematics teaching, encouraging critical thinking

and civic responsibility. Similarly, studies of pre-service mathematics teachers indicate that even short, focused ESD training can significantly improve teachers' ability to design interdisciplinary, SDG linked mathematics activities. Participants in these programs demonstrated greater confidence in teaching sustainability through mathematics and reported behavioral changes, such as reduced plastic use and more mindful consumption.

At the same time, in-service teacher development remains essential. Studies show that interventions focused on sustainability (Alsina & Silva-Hormazábal, 2023) can significantly improve teachers' ability to design project-based mathematical tasks linked to the SDGs and local environmental issues. These programs encourage collaboration and empowerment, as well as the ability to connect mathematics with community challenges, leading to increased student awareness and engagement. Nevertheless, several barriers persist. Research indicates that many teachers lack a formal understanding of sustainability and the SDGs, which often limits integration to ecological themes (Alsina & Vásquez, 2025). Challenges include linking environmental education and ESD to abstract mathematical areas, time constraints, and curriculum overload. While teachers recognize the value of real-world contexts, they often find it difficult to translate them into quantitative classroom activities, highlighting the need for ongoing professional development and practical support (Franco Seguí et al., 2024).

To effectively promote ESD, it is necessary to integrate the knowledge related to sustainability into both initial and in-service teacher training. Among the content areas, statistics, probability, numbers and operations stand out as having the highest number of objectives related to key competences for sustainability (Vásquez et al., 2022).

Although pre-service teachers were not fully aware of all dimensions of sustainability, they were motivated and willing to associate sustainability with mathematics teaching by aiming to increase students' awareness of global issues, to provide examples related to environmental subjects such as pollution, water consumption and recycling (Isler Baykal & Karaarslan Semiz, 2020; Suh & Han, 2019; Wiegand & Borromeo Ferri, 2023).

When assessing degree programs based on sustainability competencies, the master's degree in teacher training for compulsory secondary and upper secondary school education (specializing in mathematics) emerges as the most impactful in fostering sustainability competency (Moreno-Pino et al., 2021). Integrating sustainability into higher education mathematics curricula is deemed crucial for preparing teaching professionals and fostering reflective and critical thinking (Moreno-Pino et al., 2021).

Training current and future teachers to incorporate sustainability criteria into mathematics curricula is crucial (Moreno-Pino et al., 2022; Nguyen et al., 2020). Linking to ESD topics can serve as a source of motivation for learning and applying mathematical concepts and methods. This connection contributes to an improved understanding of mathematics (Wiegand & Borromeo Ferri, 2023).

Taken together, these findings show that teacher training is key to incorporating sustainability into mathematics teaching. Empowering teachers as agents of change not only strengthens their professional competencies but also enables them to guide students in applying mathematics to real-world sustainability challenges.

### *Student learning and challenges*

When confronted with mathematical challenges within the ESD framework, high school students often encounter difficulties. While they can successfully solve mathematical problems related to derivatives, such as finding the first derivative of an algebraic function, they struggle when tasked with translating real-world problems in the ESD context into a mathematical model (Nikmah et al., 2019). Similarly, a project conducted in mathematics education in line with SDG targets shows that students' awareness of the role of society in protecting the environment and creating benefits for the whole society increased (Martín-Sánchez et al., 2022), although students encountered mathematical difficulties when solving mathematical problems in this context, such as misinterpretation of the problem, lack of clear understanding of concepts related to sustainability, and errors in value change (Martin et al., 2019).

Recent studies also demonstrate that learning mathematics in a sustainability-related context fosters critical, ethical and creative thinking. Students who engaged with sustainability driven mathematical modelling tasks developed a deeper understanding of social and environmental issues, as well as enhancing their problem-solving and communication skills (de Andrade & Makramalla, 2023; Qhosola, 2023; Sharma & Ali, 2018). Integrating mathematical reasoning with digital and interdisciplinary activities was found to increase motivation, collaboration and real-world engagement (Kersanszki et al., 2024; Saimon et al., 2023). Similarly, university students who applied calculus concepts to model solar energy output and carbon emissions (Pinto et al., 2024) or developed prototypes through engineering-based projects (Tang et al., 2024) demonstrated improved systems thinking and a stronger sense of social responsibility.

Studies also indicate that sustainability-oriented mathematics instruction can be effective at all levels of education. For example, preschool learners gained a practical understanding of climate impacts, resource use,

and environmental responsibility through STEM activities that integrated indigenous knowledge. Furthermore, the development of sustainability-based numeracy assessments demonstrates growing attention to measuring students' critical thinking and problem-solving skills in real-world sustainability contexts (Kurniati et al., 2024).

The findings reflect that although students were successful in traditional mathematical tasks such as derivatives, they faced challenges when applying these skills to real-world sustainability issues. This challenge includes translating environmental and societal issues into mathematical models, pointing to the need for a clearer conceptual understanding and practical application of mathematics in SDG contexts. Despite these challenges, interventions such as online games and mathematical modelling tasks have shown to be effective in increasing students' critical awareness, motivation and ability to use mathematics as a tool for ESD.

### *Research gaps*

Finally, to answer research question 4, we summarize the research gaps identified in the reviewed studies and outline implications for future research in mathematics education for ESD.

There has been limited discussion on the use of mathematics as a subject for teaching sustainability. Further research should focus on integrating mathematics into the broader discourse on sustainability education. At the curricular level, multiple studies report that mathematics curricula and textbooks lack the systematic and explicit integration of sustainable development, despite sustainability being emphasized in broader education policies. Sustainability-related content tends to be distributed unevenly and is largely confined to ecological themes, with social, ethical and economic dimensions receiving considerably less attention (Kim & Pang, 2022; Tesfamicael & Enge, 2024; Vásquez et al., 2021). Several authors explicitly state that sustainability is often treated as an additional contextual element rather than being embedded within mathematics learning objectives, tasks and assessment practices. This indicates the need for coherent curricular frameworks that meaningfully integrate ESD into mathematics education (Said et al., 2024).

Regarding student learning, several studies indicate that students struggle to translate real-world sustainability issues into mathematical representations or models and face challenges related to problem interpretation and conceptual understanding (Kurniati et al., 2024; Martin et al., 2019; Nikmah et al., 2019). Furthermore, it remains unclear whether increased sustainability awareness achieved through mathematics instruction leads to lasting changes in students' behaviors, attitudes, or decision-making, as long-term

effects are rarely examined (Pajk et al., 2021; Sharma & Ali, 2018). This highlights the need for longitudinal research designs that capture learning processes and outcomes over time.

Assessment and measurement constitute another significant research gap. Numerous studies report the absence of validated instruments for assessing sustainability-related mathematical competencies and highlight the limitations of existing tools in capturing the multidimensional nature of sustainability (Kopeika & Zvirgzdina, 2020; Kurniati et al., 2024). Addressing this gap requires the development and validation of assessment frameworks that align mathematical learning with ESD competencies beyond short-term outcomes.

A number of studies also call for philosophical and pedagogical shifts in how mathematics is perceived. The discipline's traditional framing as "value-free" limits the integration of social and ethical perspectives, pointing to the need for a new paradigm that positions mathematics as a tool for critical and ethical inquiry (Hauge, 2024). Likewise, interdisciplinary and experiential learning approaches such as mathematical modelling, engineering-based projects, and data-driven sustainability analysis have shown promise but remain fragmented and underexplored in terms of long-term educational impact (Bulut & Borromeo Ferri, 2025; de Andrade & Makramalla, 2023; Tang et al., 2024).

In teacher education, both pre-service and in-service teachers are reported to have a limited and often fragmented understanding of sustainability that is typically focused on environmental issues. One common issue is teachers' difficulty in translating sustainability concepts into meaningful, numerate classroom activities (Franco Seguí et al., 2024; Isler Baykal & Karaarslan Semiz, 2020). Furthermore, many studies rely on short-term interventions, providing limited evidence of sustained changes in teaching practices. These findings highlight the necessity of integrating ESD competencies more systematically and over the long term into teacher education programs across different levels of education and institutional contexts (Manasia et al., 2019; Moreno-Pino et al., 2023). At the teacher education level, more comprehensive research is needed across all stages of mathematics teaching, from early education to higher education (Bulut & Borromeo Ferri, 2025; Wiegand & Borromeo Ferri, 2023). Improving university programs (Vintere, 2018) and embedding ESD competencies into both initial and in-service teacher training remains ongoing needs (Vásquez et al., 2020).

From a methodological perspective, many studies acknowledge limitations related to small or context-specific samples, which restrict the generalizability of findings. Authors repeatedly call for longitudinal, comparative, and mixed-methods research conducted across diverse cultural and educational contexts to

strengthen the empirical base of the field (Bowen et al., 2019; Chen & Wu, 2024; Martín-Sánchez et al., 2022).

Collectively, these gaps indicate the necessity for sustained, cross-level, and interdisciplinary research efforts that reconceptualize mathematics not only as a cognitive discipline but also as a critical and ethical practice contributing to sustainable development.

## DISCUSSION AND CONCLUSION

Consequently, integrating mathematics education with sustainable development is crucial to promoting a comprehensive understanding of sustainability issues. Barwell (2018) highlighted the importance of mathematics education in addressing environmental sustainability and suggested that making a deeper connection between mathematical concepts and real-world ecological challenges can significantly enhance students' learning and awareness. Renert (2011) supports this idea by advocating a "mathematics for life" approach that underlines the relevance of mathematics to everyday life and its important role in sustainable education. This systematic literature review emphasizes the need in this area and provides examples, albeit few in number. We analyzed 68 peer-reviewed articles and conference proceedings. Our results showed that although the number of studies on sustainability in mathematics education has increased slightly, there is still a need for research in this area, both in school mathematics and teacher education.

Only a minority of the reviewed articles were published in mathematics education journals, and none of the conference papers included in the review originated from mathematics education conferences. The predominance of publications in interdisciplinary and sustainability-oriented publications (e.g., Sustainability) suggests that research on ESD in mathematics education is currently more widely distributed outside the core mathematics education community. This pattern highlights the need to increase the visibility of ESD-related work within mathematics education venues, ensuring that findings reach mathematics and teacher educators more directly.

With regard to the explicit use of SDGs, more than half of the reviewed studies did not specify any SDG, even though they addressed sustainability-related themes. This suggests that sustainability in mathematics education is often operationalized implicitly through contextual topics rather than being explicitly aligned with the SDG framework. When SDGs were mentioned, SDG 4 and SDG 13 were the most frequently referenced. These findings point to the value of clearer reporting practices in future studies, including more explicit articulation of how mathematics education interventions relate to SDG targets.

The findings related to learning and teaching practices show both potential and persistent challenges.

Across studies, sustainability contexts and modelling approaches were frequently described as motivating and meaningful for learners, supporting engagement with real-world issues and encouraging discussion of ecological, social, and economic dimensions (Hauge, 2024; Wiegand & Borrromeo Ferri, 2023). At the same time, several studies reported that students experience difficulties when translating sustainability contexts into mathematical models and when interpreting complex real-world tasks (Martin et al., 2019; Nikmah et al., 2019). This combination of promise and challenge underscores the need for research that more systematically examines how learners develop modelling competencies and mathematical understanding in sustainability contexts across grade levels.

Teacher education emerged as another central area. The reviewed studies indicate that teachers and pre-service teachers often recognize the value of connecting mathematics with sustainability, yet they may hold limited or fragmented conceptions of sustainability and face difficulties in designing mathematically meaningful ESD activities (Alsina & Vásquez, 2025; Franco Seguí et al., 2024; Isler Baykal & Karaarslan Semiz, 2020). Interventions in teacher education show potential for improving teachers' capacity to design SDG-related tasks and to implement interdisciplinary approaches, but evidence remains largely based on short-term designs (Manasia et al., 2019; Moreno-Pino et al., 2023). Taken together, these results emphasize the importance of teacher professionalization for increasing the scale of ESD in mathematics education, particularly through programs that help teachers link ESD competencies with specific mathematical content and task design.

Finally, although digital technologies were reported in the reviewed studies, their role in ESD was rarely analyzed in depth. Most studies that employed digital tools described them primarily as supportive instructional resources rather than examining their contribution to sustainability understanding or ESD-related competencies. This finding suggests that future research could more explicitly investigate when and how technology-enhanced designs support learning in mathematics education for ESD.

We have already commented on the key findings in the previous section. In the following, we briefly summarize our perspective on three aspects that we see as relevant to research on ESD in the context of mathematics learning and teaching:

1. **Teacher professionalization:** One necessary step for ESD and mathematics to be integrated is teacher professionalization. Based on the findings to date, however, there is still a great need for research to formulate and evaluate competencies to be learned by pre- and in-service teachers and to ensure that these competencies are evidence-based. In concrete terms, this means investigating

the challenges and motivation of teachers who have to combine the ESD framework and mathematical concepts in a senseful way. Best-practice courses or seminars for pre- and in-service teachers are needed so that ESD and mathematics are taught in an integrated way. This leads to the "how" and "through what" ESD should be integrated with mathematics.

2. **Integrative ESD-mathematics tasks:** Complex life-world contexts and questions can be worked on and reflected on in an integrative way, for example, with mathematical modelling activities in the context of ESD. However, there are generally other possibilities for task design that must nevertheless take the ESD criteria into account. Research is needed on both the theoretical and practical sides to ensure that "ESD-mathematics tasks" are recognized and, in a way, a "special" task format to address sustainability issues. Finally, this leads to concrete implementation in schools.
3. **Students recognize the mathematical-factual as a basis for sustainability discussions:** In the current situation, we as mathematics educators have the opportunity to once again emphasize mathematics as a central discipline for learners in the ESD context. The integrative learning and teaching approach of ESD and mathematics promotes an understanding of reality in all its facets and makes room for factual and ethical complexity. Data and facts confront learners with decision-making dilemmas, encourage them to rethink their own values, and plan actions. Therefore, it is interesting to conduct research into how students perceive the importance of mathematics in the context of ESD and how and whether emotional-motivational aspects play a role in this.

Researchers and educators can use the results of this systematic literature study to improve mathematics education through the integration of ESD into school mathematics curricula and sustainability into in-service teacher training and pre-service teacher candidate training processes.

### Limitations

This systematic review has some limitations. First, it excludes literature from databases other than WoS and Scopus, potentially overlooking interesting and innovative research that has not yet appeared in peer-reviewed journals in these databases. Second, the reliance on topic, title and abstract searches for truncated search terms may have resulted in the exclusion of some relevant studies in the field, which is another limitation of the current review. Third, the review was limited to English-language publications, which may have led to

the exclusion of relevant studies published in other languages. In addition, the relatively modest number of included studies reflects both the emerging nature of research on ESD in mathematics education and the defined scope of the review and may limit the generalizability of the findings. Overall, these limitations should be considered when interpreting the results of this review.

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## APPENDIX

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