Mathematics Education Research Journal
https://doi.org/10.1007/s13394-024-00488-y

Professional development and teacher agency in Mathematics Teacher Education for Sustainability

Ángel Alsina[1] · **Claudia Vásquez**[2]

Received: 1 June 2023 / Revised: 11 March 2024 / Accepted: 19 March 2024

Abstract

In-service primary school teachers' professional development and, more specifically, their teacher agency, are analyzed regarding the integration of mathematical education and sustainability. To achieve this, based on semi-structured interviews, several questions involving Education for Sustainable Development (ESD) and links between mathematics education and sustainability are considered, which yielded 44 answers. The analysis of these answers is based on four sub-aspects: knowledge of sustainability and its connection to the SDGs; sustainability practices; links between mathematics education and sustainability; and obstacles and challenges. The results show that teachers exhibit a significant lack of knowledge about sustainability and its connection to the SDGs, making a single association with issues related to the environmental crisis, which is the main focus of the sustainability practices carried out in schools. As pertains to the links between mathematics education and sustainability, most accept the importance of this connection, but point out various obstacles and challenges, such as the lack of knowledge and time, the curriculum itself, and others. It is concluded that it is necessary to design training programs focused on these aspects, in order to contribute to the development of teacher agency, i.e. the appropriation and reconstruction of new resources to face the challenges that mathematics education for sustainability implies in teaching practice.

Keywords Teacher professional development · Teacher agency · Education for sustainable development · Mathematics teacher education for sustainability · Primary education

✉ Claudia Vásquez
cavasque@uc.cl

Ángel Alsina
angel.alsina@udg.edu

[1] University of Girona, Girona, Spain

[2] Pontificia Universidad Católica de Chile, Santiago, Chile

Published online: 01 April 2024

Introduction

In an effort to provide solutions to social, environmental, and economic crises, more and more governments are proposing that sustainability be addressed comprehensively throughout schooling, including higher education, and be integrated into the different areas of knowledge (UNESCO & Education International, 2021). A key element in this process is the teachers, their knowledge, and skills, as these are "powerful agents of change that can provide the educational response needed to achieve the SDGs. The skills that a teacher possesses are essential to restructure educational processes and institutions in pursuit of sustainability" (UNESCO, 2017, p. 51).

Against this background, this paper focuses on the research agenda called Mathematics Teacher Education for Sustainability (MTEfS). This research agenda in mathematical education, which is still emerging (Alsina, 2023), aims to integrate Mathematics Education and Education for Sustainable Development (ESD) so that, both during initial training and on-the-job learning, the necessary knowledge and tools are provided to ensure mathematics teachers can play an effective role as agents of social change (Alsina, 2022).

As noted in Alsina and Silva-Hormazábal (2023), some topics that were previously addressed exclusively through research in mathematical education, such as the professional development of educators or the interaction, context, and practice of teachers, are now starting to be studied from an integrated perspective with ESD in countries like China (Zhang et al., 2021), Great Britain (Helliwell & Ng, 2022), and others. An example of the growing interest in this emerging field of research is the Special Issue of the journal AIEM — Avances de Investigación en Educación Matemática — of the Spanish Society for Research in Mathematics Education, in which authors from different countries address issues associated with the training of mathematics teachers in connection with sustainability (No. 23, April 2023). With regard to Chile, the country in which the study was carried out, it should be noted that a recent systematic review of the literature has shown that it is the geographical context of the American continent with the most studies on this integration (Vásquez et al., 2023a), which shows that it is a topic of great interest. The topics analyzed have been the presence of sustainability in the Chilean mathematics curriculum (Vásquez et al., 2022) and in mathematics textbooks (Vásquez et al., 2021). The main findings show, on the one hand, that the content standards of statistics and probability and numbers and operations are the ones with the most ESD-related objectives; on the other hand, with respect to textbooks, there is little presence. Based on these data, authors and collaborators (e.g., Alsina & Mulà, 2019; Alsina, 2022; Vásquez et al., 2020; Vásquez & García-Alonso, 2020; Vásquez et al., 2021; Franco et al. 2024) have started a targeted line of research that connects statistics education, as part of mathematics education, with ESD. This connection is based on the idea that statistics education provides tools to understand and respond to both real-life problems and problems from other disciplines, and also allows connections to be made between different contexts and problems. Specifically, most of these studies analyze issues

such as the development of sustainability competences in mathematics teachers at different levels, both during pre-service and in-service training, and the design and implementation of training programs to develop these competences.

However, other research topics closely linked to MTEfS, such as teacher agency, have been less analyzed. We assume that teacher agency views teachers as professionals who appropriate and reconstruct the resources that have been developed and made available to them while reshaping these resources to meet new challenges (Priestley et al., 2015).

Given this history, and with the goal of contributing new data to the research on MTEfS, in this article, we pose the following research question: how do in-service teachers appropriate and reconstruct the resources available to them to address the challenges of mathematics education for sustainability? From this point of view, our aim is to investigate the professional development and, more specifically, four aspects related to the teacher agency of in-service Chilean primary school teachers involving the integration of mathematics education and ESD: knowledge of sustainability and its connection to the SDGs; sustainability practices; links between mathematics education and sustainability; and obstacles and challenges.

Current state of the research agenda on Mathematics Teacher Education for Sustainability (MTEfS): what role does teacher agency play?

Over the last decade, several international institutions and agencies strongly recommend the incorporation of ESD in the various stages of education, considering it to be one of the main instruments available to public authorities in their attempt to ensure the development of their countries. Examples include Aichi-Nagoya Declaration on Higher Education for Sustainable Development (UNESCO, 2014); Rio+20 Treaty on Higher Education, an initiative of the COPERNICUS Alliance together with its peer networks at the international level (COPERNICUS Alliance, 2015); Education for Sustainable Development: a roadmap (UNESCO, 2020); and Berlin Declaration on ESD (UNESCO, 2021), which refers not only to higher education.

These different frameworks and declarations underscore how the development of both the meaning and the values of education for sustainability is interconnected, based on the contributions of disciplines from different fields: scientific-technological, humanist, social, etc. As a result, from the time teachers are trained, authors such as Alsina and Mulà (2019, p. 2) note that:

> Teacher training cannot be reformulated based on mere intuition and experience. Progress will only be made if university professors, who are responsible for training pre-service teachers, explicitly incorporate the key knowledge and data provided by research in various fields associated with teacher training.

In the context of mathematics teacher education, one of the contemporary challenges is for both pre-service and in-service teachers to understand and assume the important role that the use of mathematics has for society. In this sense, for example, the Council for the Curriculum, Examinations & Assessment (CCEA) considers that using mathematics is one of the cross-cutting skills which form the nucleus

of the curriculum, as it makes it possible to develop the ability to suitably apply mathematical knowledge, understanding and skills in different contexts and in different ways in order to communicate, manage information, think critically, resolve problems and take decisions. In order to achieve this aim, it is desirable for teachers to use relevant real-life situations which require mathematical thinking and to give children the possibility to transfer their knowledge, where appropriate, to other contexts (CCEA, 2020).

This is, without a doubt, a challenge which extends beyond mathematics. On a global level, for example, social, economic, environmental, and recently, health crises coexist, which can be better understood via mathematics. However, these crises cannot be solved with mathematics alone, but rather via the sum of different disciplines. In other words, knowledge of different kinds must be integrated in order to confront and resolve these challenges. For this reason, the skills-based approach to mathematics refers to connections, one of the standards of processes which demonstrate how mathematical contents are acquired and used. Specifically, in Principals and Standards for School Mathematics, the National Council of Teachers of Mathematics refers to two types of connections (NCTM, 2000): (1) the connections between mathematical ideas, in order to understand how they interconnect and build upon each other to produce a coherent whole (intradisciplinary connections); (2) the recognition and application of mathematics in non-mathematical contexts, which may arise in topics from other subjects and also in the children's daily lives (interdisciplinary connections).

This article focuses on the latter type of connection and, more specifically, on the integration of mathematics and sustainability in teacher training, with the aim of providing teachers with the necessary knowledge, understanding, and skills to be able to advance in this direction. Therefore, the intention is to actively participate, from mathematics education, in the acquisition of the Sustainable Development Goals and the Competencies for Sustainability (Bianchi et al., 2022; UNESCO, 2017), in order to contribute towards a more inclusive, sustainable, and resilient future for people and the planet.

This is intended not only to provide guidance so that mathematics teachers can plan teaching practices involving sustainability contexts, or integrate sustainability knowledge when planning mathematical activities; rather, the main goal is for mathematics teachers to plan and engage in teaching practices whose purpose is to reorient the learning experiences of students so that they understand their professional responsibilities, their capacities and their personal motivations (Mulà et al., 2017).

Recent studies on MTTfS have begun to analyze the development of sustainability competencies in pre- and in-service teachers. These competences refer to systemic and critical thinking, problem solving, self-awareness, collaboration, anticipation, and rules and values (UNESCO, 2017).

The study carried out by Vásquez and García-Alonso (2020), García-Alonso and Vásquez (2021) examines the development of didactic units for teaching statistics by prospective primary school teachers in Chile and Spain. The findings reveal the need to develop models of statistical tasks that foster ESD, characterized by a high level of cognitive demand and authenticity. In addition, the importance of implementing teacher training programs that allow redirecting the teaching of statistics through contextualized projects in realistic

situations, based on the Sustainable Development Goals, is identified, with the aim of contributing to the formation of sustainability-conscious citizens in the school environment.

Helliwell and Ng (2022), for example, note that by identifying aspects of mathematics teaching that pre-service teachers deem secondary, and offering tasks that support the expansion of this vision, the educators of teachers are better situated to support the development of the teaching practices needed for a sustainable future. Moreno-Pino et al. (2023) analyze the development of the sustainability skills of 105 Spanish mathematics teachers with three different university degrees. Their results show that the development of these skills is superior in teachers in the early school stages (early childhood and primary education). García-Alonso et al. (2023) analyze the impact of a training program on the design of mathematical tasks and ESD for pre-service high school mathematics teachers. Overall, their results show that after the training, all 15 participants improved the level of achievement of all the skills.

Other studies with in-service mathematics teachers reveal, for example, how said faculty initiate informal interactions based on shared goals, how they meet the dual expectations of teaching and educational research, and how they perceive the effects of informal interactions in their teaching practices to advance toward sustainable professional development (Zhang et al., 2021). Helliwell et al. (2023) investigate the complexity that addressing climate justice issues entails for mathematics teachers. Specifically, these authors show how a high school mathematics teacher acknowledges contradictions and draws on multiple forms of knowledge during his transformation process in relation to teaching mathematics and climate justice in the context of a small-scale professional development program. Alsina and Silva-Hormazába (2023) focus on the effect of a previously validated training program, designed based on comprehensive STEAM education, in which 23 Chilean pre-primary and primary education teachers participated. The results show that, after the training program, more than half of the participants reached an advanced level on the Sustainable Development Goals (SDGs) covered in the program (SDG 5 on Gender Equality and 13 on Climate Action). Additionally, in the practical phase of the program, the participants demonstrated skills in designing and implementing a statistical task involving sustainability, which evidences the development of skills related to ESD. Vásquez et al. (2023b) investigate the belief systems of 11 Chilean primary school statistics teachers and their links to sustainability. The results show that teachers view the integration of statistical education and sustainability as a real challenge, indicating the mastery of the content and the development of skills as the most recurring topics.

But how does teacher agency play a role in these findings? Training paradigms and models that aim to go beyond the transfer of knowledge are based on the agency of the person being trained. From the agentive perspective, then, teacher education does not mechanically reproduce what they are taught to do, but rather their performance is always the result of the interplay of individual efforts, available resources, and contextual and structural factors as they come together in particular and, in a sense, always unique situations (Priestley et al., 2015). In other words, teachers do not develop by applying what is transmitted to them, but by constructing their own teaching profile from their own internal resources, as well as from all the input they receive and adapt to the environment, the person, and therefore, to their own possibilities. Thus, teacher agency is a "temporal and relational phenomenon; something

that occurs over time and is about the relationships between actors and the environments in and through which they act" (Biesta et al., 2017, p. 40). For this reason, it is essential to develop professional competences related to knowing how to decide. This means having criteria and tools to make well-argued decisions and to be able to adapt to the context (Esteve & Alsina, 2024).

As a whole, and considering our focus of study, these are competences of a more reflective and critical thinking nature, oriented towards observation and critical analysis of the reality of the classroom regarding the integration of mathematics education and ESD, as well as of one's own ideas and beliefs about the action of teaching and learning and, finally, to self-awareness of the progress of this topic both in relation to beliefs and in teaching performance. Developing these competences is no easy task, but it is necessary if we are to help trainee teachers to advance as critical practitioners (Schön, 1983). If this is fulfilled, then the trainee teacher will be able to "flexibly regulate the activity by considering various conditions and choosing between different possibilities for the necessary action prior to its physical execution" (Arievitch, 2017, p. 149).

With these aspects in mind, our purpose is to investigate the professional development and, more specifically, the teacher agency of 11 in-service Chilean primary school teachers involving the integration of mathematics education and ESD.

Methodology

Using a qualitative methodology from an interpretive approach (Stake, 2020), teacher agency in relation to the integration of mathematics education and ESD is identified and analyzed. In this way, this study explores how the 11 teachers who have participated in the study are appropriating and reconstructing their knowledge about sustainability and its connection with the SDGs, the sustainable actions implemented in schools, and the relationship between mathematics education and sustainability, in order to make decisions that help them to develop and improve teaching competences on these issues, which is the key to teacher agency.

Context

The participants are 11 Chilean teachers who teach mathematics to primary school students (Table 1). The selection of these participants has been done by non-probability and purposive sampling.

Each of the participants was recruited by means of open invitations that were sent to the directors of schools in three regions of Chile (Metropolitan Region, Araucanía Region, and Maule Region), who then forwarded the invitations to the teachers in their schools, all of whom subsequently and voluntarily signed the informed consents. The criteria for the selection of participating teachers were geographical proximity, in order to facilitate contact with the schools and the application of the interviews. It is noteworthy that the teachers involved in the research operate in various categories of educational institutions, including state-funded, partly private,

Table 1 Characterization of the study participants

Code case	Gender	Postgraduate	Years of service	Type of school where he/she teaches
P1	Female	No	22	Public
P2	Female	No	3	Semi-private
P3	Male	No	1	Private
P4	Female	No	2	Private
P5	Male	Yes	9	Public
P6	Female	Yes	14	Private
P7	Female	No	10	Public
P8	Female	No	13	Private
P9	Male	No	1	Semi-private
P10	Male	Yes	12	Semi-private
P11	Female	Yes	8	Public

and fully private establishments, which diverge in terms of their administrative and financial models. In this way, it takes into account the social and cultural diversity that characterizes the country.

Data collection technique

To obtain the data, we opted to use semi-structured individual interviews following a guided approach (Cohen et al., 2018, p. 510). From Kvale's perspective (2011), this type of interview is conceived as "a specific form of verbal exchange in which knowledge is constructed through the interaction between an interviewer and an interviewee" (p. 19). Its fundamental purpose lies in "gaining orally and in a personalised manner information about experienced events and subjective aspects of the individual, such as beliefs, attitudes, opinions, and values, in relation to the situation under scrutiny" (Bisquerra, 2019, p. 336). This way, the application of semi-structured interviews made it possible to further analyze the subject in question by providing an instance of reflection to delve into the teacher agency involving the dimensions, sub-dimensions, and questions shown in Table 2, which mainly emerge from the conceptualization of teacher agency described in the theoretical framework (e.g., Arievitch, 2017; Biesta et al., 2017; Priestley et al., 2015). Thus, they refer to what teachers do in relation to ESD and the relationships between mathematics education and sustainability (actions, strategies, practices, etc.). We consider that through these dimensions, sub-dimensions, and questions, we can inquire about a "quality" of the engagement of teachers with temporal-relational contexts-for-action, not a quality of the teachers themselves. According to these authors, viewing agency in such terms can help us to understand how teachers are able to be reflexive and creative, acting counter to societal constraints, but also how teachers are enabled and constrained by their social and material environments.

Table 2 Characterization of the dimensions analyzed in the study

Dimension	Sub-dimension	Questions
Education for sustainable development	Knowledge of sustainability and its connection with the SDGs	What is your understanding of sustainability? Have you heard of the SDGs, do you know anything about them? Do you see any connection between sustainability and the SDGs?
	Sustainable actions carried out in schools	Have actions been implemented in the different subjects in your school involving sustainability or the SDGs? Specifically in mathematics? If so, which ones?
Relationships between mathematics education and sustainability	Mathematics education and sustainability: strategies and practices	How would you relate the subject of mathematics to sustainability? If you have done so, what kind of activities did you use?
	Obstacles and challenges to address the teaching of mathematics in connection with sustainability	What obstacles and challenges do you think there might be to teaching mathematics in connection with sustainability?

An application protocol was developed that contained suggestions for conducting the semi-structured interview, as well as the driving questions to ask over the course of said interview. While the driving questions were laid out in the protocol, the interviewer had full liberty in terms of what questions to ask. Each interview lasted approximately 45 minutes.

It should be noted that during the process of designing and conducting the interviews, care was taken to comply with the quality criteria proposed by Kvale (2011). In addition, the semi-structured interview was qualitatively validated by the judgment of five experts on the subject (Table 3).

For the validation process, experts received an email invitation that detailed the context of the research project, which required the creation of a semi-structured interview including its description and purpose. The initial version of the instrument was accompanied by a specifications table and guidelines to assess the suitability of each driving question. Experts evaluated the items on three aspects — clarity, relevance, and consistency — using a Likert scale ranging from 1 to 4 points. Furthermore, a comment section was included.

The collected information underwent analysis of the scores given by the judges. A descriptive evaluation of the validity of the content was carried out, considering the values assigned to each question in terms of its clarity, relevance, and consistency. The inference study was conducted to analyze the data, employing the Aiken index to determine the level of agreement or concordance between the scores assigned by experts, which was deemed acceptable at 0.83.

The instrument was then reviewed and modified based on the experts' assessments and recommendations. Eventually, a final version of the instrument was created and tested with a teacher who was not part of the study sample. This study aimed to gather empirical data on the instrument's implementation and its applicability, usage, and estimated duration.

Table 3 Profiles of the experts involved in the validation process

Expert	Profile
1	Chilean. Primary school mathematics teacher. PhD Candidate in Education. Research area: teacher training
2	Spanish. Secondary school mathematics teacher. PhD in Education. Research area: statistics education and sustainability
3	Mexican. Secondary school mathematics teacher. PhD in Education. Research area: environmental education
4	Spanish. Primary school mathematics teacher. PhD in Education. Research area: teacher training and sustainability
5	Chilean. Primary school mathematics teacher. PhD in Education. Research area: teacher training and sustainability

Data analysis

The semi-structured interviews to obtain data about teacher agency for integrating mathematics education and ESD were administered using video calls. The resulting recordings were subsequently transcribed for processing. Subsequently, a thematic analysis was carried out (Braun & Clarke, 2006), which considered the following guidelines and stages: initial reading of the data; generation of initial codes; preliminary search for themes; review of the themes found; definition of labels and naming of the defined themes; and production of the analysis results. It is important to note that the aforementioned categories were used in the qualitative analysis in two different ways. First, they were key to defining the deductive categorization of the responses, and second, they were used as key concepts when analyzing said responses. After this process, a total of 44 responses were obtained, yielding the units of analysis of teacher agency. With these responses, then, we aim to identify how teachers are appropriating and reconstructing their knowledge and beliefs about the dimensions analyzed (Table 2). In other words, according to Priestley et al. (2015), we want to identify in an initiatory way how teachers' performance emerges from their individual efforts, available resources, and contextual and structural factors.

Results

This section contains the results of the analysis of the semi-structured interviews, organized around the different dimensions and subdimensions involved to analyze teacher agency.

Education for sustainable development

Knowledge of sustainability and its relevance to the SDGs

Based on participants' responses to the questions posed (Table 2), we identified three main categories of knowledge: none/intuitive knowledge; intermediate

knowledge in connection with an SDG; and high/applied knowledge in connection with multiple SDGs.

Sample excerpts from the teachers' answers that support our analysis are provided in Table 4. While many of the teachers ($n=6$) stated being unaware of a specific definition of sustainability and the SDGs (Ex. 1 in Table 4), they did manage to express certain ideas and knowledge on an intuitive level about sustainability and its connection with issues of nature and the environment, the use of resources, caring for the environment and others, which we could describe as an intuitive knowledge of what sustainability is. In this regard, their answers primarily mention elements that relate to reflection on nature (Ex. 2 in Table 4).

In the second group are those teachers ($n=3$) who expressed an intermediate knowledge of sustainability in connection with an SDG, since in some cases, they linked sustainability to gender issues, as well as reflection on lifestyles and how they, in conjunction with our actions, can impact the future (Ex. 3 in Table 4). More specifically, in relation to sustainability and its connection with the SDGs, there are answers from teachers who, to varying degrees of accuracy, managed not only to mention some of the relevant themes of the SDGs but also to give some examples of how they have presented them in their classes (Ex. 4 in Table 4). These answers showcase the link between the SDGs and inclusion. In this sense, knowledge that is defined as "not as entrenched" is latched on to other knowledge that is entrenched, particularly that related to issues of inclusion, in order to provide a more robust argument.

Finally, a third group of participating teachers ($n=2$) gave highly accurate answers, manifesting high/applied knowledge of sustainability in connection with multiple SDGs. In one particular case, one of the teachers stated having had the opportunity to conduct research on sustainability and its connection with the SDGs and was able to provide a more precise and articulate response with respect to these two issues compared to the previous ones, not only giving a definition but also pointing out some of the elements that comprise it, its purposes, and ending with a reflection regarding the problem (Ex. 5 in Table 4). We also found answers in which the teachers not only mention some relevant sustainability issues in connection with the SDGs but also give examples of how they addressed it in their classes (Ex. 6 in Table 4). This shows applied and accurate knowledge of how to address one of the SDGs in the school classroom, in this case, through interdisciplinary work with other subjects.

The data in Table 4 show that, although there are different levels, some teachers are developing and improving their knowledge of sustainability and its links to the SDGs, which enables them to have criteria and tools to make informed decisions about their own teaching practices and to be able to adapt progressively to the context. In other words, they are developing their capacity for teaching agency which, in addition to knowing how to decide, contributes to knowing how to do and how to be.

Sustainable actions implemented in schools

Regarding the sustainable actions implemented in schools, a qualitative analysis of the participants' answers revealed that only one of the teachers stated that no actions related to sustainability or the SDGs were implemented in his school (Ex. 7 in

Table 4 Excerpts from the teachers' answers involving the knowledge of sustainability and its connection to the SDGs

Categories of knowledge		Quote
Zero or intuitive knowledge	Zero knowledge	Ex. 1: I really do not remember or know anything about the theoretical definition of sustainability and SDGs (P 9)
	Intuitive knowledge of sustainability and nature/environment	Ex. 2: In some way, it is related more to that, to prepare the environment or to provide the resources now so this can be planned over time, and somehow also relate it to the theme of our natural, cultural and social environment, for the benefit of everything, to have a balance between all these elements (P 4)
Intermediate knowledge: connection with an SDG	Knowledge of SDGs 5 and 13	Ex. 3: I think it is in relation to certain issues (…) for example, climate change, or secondary issues, such as gender equality, or things that allow us to continue evolving and drawing conclusions in relation to how we live (P 7)
	Knowledge of SDGs 5, 10 and 15	Ex. 4: The subject of SDGs is one I don't have a firm grasp of, because I've been reading about it little by little, but I only focused on the issue of gender equality. In a way, it is closely related with inclusion, with reflection, respect for nature, respect for people, respect for inequalities, for me it goes hand in hand with inclusion (P1)
High/applied knowledge: connection with multiple SDGs	Knowledge of SDGs 5, 6, 11, 15, 16…	Ex. 5: We did a lot of research on sustainability and the SDGs (…) things involving water, gender identity, justice, access to housing, peace. That is, viewing sustainability as a system in which we worry that our time on earth, and that of the next generations, is habitable, livable and living with dignity as well (…) the SDGs helped me to widen the scope much more, such as talking about what gender is, talking about what housing is, talking about SDGs, and I think that the experience of having investigated it, I feel that the scope opens up much more in terms of what sustainable development is, what we are looking for and what these countries committed themselves to seven years ago now (P3)
	Applied knowledge	Ex. 6: I know the SDGs; in fact, I am now working on SDG2, which is zero hunger. We relate natural science with math, I'm doing fractions and decimals, and the science teacher is doing healthy eating. So in general we work with a problem, I'm working on zero hunger and misuse or loss and waste of food. So as we work on them one by one, we see them individually. I know there are 17, I'm working on one right now (P6)

Table 5), while the rest of the teachers indicated the presence of practices related to the implementation of actions linked to sustainability and the SDGs in their schools.

Sample excerpts from the teachers' answers that support our analysis are provided in Table 5. The first relevant fact is that the sustainable actions implemented in the participants' schools focus on ecological actions (Ex. 8 in Table 5), which tends to show that a relatively reductionist view of these practices persists. Specifically, the answers refer to recycling points, implementing gardens and greenhouses, campaigns to raise awareness of water use, implementation of ecological, environmental and composting workshops, attention to waste recycling and sorting practices, connection between environmental education and sustainable development through different subjects, planning of "thematic weeks" dedicated to the environment, inviting experts and implementing ecological points in the school.

Although most of the answers refer to practices focused on the connection with nature, waste management or awareness of environmental problems, other situations that put the focus on other SDGs are also present, albeit much less frequently (Ex. 9 in Table 5). While no details were given in the situation described about the ways in which the school acts at the practical and institutional level, it is worth at least mentioning that some of the participants expanded their answers beyond the bounds of strictly ecological problems. Along this same line is the answer provided by another participating teacher, who put inclusive education as one of the ways in which his school is taking actions to implement actions related to sustainability and the SDGs (Ex. 10 in Table 5).

Finally, it is important to note that only one of the participants mentioned that the sustainability practices implemented in his school are planned based on interdisciplinarity, that is, on joint work across different subjects, referring in particular to the subject of mathematics (Ex. 8 in Table 5).

Table 5 Excerpts from the teachers' answers involving the sustainable actions implemented in schools

Categories of actions	Quote
Zero implementation	Ex. 7: I haven't seen any projects. I think there was an organic waste dumpster, but it hasn't been used since I got here, or at least I haven't seen it used. But it's there (P 9)
Implementations of an ecological nature/related to nature and the environment	Ex. 8: Well, it does have to do with caring for the environment. (…) we discuss the topic of recycling, the natural sciences teacher is in charge of coordinating these topics with the different subjects and with other schools in the area, there are annual presentations; (…) they were done in previous years and lots of people come, children work on experiments and they often combine them a little with other subjects. In mathematics, we were able to relate them with some content, such as graphs (P5)
Implementations with other SDGs	Ex. 9: The issue of gender equality has been very prominent, because as in every school, I imagine there has been a situation with a girl who wants to be a boy. And it has been a bit difficult, I see that in the higher grades. For example, I had an eighth-grade class where I had two kids with different tendencies, so to speak (P1)
Implementation of actions related to inclusive education	Ex. 10: I think there's also a consideration, for example, of inclusion in a school that has the option for inclusion. I think that also provides an aspect of justice, an aspect of equality that is evident in the students, in how they behave when confronted with diversity. I think it is also sustainable in the long term. In class, I have looked for it, I worked on it as much as I could, and within my ability to plan it (P3)

The teachers' responses show that they are progressively building their own teaching profile around the incorporation of sustainability in their teaching practices. This is possible thanks to their own resources (Table 4), but also thanks to the input they receive and adapt to their own possibilities, as suggested by Johnson and Golombek (2016).

Relationships between mathematics education and sustainability

Mathematics education and sustainability: strategies and practices

The answers obtained were mixed, exhibiting different approaches, strategies, and practices that are worth discussing, as they reveal skills of teaching agency, how to solve the challenges of the teaching profession appropriately, and even how they are becoming more autonomous, more self-confident and more proactive in their own professional development. As a result, in this section, instead of trying to capture the general structure of the answers, they are compiled and ordered so as to highlight this heterogeneity. Specifically, the topics have been organized around three categories: (a) the importance of relating mathematics to sustainability and the use of contingency for that purpose; (b) the teaching of geometry as a tool to link mathematics and sustainability; and (c) the discussion of a specific case that is noticeably different from the general structure of the answers analyzed. Sample excerpts from the teachers' answers that support our analysis are provided in Table 6.

Regarding the importance of relating mathematics to sustainability and the use of contingency for this purpose, the participants' accounts show that, in general terms, they endorse the idea of relating the teaching of mathematics to sustainability. A first impression might lead us to think that one of the two themes (mathematics or sustainability) could play an instrumental role that is, so to speak, purely methodological, when developing skills or certain behaviors. Namely, we might think that taking as an example a social or environmental situation is, in and of itself, one possibility among many to express a mathematical problem, regardless of the type of example used, whether it relates to dealing with a sum of money or the times when two traveling at different speeds will reach a certain destination. This could be a problem, as true integration of disciplines is antagonistic to thinking that one discipline is at the service of the other. Fortunately, what the answers reveal is a different proposition: in general, the faculty expressed a much more articulated approach where both sustainability and the development of mathematical thought are *ends* in themselves, being able only momentarily to exchange their position and become *means*, but without ever losing a sense of importance that permeates them constantly.

As evidenced from the answer presented in Ex. 11 in Table 6, mathematics is proposed as a field of study that is *consistent* with sustainability and the SDGs. According to the teacher, the skills that mathematical thinking is able to develop are not simple *means* to achieve the SDGs as an *end*, but are themselves the types of skills that make a sustainable world possible.

Similarly, in Ex. 12 in Table 6, the focus is on contingency as a way to understand causal relationships and proportions, while at the same time motivating the students.

Table 6 Excerpts from teacher answers on mathematics education and sustainability: strategies and practices

Categories	Quote
The importance of linking mathematics to sustainability and the use of contingency	Ex. 11: I know a little about education skills for sustainable development and I think that mathematics provides many tools, such as a systemic and orderly thinking, clarity, logical thinking, understanding consequences, understanding causalities of problem solving, modeling solutions. (…) Mathematical skills are also very much related to that ability to anticipate, the capacity for the future, not only calculating but how logical reasoning is generated logically, I think it contributes to that, to development. (…) value in the sense of awareness of the future, of empathy, of the future, of current empathy. (…) planning. To have students consider these goals, these values involving education and sustainable development, from a very early stage to they become aware of the effects of using certain materials, of how much they consume and how they use these products in order to minimize the waste they generate (P3)
	Ex. 12: We are doing ratios and proportions with an image from a 2015 news story that says that two out of three people will suffer water shortages. Apart from understanding what a ratio is, it also created a special motivation in the children because they said; "but, Teacher 8, that may be today, it may be much more". How much more do you think? So of course, you motivate them with those kinds of terrible things and they accept it too, but it is possible. Deep down, one might think that in mathematics it is super dry to mix two things, but that is what we have to do, because if not, the children will always be asking us why? So, yes, there is a lot of relationship with that kind of thing (…) in general, how presenting information about one of these topics contributes a lot to their involvement in the topic (P8)
Teaching geometry as a tool for linking mathematics and sustainability	Ex. 13: For example, if we work with geometry in nature, it could be approached from that angle. Also in the environment. For example, in geometry we are now working on parallel and perpendicular lines, and so on. And we saw how spiders make their webs, the parallel lines. Then in any subject one could, that is, any topic, one could work it simultaneously with mathematics (P6)
	Ex. 14: Take this bucket we have in the school for organic recycling. We could get its volume. How much trash it can fit. That falls within the scope of geometry, figuring out the volume, the area of the sides. How high, how wide the container is (P9)
Teaching from the abstract to the concrete	Ex. 15: In mathematics one can always pose a problem, like the beginning or end of some activity. At any rate, with core concepts like multiplication tables, it would be good to start with concepts like the operation and finish with concrete examples (P10)

In this case, the answer, rather than focusing on skills, shifts toward the problem of motivation and the learning processes that make sense to students. In fact, it is worth noting how the teacher takes the contingency of a socio-environmental problem, such as water scarcity, to solve one of the most repeated common places in the teaching of mathematics; namely, the one that presents contents as mere abstractions with no utility or practical application in everyday life.

A second category of responses that appeared in multiple answers was the relationship that teachers establish between geometry with sustainability and the SDGs, for example, to explore certain contents in nature (Ex. 13 in Table 6). One case worth mentioning in this regard is that of a teacher who, shifting away from the topic of "geometry in nature," approaches the problem of the volume of geometric bodies through one of the concrete sustainable actions in place at the school where he teaches (Ex. 14 in Table 6). The interesting thing about the above case is that it manages to incorporate sustainability and the SDGs and geometry by relying on a very specific instance, prompting the students to think mathematically about a problem such as waste management without letting geometry, sustainability and the SDGs be two different "moments" of reflection. The proposal to calculate the volume of a garbage container implies simultaneity in mathematical and environmental reflection. It is not a question of taking stock of a problem by first using the tools offered by geometry; rather, through the very nature of the problem addressed, one becomes aware of the amount of waste produced simultaneously with mathematical learning.

Finally, there is a third category opposite to that of the general group that is worth mentioning. While most of the answers referred to the importance of presenting knowledge through concrete situations, and even alluded to the relationship between mathematics, sustainability, and the SDGs as topics that are simultaneously fed back to develop skills, one participant noted the importance of traveling the path in the opposite way, by focusing on the concept, presenting it in a technical and abstract way, and only at the end or beginning of the learning activity, introducing contextual elements (Ex. 15 in Table 6).

These categories are, in general, linked to reflective and critical thinking competences, oriented to the observation and critical analysis of the reality of the classroom, as well as of one's own ideas and beliefs about teaching and learning mathematics in connection with sustainability and, finally, to self-awareness of progress in relation to both beliefs and teaching practice.

Obstacles and challenges to address the teaching of mathematics in connection with sustainability

The first element to consider in the analysis of this section is that the question that is posed to the teachers has an implicit affirmation, which is that education on sustainability would be an end in itself to develop, and the teaching of mathematics could function as a means to achieve it. However, as noted earlier, it is striking that the majority of the teachers' answers (with some exceptions) refer to the teaching of sustainability in connection with mathematics as a simultaneous process. It seems important to emphasize this point, because it shows that the teachers think that the

learning process of students is intertwined with different purposes or objectives, recognizing their complexity. Regarding this same point, it is striking that on several occasions, the idea of working in an interdisciplinary way with other subjects is mentioned, proposing projects that can be used to cover several objectives in a single educational experience.

That said, the teachers report what they perceive as the greatest obstacles to teaching mathematics in connection with sustainability, among which heterogeneous elements stand out, such as, for example: (a) the mastery they have of the contents; (b) the teaching of complex ways of thinking to students; (c) the curriculum; and (d) time. The last point will be addressed at the end, since it tends to be uniform across the other topics indicated. That is, while there is heterogeneity in the answers to the question posed, there is a common theme to almost all of them when it comes to discussing the challenges to teaching: *time*. Sample excerpts from the teachers' answers that support our analysis are provided in Table 7.

Regarding the first obstacle, on their mastery of the contents, the answers make reference to the knowledge of topics or contingency problems that could be of interest to students (Ex. 16 in Table 7).

Other types of answers were those that alluded to the difficulty of teaching complex ways of thinking to students (Ex. 17 in Table 7). In this regard, what the testimonies collected so far have in common is that teachers feel a certain lack of confidence in the skills, abilities, and tools they can bring to bear during the teaching process, emphasizing different elements: the contents to be taught, the mastery of contingent problems, and the mastery of complex learning processes in children and young people. What these elements have in common is that they are located in the individual, meaning they are perceived as personal elements that must be improved, a responsibility that lies with teachers, not external variables.

The participants further manifest certain obstacles that are located "outside" their individuality and are rather part of the context. One of them is the curriculum. Before analyzing this element, it is necessary to make two clarifications: (a) the curriculum does not usually appear in the answers spontaneously, but rather the teachers report their experiences about it because they are explicitly asked to do so, and (b) we cannot conclude that the curriculum is generally perceived as an obstacle by the teachers. The answers vary greatly in their assessment of the curriculum, with some deeming it an obstacle, and others a facilitator.

The responses that view the curriculum as a facilitator allude to the flexibility of the curriculum and the possibility of changing or modifying its contents and objectives (Ex. 18 in Table 7). Another group of teachers views the curriculum as an obstacle that complicates their work in the classroom (Ex. 19 in Table 7). These testimonials show that the amount of content in the curriculum is regarded as an obstacle to their work during the academic year. Some participants point out that at the beginning of the year, they are usually busy reviewing previous subjects, since some students would return with gaps in their knowledge, which is another factor that restricts the time that can be devoted the curricular contents and objectives that involve mathematics.

As noted earlier, the problem of time appears in the interviews conducted as a common obstacle to the teaching of mathematics in connection with sustainability,

with some distinctions. It takes, on the one hand, the form of a *lack of time* in teachers to plan and carry out learning activities, content, or strategies that manage to effectively align the SDGs with the study of mathematics (Ex. 20 in Table 7), but it can also take the form of a *lack of time* in the classroom to impart a sense of depth and reflection to the learning.

The respondents also note how the lack of time hampers their interdisciplinary work and the connection and cooperation between teachers within the school (Ex. 21 in Table 7). Thus, the planning and execution of activities, whether individually or across subjects, encounters an obstacle in the time that is available to teachers.

Finally, on the challenges perceived by the teachers around the teaching of mathematics in connection with sustainability, as well as whether they identified proportions, ratios, statistics, and geometry as useful contents to present both sustainability and mathematics, the algebra content stood out as the most challenging in terms of establishing links between the two topics. According to the teachers' answers, algebraic expressions are the most difficult content to relate to the students' daily life and to specific situations (Ex. 22 in Table 7).

Awareness of these obstacles and challenges is fundamental for teachers to go beyond mechanically reproducing what they are taught to do, to assume that embedding sustainability in their mathematics teaching practices is the result of the

Table 7 Excerpts from teacher answers involving the obstacles and challenges to teaching mathematics in connection with sustainability

Categories	Quote
Mastery of content	Ex. 16: There are some contingency subjects that I can work with, but I might need to expand my knowledge a little, because this limits the activities I can do, because if I don't have more information, that will limit me (P7)
Teaching complex forms of thought	Ex. 17: What I find hardest is this idea of systemic thinking, of getting students to be able to look beyond what the number is, what the reason is (…) this ability to look as if from above and say 'this is what I have to do', 'this is why I'm doing this', 'this is useful' (P3)
The curriculum	Ex. 18: There aren't many impediments for us, because we have a lot of freedom when making decisions (P6) Ex. 19: This idea of the curriculum and the subjects it covers (…) I feel like I'm coming up short this year (…) we don't have the time to work on analysis tools". Also with respect to the curriculum. (…) there are so many objectives, so many contents, that the students fall back on their school assignments and can't keep up (P2)
Time	Ex. 20: Time can be (…) I realized I needed more hours to do all the things I had planned. And worst of all, I don't know if I'm in charge of my own time (P1) Ex. 21: Synchronize times so we can all have the same goal or be on the same subject. Perhaps how to make a connection beyond this course or the subject of mathematics, and how to involve other teachers, other subjects. (…) So I think one of the keys could be time (P4)
The challenges	Ex. 22: Algebraic expressions, algebraic terms, it is very difficult to relate that to everyday life. And [as a] teacher, the hardest thing to relate to everyday life is algebra, because I do that through games, not with real life. At most, I can relate algebraic language to everyday life when I explain it, but I have problems with that part, and I don't think it's very relatable to sustainability (P5)

interplay of individual efforts to overcome difficulties, available resources (i.e., own knowledge), and contextual and structural factors (Priestley et al., 2015).

Final considerations

This study investigated the teacher agency of mathematics teachers on how to integrate mathematics education and ESD within the research agenda in mathematics education called MTEfS (Alsina, 2023). In addition to ascertaining teacher agency that, according to Priestley et al. (2015), views teachers as professionals who appropriate and reconstruct the resources that have been developed and made available to them, while reshaping these resources to meet new challenges, the goal is to expand the set of data obtained to date on MTEfS, which has focused mainly on analyzing the sustainability skills of pre- and in-service mathematics teachers of various educational stages (e.g., Vásquez & García-Alonso, 2020; García-Alonso & Vásquez, 2021; Moreno-Pino et al., 2023; García-Alonso et al., 2023; Vásquez et al., 2020, 2023b), and on the design and implementation of training programs to develop these skills (e.g., Vásquez & García-Alonso, 2020; Franco et al., 2024; Alsina & Silva-Hormazábal, 2023; García-Alonso & Vásquez, 2021; Helliwell & Ng, 2022; Helliwell et al., 2023).

The data from our study, while nascent, are revealing because they explore four relevant themes in the teaching practices of mathematics teachers for sustainability: (1) knowledge of sustainability and its connection to the SDGs; (2) sustainability activities carried out in schools; (3) strategies and practices to connect math education and sustainability; (4) obstacles and challenges to teaching mathematics in connection with sustainability. According to Priestley et al. (2015), the findings on these four themes begin to show how teachers are developing their teaching agency around the integration of mathematics education and ESD from their own internal resources, together with the input they receive and adapt.

Regarding the teachers' knowledge of sustainability and the SDGs, our data have shown a significant lack of knowledge on the part of more than half of the participants, who make a single association with issues related to the environmental crisis. According to Coles (2023), this vision must be overcome in order to move towards "socio-ecological" practices in mathematics education. For this purpose, a starting point can be "integrate the awareness of the interconnection of socio-political and ecological questions, for example through work on mathematical modelling" (Coles, 2023, p. 31), this will facilitate the development of socially meaningful mathematical learning, enabling the application of mathematical knowledge to real-world problem solving.

A smaller group includes other issues of a social nature, such as gender or lifestyles, and finally, an even smaller number of teachers exhibit a high degree of knowledge. As noted above, this data shows that some teachers are developing their capacity for teaching agency. Thus, in addition to beginning to decide on the incorporation of sustainability into their teaching practice, they are also

beginning to flexibly regulate this practice, considering different conditions and choosing between different possibilities before action (Arievitch, 2017).

This initial finding highlights the need to promote the design and implementation of teacher education programs to improve teachers' knowledge on this topic, along the lines initiated by several authors (e.g., García-Alonso & Vásquez, 2021; Vásquez & García-Alonso, 2020; Franco et al., 2024; Vásquez et al., 2020, 2023b; García-Alonso et al., 2023; Helliwell et al., 2023). Moreover, if these programs really want to promote the development of teacher agency, they should focus on reflection and critical thinking about one's own practice (Esteve & Alsina, 2024).

When the focus is on the actions that participants have taken in their respective schools, almost all of the participants described practices related to sustainability and the SDGs. Again, the data underscore a reductionist view of the issue by focusing these practices on environmental and ecological problems. Another very revealing fact is that practically no reference is made to interdisciplinary practices, except for one teacher who mentions the relationship with mathematics. These results reinforce, as noted, the need to design initial and continuous training programs for teachers. Against this backdrop, for some time now various authors have been promoting sustainable development as a key strategy for transforming policies, investments, and practices in the field of education, not only to try to change education but also the quality of life of many people around the world (Mulà et al., 2017; Orr, 2013; Tilbury, 2011; and others). In this spirit, as indicated in the introduction, various international institutions and organizations recommend the incorporation of ESD in higher education, regarding it as one of the main instruments available to public officials in their attempt to ensure the development of their countries (COPERNICUS Alliance, 2015; UNESCO, 2014, 2015, 2020, 2021).

Within the MTEfS agenda, three categories of responses have been obtained from the teachers participating in the study on strategies and practices to connect mathematical education and sustainability:

- The first group of teachers acknowledges the importance of this connection, rejects an instrumental approach (one at the service of the other), and highlights the feedback between the two to enrich each other, always starting from contextualized situations. This approach involves, for example, one of the main foundations of integral STEAM education (Rodrigues-Silva & Alsina, 2024), which is to promote literacy in the different areas that comprise the acronym from an interdisciplinary perspective, such that the disciplines involved in a STEAM activity feed and enhance one another.
- Another group of teachers places the focus on mathematical content standards and their links with sustainability, showing that the standard that is easiest to connect with sustainability is geometry, and the most complex is algebra, while also considering these connections from context that is real and relatable to children. This belief could be interpreted, above all, from the teachers'

lack of knowledge about what algebra really is and what knowledge is presented in primary school (Pincheira & Alsina, 2022).
– Finally, a single professor mentions an inverse approach to the two previous groups, noting the importance of starting from the mathematical concept and then contextualizing. This deductive approach, which focuses on the theory to then transition to practice (Carlson, 1999), has been questioned by various authors who consider it insufficient. For example, Wideen et al. (1998) point out that teachers trained using this perspective tend to feel unprepared for practice.

In general, these responses show that, more than accumulating knowledge, teacher agency implies a process of developing and improving teaching skills throughout their professional career (Esteve & Alsina, 2024).

The last question analyzed was the obstacles and challenges to address the connection between mathematics education and ESD. Although the teachers are aware of the need for this connection, several aspects have been identified that provoke concerns:

– The mastery of the contents: although the answers are dissimilar, reference is made to the scarce knowledge of topics or problems that are current and of interest to students, an aspect that has been discussed previously.
– Teaching complex forms of thought: a lack of mastery of how children learn complex processes makes teachers feel insecure. Various models and/or characterizations on the knowledge of teachers to teach mathematics emphasize the need to have one of the subdomains of knowledge for teaching mathematics be, precisely, how children learn mathematics (for a review, see Alsina & Delgado-Rebolledo, 2022).

  The curriculum: although some respondents regard it as a facilitator, several teachers view it as an obstacle due to the large amount of content. Although it is obvious that teachers must be knowledgeable of the mathematics curriculum, as indicated by various models of knowledge (Alsina & Delgado-Rebolledo, 2022). Perhaps it would be appropriate for teachers to be able to identify the big ideas in mathematics, which refer to "a statement of an idea that is central to the learning of mathematics, one that links numerous mathematical understandings into a coherent whole" (Charles, 2005, p. 10). According to Toh and Yeo (2019), this would help students see mathematics as a highly connected system of thinking and concepts across various topics, rather than as isolated concepts.
– The time available: in a way, this category permeates the others, placing the focus on the lack of time to plan and implement interdisciplinary activities and to promote deep learning.

As highlighted above, awareness of these difficulties and challenges is essential for teachers to assume that incorporating sustainability in their mathematics teaching practices is the result of the interplay of individual efforts to overcome difficulties, available resources (i.e., own knowledge), and contextual and structural factors (Priestley et al., 2015).

In conclusion, our main results have shown that teachers do not yet have extensive knowledge of sustainability and the SDGs, which makes it difficult for them to design and implement practices based on this perspective. In addition, with regard to the connection with mathematical education, the great majority of teachers believe it is a necessary link, but that certain obstacles and challenges, such as the expansion of knowledge and time management, must be overcome first.

The results of this research can contribute to the development of a roadmap to help propose recommendations and practical guidelines to help in-service teachers address the challenge of integrating mathematics education and ESD. The development of a line of research on this topic is essential because "for education to be an effective vehicle for social change, teacher education is invariably indispensable. A holistic approach to ESD should take into account how new teachers are prepared for real-life tasks in school" (Chin et al., 2018, p. 14). Finally, considering that teacher agency is a complex construct that involves processes such as appropriation, reconstruction, and remodeling of knowledge and beliefs (e.g., Arievitch, 2017; Biesta et al., 2017; Priestley et al., 2015), the main limitation of the study is that it has been a cross-sectional analysis, at one point in time, but has not examined the development of teacher agency on the links between mathematics education and ESD over a long period of time, which would have provided more in-depth data on teachers' professional changes or transformation. Consequently, future studies should present more longitudinal designs to overcome this limitation. Additionally, it will be necessary to obtain data from larger samples from several countries to have a more global picture and to continue taking actions aimed at promoting the professional development in general, and the agentivity in particular, of mathematics teachers for sustainability, so they can become agents of social change (Alsina & Calabuig, 2019; Vásquez et al., 2023b; Vásquez, 2020). On the other hand, although the interviews conducted with in-service primary school teachers are unquestionably rich material, given the characteristics of the study, it is not possible to generalize the results to a wider group. However, the relevance of this study lies in the opportunity to systematize information on a topic that has not yet been addressed, namely teacher agency with respect to the links between mathematics education and sustainability.

Funding Work carried out as part of FONDECYT N°. 1200356, funded by the Agencia Nacional de Investigación y Desarrollo (ANID) of Chile and project SGR 2021 00767, funded by the Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) of Catalonia (Spain).

Declarations

Ethics Approval Attached is the ethics approval letter for the Fondecyt Regular 1200356 project. Ethics approval protocol ID UC 190613048. The research study that underpins this publication was provided by project Fondecyt Regular 1200356 of Pontificia Universidad Católica de Chile, Registration number 190613048.

Informed Consent Informed consent was obtained as follows, as indicated in the methodology section of the article. The participants were recruited by means of open invitations that were sent to the directors of schools in various regions of Chile, who then forwarded the invitations to the teachers in their schools, all of whom subsequently and voluntarily signed the informed consents.

References

Alsina, Á. (2022). On integrating mathematics education and sustainability in teacher training: Why, to What End and How? In D. Ortega-Sánchez (Ed.), *Controversial Issues and Social Problems for an Integrated Disciplinary Teaching.Integrated Science*, vol 8. (pp. 9–21). Springer. https://doi.org/10.1007/978-3-031-08697-7

Alsina, Á. (2023). Mathematics Teacher Education for Sustainability (MTEfS): An emerging research agenda. *AIEM - Avances de Investigación en Educación Matemática, 23*, 1–4. https://doi.org/10.35763/aiem23.5726seiem.es

Alsina, Á., & Calabuig, M. T. (2019) Vinculando educación matemática y sostenibilidad: Implicaciones para la formación inicial de maestros como herramienta de transformación social. *Revista de Educación Ambiental y Sostenibilidad, 1*(1), 1203. https://doi.org/10.25267/Rev_educ_ambient_sostenibilidad.2019.v1.i1.1203

Alsina, Á., & Delgado-Rebolledo, R. (2022). ¿Qué conocimientos necesita el profesorado de Educación Infantil para enseñar matemáticas? *Matemáticas, Educación y Sociedad, 5*(1), 18–37.

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*(15), 4039. https://doi.org/10.3390/su11154039

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

Arievitch, I. (2017). *Beyond the brain: An agentive activity perspective on mind, development, and learning*. Sense Publishers.

Bianchi, G., Pisiotis, U., & Cabrera-Giraldez, M. (2022). GreenComp The European sustainability competence framework. *Publications Office of the European Union*. https://doi.org/10.2760/13286

Biesta, G., Priestley, M., & Robinson, S. (2017). Talking about education: Exploring the significance of teachers' talk for teacher agency. *Journal of Curriculum Studies, 49*(1), 38–54. https://doi.org/10.1080/00220272.2016.1205143

Bisquerra, R. (2019). *Metodología de la Investigación Educativa*. España: La Muralla.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101.

Carlson, H. L. (1999). From practice to theory: A social constructivist approach to teacher education. *Teachers and Teaching: Theory and Practice, 5*(2), 203–218.

CCEA. (2020). *Using Mathematics*. https://ccea.org.uk/foundation-stage/curriculum/using-mathematics. Retrieved March 15, 2021.

Charles, R. (2005). Big ideas and understandings as the foundation for elementary and middle school mathematics. *Journal of Mathematics Education Leadership, 7*, 9–24.

Chin, C. K., Munip, H., Miyadera, R., Thoe, N. K., Ch'ng, Y. S., & Promsing, N. (2018). Promoting education for sustainable development in teacher education integrating blended learning and digital tools: An evaluation with exemplary cases. *Eurasia Journal of Mathematics, Science and Technology Education, 15*(1), em1653. https://doi.org/10.29333/ejmste/99513

Cohen, L., Manion, L., & Morrison, L. (2018). *Research methods in education*. Routledge.

Coles, A. (2023). Towards a socio-ecological practice of mathematics teacher education. *AIEM - Avances De Investigación En Educación Matemática, 23*, 19–35. https://doi.org/10.35763/aiem23.5489

COPERNICUS Alliance. (2015). *Rio+20 Treaty*. https://www.copernicus-alliance.org/rio-20-treaty. Retrieved June 21, 2020.

Esteve, O., & Alsina, Á. (2024). *Hacia una formación transformadora de docentes. Estrategias eficaces para formadores*. Narcea, S.A. de Ediciones.

Franco, J., Alsina, A., & Vásquez, C. (2024). Teaching statistics for sustainability across contexts: Exploring the knowledge and beliefs of teachers. *Sustainability, 16*, 692. https://doi.org/10.3390/su16020692

García-Alonso, I., & Vásquez, C. (2021). Educación Estadística en el contexto de la sostenibilidad: una perspectiva de formación con futuros profesores de Educación Primaria. *Revista Tangram, 4*(4), 3–34. https://doi.org/10.30612/tangram.v4i4.15407

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

Helliwell, T., & Ng, O. L. (2022). Imagining possibilities: Innovating mathematics (teacher) education for sustainable futures. *Research in Mathematics Education, 24*(2), 128–149. https://doi.org/10.1080/14794802.2022.2079553

Helliwell, T., Hennessy, L., & Bushnell, K. (2023). Conceptualising one mathematics teacher's process of becoming in relation to teaching mathematics and climate justice: The story of Karl. *AIEM - Avances De Investigación En Educación Matemática, 23*, 85–104. https://doi.org/10.35763/aiem23.5533

Johnson, K. E., & Golombek, P. R. (2016). *Mindful L2 teacher education*. Routledge.

Kvale, S. (2011). *Las entrevistas en investigación cualitativa*. Ediciones Morata.

Moreno-Pino, F. M., Jiménez-Fontana, R., & Romero-Portillo, D. (2023). Development of sustainability competencies in the area of didactics of mathematics. *AIEM - Avances De Investigación En Educación Matemática, 23*, 37–60. https://doi.org/10.35763/aiem23.5373

Mulà, I., Tilbury, D., Ryan, A., Mader, M., Dlouha, J., Mader, C., Benayas, J., Dlouhy, J., & Alba, D. (2017). Catalysing change in higher education for sustainable development: A review of professional development initiatives for university educators. *International Journal of Sustainability in Higher Education, 18*(5), 798–820. https://doi.org/10.1108/IJSHE-03-2017-0043

NCTM. (2000). *Principles and Standards for School Mathematics*. NCTM.

Orr, D. W. (2013). *Gobernanza durante la emergencia de larga duración. En Worldwatch Institute, The State of the World 2013: Is Sustainability Still Possible?* New York: W.W. Norton.

Pincheira, N., & Alsina, Á. (2022). Mathematical knowledge of pre-service early childhood and primary education teachers: an approach based on the design of tasks involving patterns. *Australian Journal of Teacher Education, 47*(8), 50–69.

Priestley, M., Biesta, G. J. J., & Robinson, S. (2015). Teacher agency: What is it and why does it matter? In R. Kneyber & J. Evers (Eds.), *Flip the system: Changing education from the bottom up* (pp. 1–11). Routledge. https://doi.org/10.4324/9781315678573-15

Rodrigues-Silva, J., & Alsina, Á. (2024). Enhancing Teachers' Professional Identity in a Reflective Learning MOOC. *International Journal of Emerging Technologies in Learning (iJET), 19*(1), 23–38. https://doi.org/10.3991/ijet.v19i01.38897

Schön, D. (1983). *The reflective practitioner: How professionals think in action*. Temple Smith.

Stake, R. (2020). *Investigación con estudio de casos*. S.L.: Morata.

Tilbury, D. (2011). *Education for sustainable development: An expert review of processes and learning*. UNESCO.

Toh, T. L., & Yeo, J. B. W. (2019). *Big ideas in mathematics: Yearbook 2019, Association of Mathematics Educators*. WSPC.

UNESCO. (2014). *Aichi-Nagoya Declaration on Higher Education for Sustainable Development*. https://sustainabledevelopment.un.org/content/documents/5859Aichi-Nagoya_Declaration_EN.pdf. Retrieved June 21, 2020.

UNESCO. (2015). *Global citizenship education: Topics and learning objectives*. UNESCO.

UNESCO. (2017). *Education for Sustainable Development Goals. Learning Objectives.* https://unesdoc.unesco.org/ark:/48223/pf0000247444. Retrieved June 23, 2020.

UNESCO. (2020). *Education for sustainable development: A roadmap*. UNESCO.

UNESCO. (2021). *Berlin Declaration on Education for Sustainable Development*. https://en.unesco.org/sites/default/files/esdfor2030-berlin-declaration-en.pdf. Retrieved March 23, 2022.

UNESCO, & Education International. (2021). *Teachers have their say: Motivation, skills and opportunities to teach education for sustainable development and global citizenship.* UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000379914. Retrieved March 23, 2022.

Vásquez, C. (2020). Educación estocástica: Una herramienta para formar ciudadanos de sostenibilidad. *Revista Matemática, Educación y Sociedad, 3*(2), 1–20.

Vásquez, C., & García-Alonso, I. (2020). La educación estadística para el desarrollo sostenible en la formación del profesorado. Profesorado. *Revista de Currículum y formación de profesorado, 24*(3), 125–147. https://doi.org/10.30827/profesorado.v24i3.15214

Vásquez, C., Alsina, Á., Seckel, M. J., & García-Alonso, I. (2023a). Integrating sustainability in mathematics education and statistics education: A systematic review. *Eurasia Journal of Mathematics, Science and Technology Education, 19*(11), em2357. https://doi.org/10.29333/ejmste/13809

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*(6), 3115. https://doi.org/10.3390/su13063115

Vásquez, C., Piñeiro, J. L., & García-Alonso, I. (2022). What challenges does the 21st century impose on the knowledge of primary school teachers who teach mathematics? An analysis from a Latin American perspective. *Mathematics, 10*, 391. https://doi.org/10.3390/math10030391

Vásquez, C., Seckel, M. J., & Alsina, Á. (2020). Sistema de creencias de los futuros maestros sobre Educación para el Desarrollo Sostenible en la clase de matemática. *Revista Uniciencia, 34*(2), 16–30. https://doi.org/10.15359/ru.34-2.1

Vásquez, C., Seckel, M. J., & Rojas, F. (2023b). Connecting statistics education and sustainability: Beliefs of primary education teachers. *Avances de Investigación en Educación Matemática, 23*, 127–146. https://doi.org/10.35763/aiem23.5415

Wideen, M. F., Mayer-Smith, J. A., & Moon, B. J. (1998). A critical analysis of the research on learning to teach: Making the case for an ecological perspective on inquiry. *Review of Educational Research, 68*(2), 130–178.

Zhang, S., Zhao, W., & Cao, Y. (2021). Toward sustainable professional development: An investigation of informal interactions among Chinese mathematics teachers. *Frontiers in Psychology, 12*, 681774. https://doi.org/10.3389/fpsyg.2021.681774