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Education for sustainable development through mathematical modelling in higher education: conceptual considerations, empirical explorations and implications

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ABSTRACT
Education for sustainable development (ESD) is becoming increasingly important as an interdisciplinary task for all disciplines at all levels of education, including mathematics education. However, what is meant by ESD quite often remains unclear or is regarded as a highly contested construct. Based on these considerations, this article addresses two issues: (1) Firstly, it discusses the conceptualisation of ESD as a construct in the field of tension between instrumental and emancipatory approaches. Based on these discussions, it is highlighted (focusing on the example of mathematical modelling in mathematics education) that mathematics must be seen as an indispensable part of ESD, especially in higher education. (2) Since there are few concepts for concrete interdisciplinary implementation of ESD, and it is largely unclear how learners' awareness of the importance of mathematical modelling for sustainability issues can be promoted in educational processes, this article secondly presents a conceptually based and empirically demonstrated concept of a university seminar on mathematical modelling of sustainability issues. The implementation of the seminar was scientifically monitored by means of an intervention study, investigating the extent to which university students' beliefs and self-efficacy changed while participating in such a seminar. Empirical results highlight positive effects of this intervention.

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Education for sustainable development (ESD); mathematical modelling; mathematics education; higher education; beliefs; self-efficacy

1. Introduction

Climate crisis, lack of food security, forced migration, and growing social injustice – even before the global COVID-19 pandemic in the early 2020s, it was clear that the twenty-first century would be a century of existential challenges. In response to these challenges, United Nations (UN) member states adopted the '2030 Agenda for Sustainable Development' back in 2015 (United Nations, 2015). The international community has thus set itself a total of 17 global sustainability goals, including the complete eradication of poverty and hunger

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worldwide. One of these goals is to 'ensure inclusive and equitable quality education and promote lifelong learning opportunities for all' (United Nations, 2015, p. 14). The concept of education for sustainable development (ESD) is explicitly cited as a key lever for achieving this goal and as an 'enabler' to all sustainability goals (UNESCO, 2022, p. 3; United Nations, 2015, p. 17). However, the implementation of ESD in educational systems is by no means trivial, and there are different, sometimes contradictory approaches. The overall aim of ESD is to empower all learners to participate actively in promoting sustainable development, and it is addressed to all subjects as an interdisciplinary task. ESD is therefore also relevant to mathematics education, and achieving such societal goals is seen as one of the future themes of mathematics education (Bakker et al., 2021; Coles et al., 2024; Li & Tsai, 2021). In this context, mathematical modelling, in particular, is considered a promising approach to implementing ESD through or in mathematics education (Vorhölter & Siller, 2023). However, whilst higher education is considered crucial for successful ESD, there are few concepts for concrete implementation at the tertiary level, and it is largely unclear how learners' awareness of the importance of mathematical modelling for sustainability issues can be created or promoted in educational processes in the sense of ESD.

Following on from this, this article addresses two key issues and is organised into the following sections. *Section 2* is devoted to the conceptual treatment of ESD and mathematical modelling in higher education. As a first outcome of the article, this section presents a conceptualisation of ESD in the field of tension between instrumental and emancipatory approaches. Subsequently, mathematical modelling is conceptually derived as a possible approach to the implementation of ESD, both in general and in relation to higher education. *Section 3* presents an exploratory empirical research study. Here, in line with *section 2*, a new conceptually based and empirically proven concept of a university seminar on mathematical modelling of sustainability issues is presented. An accompanying study, in the sense of an intervention study, is described for this seminar, investigating the extent to which university students' beliefs about the importance of mathematics for sustainable development and self-efficacy change while participating in such a seminar. It will be highlighted: Sensitising university students (future leaders) for the importance of mathematics when dealing with open questions of sustainable development can be done successfully in higher education. The article closes with an overall discussion in *section 4*.

2. Conceptual part: education for sustainable development and mathematical modelling (in higher education)

The first of the two main sections of the article addresses the conceptual treatment of ESD and mathematical modelling in higher education. *Subsection 2.1* first introduces different approaches to the educational concept of ESD and derives a conceptualisation that will serve as the basis for this article. Following this, mathematical modelling is presented and legitimised as a means of promoting ESD, firstly in general terms in *subsection 2.2* and specifically in relation to higher education in *subsection 2.3*.

2.1. Conceptualisation of education for sustainable development in the field of tension between instrumental and emancipatory approaches

In recent years, ESD has become a new focus of educational policy and practice worldwide. However, what is actually meant conceptually by implementing ESD in an educational context quite often remains unclear or is regarded as a highly contested construct (Connelly, 2007; Kopnina, 2020). In deriving and conceptualising an understanding of ESD for this article, it is useful first to take a step back and clarify what is meant by sustainable development (SD). Again, there are many different definitions, most of which remain very abstract (see Ruggerio, 2021). A central and still widely used definition for the international community comes from the World Commission on Environment and Development (WCED, 1987, Chapter 2), according to which development is sustainable if it 'meets the needs of the present without compromising the ability of future generations to meet their own needs'. Modern definitions of SD typically refer to specific dimensions that are crucial for sustainable development (Ruggerio, 2021). This typically encompasses environmental, economic, and social dimensions (referred to as the 'triple bottom line'; see Tseng et al., 2020). So Krasny (2020, p. 47) summarises succinctly that 'the notion of sustainable development proposes that society can meet goals for economic development and equity, while also sustaining natural systems'. While SD describes the development towards such a goal in terms of sustainability, ESD refers to enabling learners to participate actively in such a development. Regarding the focus on the conceptualisation of ESD, it is essential to note that the concept of ESD has not been limited to educational science since the United Nations' '2030 Agenda for Sustainable Development'. Discourses around ESD and other related or synonymous concepts have existed for decades (see Hopkins & McKeown, 2002; Sherren, 2008). Although there are many different ways of implementing ESD, two overarching approaches can be distinguished in simple terms from these discussions and different trends (based on Vare & Scott, 2007; Wals, 2011; Wals et al., 2008): 'ESD 1' (learning *for* sustainable development) describes an instrumental approach aiming at promoting changes in human behaviour, whilst 'ESD 2' (learning *as* sustainable development) describes an emancipatory approach aiming at fostering humans' critical reflection skills. In the remainder of this subsection, both approaches are discussed in more detail, and a conceptual understanding of ESD is derived for the article based on this area of tension.

2.1.1. Instrumental education for sustainable development approach

The instrumental approach is often referred to as 'ESD 1' or 'learning *for* sustainable development' (Vare & Scott, 2007), which aims at promoting sustainable attitudes and behaviours in learners. This is based on the idea that experts can identify which behaviours are recognised as sustainable, and these should be normatively promoted among learners. In terms of learning theory, this ESD approach is based on a behaviourist understanding of education (Sterling, 2010). The approach is considered useful in that it is expected to make rapid and direct contributions to sustainable development. This understanding of ESD is reflected in many education policy documents from government departments, NGOs, or UNESCO itself. For example, in the 'Berlin Declaration on Education for Sustainable Development', UNESCO (2022, pp. 3–4) states: 'Implement ESD with joint emphasis on the cognitive skills, social and emotional learning, and action competences for the individual and societal dimensions of transformation, promoting individual behavioural change for sustainable development, equality and respect for human rights as well as fundamental structural and cultural changes at the systemic level of economies and societies, and also promoting the required political action to bring about these changes'. It explicitly states the promotion of (1) individual behavioural change for sustainable development and (2) required political action to bring about these changes as ESD goals. Such an instrumental understanding of education raises some central problems, at least if fostering autonomous thinking is seen as a key goal in education (Wals, 2011). In his examination of ESD perspectives, Wals draws on Jickling's (1992) critical consideration that this instrumental approach reduces education to the training of technical skills without fostering meaningful understanding, which contradicts the fundamental idea of education.

2.1.2. Emancipatory education for sustainable development approach

The emancipatory approach ('ESD 2' or 'learning *as* sustainable development') aims to enable learners to think independently and critically about sustainability issues (Vare & Scott, 2007). In terms of learning theory, the approach can be categorised as constructivist (Sterling, 2010). In contrast to the previous approach, it is not based on following the knowledge of experts but on critically questioning it (Vare & Scott, 2007). This assumes that the application of what is currently considered sustainable by experts will not help us to meet future, as yet unforeseeable challenges, and that critical reflection skills should therefore be encouraged. The aim is merely enabling learners to commit themselves to sustainable development; the path, if any, is up to them: 'In this view, environmental and sustainability issues provide an important context through which learning takes place, but ultimately, whether or not the learner engages in more sustainable behaviours or environmental protection is of important but of secondary value and is a judgement that needs to be made by the critically reflective learner' (Sterling, 2010, p. 514).

2.1.3. Derivation with recourse to the Beutelsbach Consensus

Before implementing ESD in education, it is therefore essential to clarify (and transparently emphasise) which understanding of ESD is being referred to in this area of tension. Ultimately, the discussion about ESD 1 and ESD 2 can be traced back to the question of how instrumental we can be or how neutral we should be on controversial (sustainability-related) issues. However, as is often the case, this is not a new discussion altogether. Therefore, it is worthwhile to examine analogous discussions and their solutions. One such possible solution is to fall back on the German concept of the so-called 'Beutelsbach Consensus' (see Christensen & Grammes, 2020; Reinhardt, 2016). The question of how to address controversy and neutrality in schools was the subject of a contentious debate in West Germany, particularly in the 1970s. At a conference, the contending authors laid down their minimum consensus, which is still regarded as a cornerstone and basic framework of civic education in Germany. This 'Beutelsbach Consensus' comprises three points (originally in Wehling (1977), based on the translation from Reinhardt (2016)):

(1) *Prohibition against overwhelming the student*. It is not permissible to catch students off-guard, by whatever means, for the sake of imparting desirable opinions, thereby hindering them from 'forming an independent judgment'. This is the difference between political education and indoctrination. Indoctrination is incompatible with the role of a teacher in a democratic society and the generally accepted objective of enabling students to develop independent responsibility and maturity.
(2) *Treating controversial issues as controversial*. Matters that are controversial in scholarship and political affairs should also be presented as controversial in the classroom. This requirement is very closely linked to the first point: a teacher who loses

sight of differing points of view, suppresses options, and leaves alternatives undiscussed is already well on their way to indoctrinating students. We must ask, on the contrary, whether teachers should, in fact, play a corrective role.

(3) *Giving weight to the personal interests of students.* Students should be placed in a position to analyse a political situation and their own personal interests, as well as to seek ways to influence given political realities in light of these interests. Such an objective strongly emphasises the acquisition of operational skills, which follows logically from the first two principles set out above.

In terms of ESD, these principles clearly favour ESD 2. Instrumentalisation, here understood as indoctrination, is therefore incompatible with the principles of education in democracies (point 1), and there is even an obligation to address controversies (point 2) rather than just teaching behaviour considered sustainable. It is also explicitly emphasised that students should be able to analyse the political situation in terms of their own interests (point 3), rather than focusing on a specific interest in sustainability. This could lead to the conclusion that, in modern democratic societies, ESD should only be implemented as 'ESD 2' and therefore educational processes should be accompanied neutrally. However, no such 'neutrality requirement' can be derived from the Beutelsbach Consensus (Christensen & Grammes, 2020). Accordingly, teachers in democracies are not neutral but are obliged to actively promote democracy and human rights. Thus, anti-democratic, inhuman, or anticonstitutional positions are explicitly not treated as equal and value-neutral by teachers as part of the controversy requirement (point 2). Consequently, not only can an understanding of education in the sense of ESD 2 be derived from the considerations surrounding the Beutelsbach Consensus, but also an instrumental framework that is more in line with ESD 1.

In summary, from the previous conceptual considerations, it can be deduced that ESD (in the sense of a hybrid approach) should be fundamentally emancipatory in nature and that no specific sustainability concept should be imposed in the sense of indoctrination, but not completely without a normative framework, as educational institutions have a clear mandate to uphold democracy and human rights. Based on this, the article understands ESD as *enabling students to become responsible citizens, able to judge independently but within a normative framework (democracy and human rights).*

2.2. Education for sustainable development and mathematical modelling

Regardless of the understanding of the concept of ESD, there is a consensus that ESD is a cross-cutting task for all disciplines and educational levels. Also, the Mahatma Gandhi Institute of Education for Peace and Sustainable Development of UNESCO (UNESCO MGIEP) states: 'Embedding ESD into core subjects is one of the most effective and efficient ways to achieve SDG [Sustainable Development Goals] Target 4.7' (UNESCO MGIEP, 2017). Accordingly, ESD must also be understood as a clear mission for mathematics education. It is evident that the fundamental ideas of ESD derived above can be directly linked to the underlying ideas of mathematical literacy. For example, mathematical literacy is defined in the PISA framework (OECD, 2023, p. 22) as: 'Mathematical literacy is an individual's capacity to reason mathematically and to formulate, employ, and interpret mathematics to solve problems in a variety of real-world contexts. It includes concepts, procedures, facts and tools to describe, explain and predict phenomena. It assists individuals to know the role that mathematics plays in the world and to make the well-founded judgments and decisions needed by constructive, engaged and reflective twenty-first century citizens'. Mathematics is thus understood here as a support for making independent, well-founded judgements and decisions as a responsible citizen, which precisely matches the core of the ESD understanding derived above. References to the need for a foundation in terms of democracy and human rights can also be found in the normative reflections on mathematics education (Skovsmose, 2023).

A significant possibility for implementing ESD through mathematics education is mathematical modelling (Lucas & Paulo, 2024; Vorhölter & Siller, 2023; Wiegand & Borromeo Ferri, 2023). Modelling in mathematics education (despite many different perspectives, see Kaiser, 2017) is basically understood as being the process of working on and solving real-world problems by using mathematics (Geiger et al., 2022; Kaiser, 2017; Maaß, 2010; Niss et al., 2007). In particular, the competency of mathematical modelling characterises the necessary translation processes between the extra-mathematical and the intra-mathematical realm (Leiss et al., 2019; Niss & Blum, 2020). The entire modelling process itself is often idealised as a cycle that describes different sub-competencies (here, using the example of the cycle established in the scientific community by Blum & Leiss, 2007; see Figure 1a). First, the student constructs their own mental model of the real situation (Step 1 – Understanding) and then simplifies the situation, for example, by making assumptions (Step 2 – Simplifying/Structuring). The student then transfers relevant variables and relationships into a mathematical model (Step 3 – Mathematising), processes the problem mathematically (Step 4 – Working mathematically), and relates the mathematical result back to the real situation (Step 5 – Interpreting). Finally, the student checks the appropriateness of the solution (Step 6 – Validating) and answers the initial question (Step 7 – Exposing).

Modelling can develop the potential for ESD, especially if the initial real-world problems are based on ESD-relevant environmental, economic, or social problems (as this is obviously the case in the sample in Figure 1b, addressing the problem of working conditions in textile production; modelling task and ideal processes (here very shortened) from Krug et al. (2025)). Here, the perspective of socio-critical modelling comes to the fore. The aim of this approach is to foster a critical understanding of the world by modelling socio-critical and socio-cultural phenomena (Kaiser, 2017; Rosa & Orey, 2015; Stillman et al., 2013). In this approach, mathematical modelling offers students a way of working with reality by reducing its complexity and using mathematical models to understand real problems. Students learn to simplify, formulate, test, and correct hypotheses, reflect on solutions, and make decisions (Rosa & Orey, 2015). However, part of the approach is not only to use mathematical modelling to gain a critical view of reality but also to reflect on the limits of mathematical models in reality itself (Kaiser, 2017). This interrelationship between ESD on the one hand and mathematical modelling on the other is also evident when examining task criteria. Haier et al. (2022) showed (also drawing on socio-critical modelling) that there is an overlap between the criteria for good modelling and good ESD tasks and that common criteria for ESD modelling tasks can be derived from this. In addition, Vorhölter and Siller (2023) write about the symbiosis of ESD and mathematical modelling: 'Applying mathematics in real and meaningful contexts by means of real problems, issues, or existing problems, enables learners not only to recognise the value of mathematical concepts for

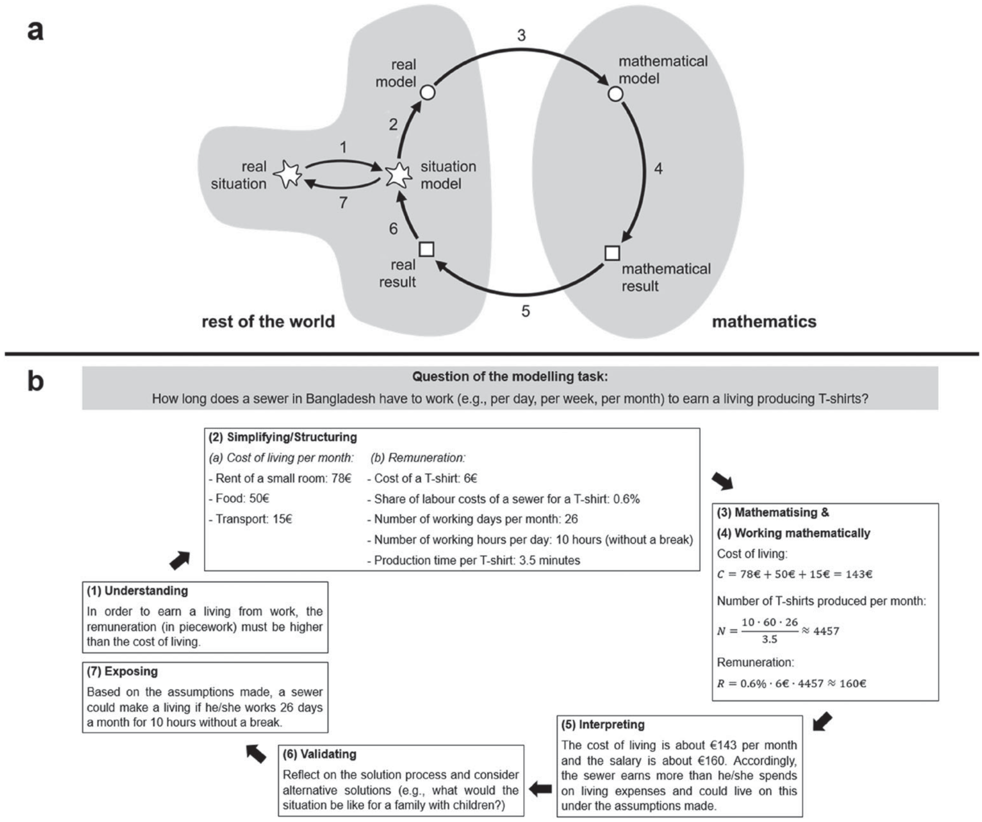

Figure 1. (a) Modelling cycle (based on Blum & Leiss, 2007; redrawn by the authors). (b) Exemplary ESD modelling task from Krug et al. (2025) with very shortened processing.

understanding SDG-specific problems, but also to find arguments for specific actions as well as to evaluate recommendations and proposals for action resulting from modelling'.

These conceptual considerations demonstrate that mathematical modelling can make a fundamental contribution to ESD. Conversely, it can also be deduced that successful ESD cannot only rely on mathematical modelling but also depends on it. It is evident that sustainability problems are often linked to quantitative data or arguments (Gibson et al., 2023). The processes of understanding and critically reflecting on the underlying models outlined above can only be achieved through mathematics (more precisely, mathematical modelling), which makes it an indispensable part of ESD in terms of an interdisciplinary approach. However, the practical implementation of ESD through mathematical modelling at different levels of education has been little researched and remains largely unclear (Haier et al., 2022).

2.3. Education for sustainable development through mathematical modelling in higher education

In addition to primary and secondary education, the tertiary sector is also crucial for successful ESD (Chankseliani & McCowan, 2021; Fehlner, 2019; Žalėnienė & Pereira, 2021).

Higher education institutions are seen as key players in shaping future leaders and enabling them to meet the challenges of the twenty-first century (Žalėnienė & Pereira, 2021). Despite this outstanding importance, tertiary education is sometimes considered to be underestimated in relation to ESD, and there are considerable gaps in research (Fehlner, 2019). The implementation of ESD in mathematical modelling is particularly important in tertiary mathematics education because an increasing number of academic professions rely on data and therefore need to be able to use mathematical models responsibly.

For implementing ESD in higher education, different competency models exist. Here, Brundiers et al. (2021) can be used as a central reference framework, which represents an extension of the widely known framework of key competencies in sustainability by Wiek et al. (2011). This includes systems-thinking competency, futures-thinking competency, values-thinking competency, strategic-thinking competency, implementation competency, interpersonal competency, integrated problem-solving competency, and intrapersonal competency. A closer examination of these competencies reveals that mathematical modelling plays a central role here. For instance, Brundiers et al. (2021) emphasise that the so-called 'futures-thinking competency' requires knowledge of pertinent concepts, such as plausibility versus probability, and methods, including forecasting from statistical models (both of which are directly linked to mathematical modelling). Wiek et al. (2011) even explicitly refer to qualitative and quantitative modelling, here in the context of the systems-thinking competency.

In summary, it becomes apparent that mathematical modelling is not only compatible with and an indispensable part of ESD in general but is also directly aligned with the goals of ESD in higher education. Against this background, the question arises as to how the potential of mathematical modelling can be realised in the context of higher education. This question is addressed in the following part by taking an empirical step into this field of research.

3. Empirical part: exploratory research on the implementation of education for sustainable development through mathematical modelling in higher education

Based on the previous conceptual considerations, this second section of the article deals with an exploratory study on the implementation of ESD in higher education. *Subsection 3.1* begins by outlining the specific research interest and presenting the research questions. Afterwards, the seminar on which the study is based is presented in terms of its conception in *subsection 3.2,* and the methods used to investigate the research questions are outlined in *subsection 3.3*. The results are presented in subsection 3.4 and then discussed in *section 4*.

3.1. Research interest

There are few studies on the implementation of ESD through mathematical modelling in higher education, and existing ones tend to focus selectively on the teaching of prospective teachers (Çibik & Boz-Yaman, 2025; Wiegand & Borromeo Ferri, 2023). One example is Wiegand and Borromeo Ferri (2023), who developed an ESD-modelling seminar for pre-service teachers and identified teacher profiles using qualitative content analysis of participants' written reflections. There are very few studies on the implementation of ESD in other programmes or across programmes, and when there are, they highlight the need for more in-depth research (Karjanto, 2023; Lafuente-Lechuga et al., 2024). In addition to the shortage of concrete approaches to implementing ESD through mathematical modelling in higher education, there are also open empirical questions. It is widely recognised that in the context of ESD educational processes, the empirical study of, e.g. beliefs, competencies, self-efficacy, knowledge, or values is important. For instance, Sterling (2010, p. 512) considers transformative learning in the sense of ESD to be 'a quality of learning that is deeply engaging, and touches and changes deep levels of values and belief through a process of realization and recognition' that 'inevitably gives rise to a heightened relational sensibility and a sense of ethical responsibility'. Leicht et al. (2018, p. 7) also emphasise the importance of 'changes in knowledge, skills, values and attitudes to enable a more sustainable and just society for all'. The extent to which such concepts, particularly in relation to mathematical modelling and sustainability, actually change as a result of being addressed in higher education teaching remains largely unclear.

Two aims for the empirical study can be derived from these considerations: (1) Developing a concept of a university seminar on mathematical modelling of sustainability issues with students from various degree programmes and (2) gaining initial insights into the extent to which such a seminar enables learners becoming aware of the importance of mathematical modelling for sustainability issues in educational processes in the sense of ESD. Regarding the second aim of investigating open empirical questions, the change in a few selected constructs among participants in such a seminar will be explored.

As shown above, the importance of beliefs is often cited in the consideration of ESD education processes. Basically, beliefs are 'psychologically held understandings and assumptions about phenomena or objects of the world that are felt to be true, have both implicit and explicit aspects, and influence people's interactions with the world' (Voss et al., 2013, p. 249). The aim of implementing ESD through modelling should be to ensure that the existential importance of mathematics for investigating sustainability issues, as outlined in the article, is reflected in the beliefs of such learners. The aim is to develop learners' powers of judgment so that they can make informed decisions (also based on mathematical considerations) as responsible citizens. The extent to which such beliefs actually change empirically when participating in a seminar on mathematical modelling of sustainability issues is to be investigated in this study by research question 1:

> Research question 1: How does learners' belief in the importance of mathematics for sustainable development change in the course of participation in a seminar on mathematical modelling of sustainability issues?

Additionally, self-efficacy, which is strongly linked to performance, is important for educational processes and will be examined in more detail as part of the scientific monitoring of the ESD seminar. Essentially, self-efficacy refers to a person's belief in their ability to apply their skills effectively under specific conditions (Maddux, 2005; Street et al., 2024; Thompson, 2005). More precisely, self-efficacy is not merely a prediction of what one will do in terms of behaviour, but a belief about what one can do (Maddux, 2005). In the context of a seminar on mathematical modelling of sustainability issues, two areas are of particular importance, as highlighted in the conceptual part. (1) Mathematical modelling self-efficacy, meaning the belief of students in their ability to apply their mathematical modelling skills effectively (Koyuncu et al., 2017). (2) Political self-efficacy, meaning the belief of students in their ability to effectively understand, analyse, and influence political and societal processes through personal engagement and action (Balch, 1974; Beierlein et al., 2012). Accordingly, research question 2 is:

> Research question 2: How do learners' mathematical modelling and political self-efficacies change in the course of participation in a university seminar on mathematical modelling of sustainability issues?

3.2. Conception of the seminar

The seminar on mathematical modelling of sustainability issues on which the study is based was conceptualised and realised as part of the educational development project "Speed limit, heat pump, electric car - mathematical modelling of sustainability" (funded by the "Ministry of Science and Culture of Lower Saxony" from Germany as part of the "Innovation Plus" funding line). The seminar was held in German in the winter semester 2023/2024 as part of the introductory semester ("Leuphana Semester") at Leuphana University Lüneburg and comprised 14 learning sessions. During this "Leuphana Semester", all first-year students in all degree programmes complete various interdisciplinary modules in which they acquire the fundamental methods for a scientific course of study (Barth & Timm, 2011; Michelsen, 2013). The present seminar was embedded in the module 'Producing knowledge: methodologies' and was entitled 'Using mathematics to think and act sustainably'. Students have selected the seminar by interest.

3.2.1. Basic conceptual considerations of the seminar

The overarching aim of the seminar is to enable students to analyse and understand sustainability issues in greater depth by using mathematics. It also aims to sensitise students to the importance of mathematical models in the discourse on sustainability issues, as outlined in the conceptual section. The carbon footprint is chosen as the focus of the seminar's content to make the topic tangible and actionable. In terms of socio-critical modelling, the topic is suitable because it enables both a critical examination of carbon emissions through mathematical modelling and an exploration of the limits of modelling itself. When implementing ESD in or through mathematics education, it is crucial to clearly disclose the underlying conceptual considerations (Li & Tsai, 2021). The design of the seminar is based on the conceptualisation of ESD in the field of tension between instrumental and emancipatory approaches derived in subsection 3.1.2. Implementing the mathematical modelling of CO_2 emissions via this approach illustrates the tensions involved and highlights the practical implications of this conceptualisation for the seminar. This becomes particularly apparent when reflecting on the real results of the respective modelling processes, corresponding to steps 6 and 7 of the modelling cycle (Blum & Leiss, 2007). For example, a model might indicate that activity A emits more climate-damaging CO_2 than activity B. This result raises the question of what its real-life consequences are. In line with the conceptualisation, the goal is not to educate students instrumentally to stop engaging in activity A in the name of sustainability. Rather, the goal is to enable them to engage with such quantitative information in the context of sustainability (as described in the framework of Brundiers et al., 2021) and to provide the foundation for making autonomous,

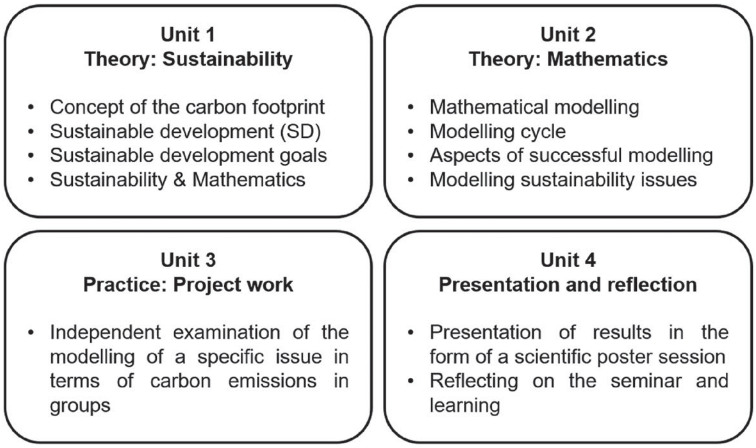

Figure 2. Structure of the seminar.

well-informed decisions as future leaders. Therefore, the emphasis is on an emancipatory approach, while acknowledging that this does not occur independently of instrumentally set frameworks. Many discussions about sustainability are politically and socially charged. Reflecting on the CO_2 emissions of different activities inevitably raises questions of social and global justice, intersectional inequalities, religious and cultural value systems, as well as political and economic responsibilities. Controversial discussions are welcomed as part of fostering critical and mature judgment. At the same time, as an institution committed to democracy, the university must ensure that these debates are conducted in accordance with democratic principles and human rights. For example, misanthropic and discriminatory statements are not acknowledged as legitimate opinions. In summary, the focus is on the emancipatory approach, although it operates within an instrumental framework. A seminar designed purely for instrumental purposes, with the sole goal of reducing students' CO_2 consumption, would be fundamentally different.

3.2.2. Structure of the seminar

Following the previous considerations, the central question of the seminar was the one that the students worked on: How can issues related to carbon emissions be modelled mathematically? In order to address this question, students first developed conceptual foundations in the seminar, then worked on the question concretely using specific contexts and presented their results at the end of the seminar. The seminar was divided into four units, which are illustrated in Figure 2 and described below.

Unit 1 comprises the elaboration of the conceptual foundations of sustainability. This began with a close and, in particular, critical look at the concept of the carbon footprint (see Wiedmann & Minx, 2008). Following this, the students worked on the fundamentals of the concept of sustainable development and the UN Sustainable Development Goals. At the end of Unit 1, the role of mathematics in sustainable development was first addressed. This was followed in Unit 2 by the basics of mathematical modelling, including Blum & Leiss' (2007) modelling cycle and aspects of successful modelling. The theoretical sessions were concluded by linking mathematical modelling to sustainability issues. In Unit 3, students were asked to investigate sustainability problems independently using mathematical modelling. The students were allowed to choose their own issues, and the level of mathematics could vary from one to another. In Unit 4, students presented their results in a scientific poster and discussed them in a poster session. The seminar concluded with a reflection on the seminar itself and a summary of what had been learned.

3.3. Exploratory intervention study

An intervention study was conducted to answer the research questions derived in *Section 3.1*, based on the seminar.

3.3.1. Sample and research design

The sample consisted of 295 students (238 female, 51 male, 4 diverse, 2 no indication). Participants' age ranged from 17 to 57 years ($M = 21.7$, $SD = 4.5$). 25 students participated in experimental condition A (EC A). These are the students who took part in the seminar on mathematical modelling of sustainability issues (described in section 3.2) in the winter semester 2023/2024, coming from a variety of degree programmes, including engineering, teaching, economics and law, among others. 270 students participated in experimental condition B (EC B). These are students who did not participate in the intervention, i.e. did not attend the seminar, and serve as a comparison group. These students were assessed as part of various first-semester courses on mathematics education at the Leuphana University Lüneburg and the University of Hamburg. All 295 students (EC A = 25, EC B = 270) completed a paper-and-pencil questionnaire assessing their belief in the importance of mathematics for sustainable development, mathematical modelling self-efficacy, and political self-efficacy twice – once before and once after the intervention.

3.3.2. Instruments

Belief in the importance of mathematics for sustainable development, mathematical modelling self-efficacy, and political self-efficacy were assessed using Likert scales. The items on the belief in the importance of mathematics for sustainable development are novel and had been designed on the basis of the German curriculum framework for ESD (Schreiber & Siege, 2016) (12 items, Cronbach's $\alpha > .88$, sample item: '*Mathematics provides a basis for taking a stand on issues related to sustainability*'., more information about the scale published in Göller et al., 2025). The items on students' mathematical modelling self-efficacy had been formulated in accordance with Koyuncu et al., 2017 (7 items, Cronbach's $\alpha > .86$, sample item: '*I can explain the meaning of mathematical formulas in real-life situations*'., more information about the scale published in Schlüter et al., 2025). Items from Krampen (1986) and Beierlein et al. (2012) had been combined to measure students' political self-efficacy (6 items, Cronbach's $\alpha > .92$, sample item: '*Participating in discussions about political issues is easy for me*'.). Every item was rated from 1 to 4 (1 = strongly disagree, 4 = strongly agree). The supplemental online material provides details of all the instruments used.

Table 1. Mean Scores, Standard Deviations, and Differences in the Mean Scores.

	MP 1	MP 2	Differences Mean Scores
Importance of mathematics for sustainable development			
Whole sample ($n = 282$)	2.99 (0.47)	3.09 (0.48)	$t(281) = -4.54$, $\mathbf{p < .001, d = .27}$
EC A ($n = 25$)	3.12 (0.44)	3.36 (0.37)	$t(24) = -3.22$, $\mathbf{p = .004, d = .64}$
EC B ($n = 257$)	2.98 (0.47)	3.07 (0.48)	$t(256) = -3.78$, $\mathbf{p < .001, d = .24}$
Mathematical modelling self-efficacy			
Whole sample ($n = 293$)	2.34 (0.55)	2.62 (0.55)	$t(292) = -10.78$, $\mathbf{p < .001, d = .63}$
EC A ($n = 25$)	2.68 (0.39)	3.13 (0.45)	$t(24) = -4.31$, $\mathbf{p < .001, d = .86}$
EC B ($n = 268$)	2.31 (0.55)	2.57 (0.53)	$t(267) = -9.95$, $\mathbf{p < .001, d = .61}$
Political self-efficacy			
Whole sample ($n = 283$)	2.52 (0.74)	2.51 (0.76)	$t(282) = 0.41, p = .681$
EC A ($n = 25$)	2.47 (0.64)	2.45 (0.74)	$t(24) = 0.31, p = .758$
EC B ($n = 258$)	2.53 (0.75)	2.52 (0.77)	$t(257) = 0.35\ p = .731$

3.3.3. Analyses

In order to answer our research questions, the scales on belief in the importance of mathematics for sustainable development, on mathematical modelling self-efficacy, as well as on political self-efficacy were analysed: Mean scores were calculated for the three different scales, separated for the two measurement points. Higher scores indicated that the participants agreed more with the different statements. To assess whether the students' belief in the importance of mathematics for sustainable development, in mathematical modelling self-efficacy, and political self-efficacy changed from measurement point one to measurement point two, t-tests for dependent samples were applied. Based on these findings, a repeated measures ANOVA was used to determine the extent to which changes in specific facets differed depending on the experimental condition (and not only on the repeated measure itself). Before running the repeated measures ANOVAs, the normal distribution of the data was checked (successfully). All analyses were conducted using SPSS 29.

3.4. Results

3.4.1. Descriptive data and correlations

Descriptive data for all participating students are presented in Table 1 (both separated for the experimental conditions as well as summed for all participating students). Table 2 shows that correlations between the different constructs within measurement points are small ($r < .35$), while correlations within the constructs but between the measurement points are high ($.67 < r < .87$). For a closer look at the correlations between the variables, see also Table 2.

3.4.2. Belief in the importance of mathematics for sustainable development (research question 1)

The results of a paired t-test confirm a significant increase in the agreement on the importance of mathematics for sustainable development for both experimental conditions. Students from EC A have a mean of 3.12 on measurement point one and a mean of 3.36 on measurement point two ($p = .004$; Cohen's $d = 0.64$). Students from EC B have a mean of 2.98 on measurement point one and a mean of 3.07 on measurement point two ($p < .001$; $d = 0.24$) (see Table 1). The results of the repeated measure ANOVA

Table 2. Correlations of Pre- and Post-Test Research Instruments.

	Pre-test			Post-test		
	(1)	(2)	(3)	(4)	(5)	(6)
Pre-test						
(1) Importance of mathematics for sustainable development	1					
(2) Mathematical modelling self-efficacy	.211**	1				
(3) Political self-efficacy	.350**	.102	1			
Post-test						
(4) Importance of mathematics for sustainable development	.680**	.223**	.246**	1		
(5) Mathematical modelling self-efficacy	.159**	.672**	.059	.260**	1	
(6) Political self-efficacy	.328**	.056	.871**	.255**	.084	1

**: Significant with $p < .01$ (two-tailed).

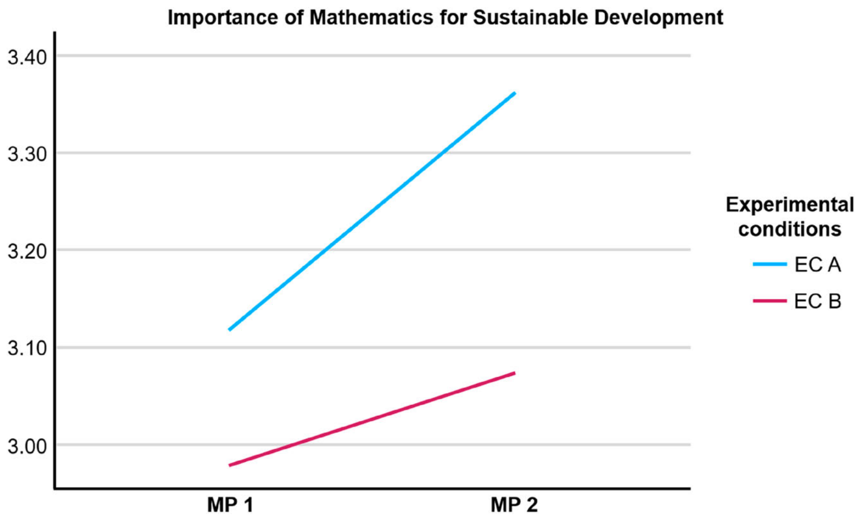

Figure 3. Trends in the Importance of Mathematics for Sustainable Development over time.

reveal a significant main effect of the measurement point ($p < .001$, $\eta^2 = .06$), a significant main effect of the two different conditions (EC A being superior to EC B; $p = .016$, $\eta^2 = .02$), as well as a marginally significant interaction effect ($p = .051$, $\eta^2 = .01$) (see Table 3 and Figure 3). In other words, students in both experimental conditions were able to positively change their belief in the importance of mathematics for sustainable development over time (the first half year of studying at university). Participating in the seminar on mathematics and sustainable development (EC A) amplified this change compared to EC B.

3.4.3. Mathematical modelling self-efficacy and political self-efficacy (research question 2)

The results of paired t-tests confirm significant increases in the mathematical modelling self-efficacy for both experimental conditions. Students from EC A have a mean of 2.68 on measurement point one and a mean of 3.13 on measurement point two ($p < .001$; $d = 0.86$). Students from EC B have a mean of 2.31 on measurement point one and a

Table 3. Results of the Repeated Measures ANOVA.

	F	p	η^2
Importance of mathematics for sustainable development ($n = 282$)			
	(1, 280)		
Within-Subjects Effects: MP (importance of mathematics for sustainable development)	17.72	**< .001**	**.06**
Within-Subjects Effects: MP (importance of mathematics for sustainable development) * EC	3.86	**.051**	**.01**
Between-Subjects Effects: EC	5.83	**.016**	**.02**
Mathematical modelling self-efficacy ($n = 293$)			
	(1, 291)		
Within-Subjects Effects: MP (self-efficacy for mathematical modelling competencies)	58.75	**< .001**	**.17**
Within-Subjects Effects: MP (self-efficacy for mathematical modelling competencies) * EC	3.78	**.053**	**.01**
Between-Subjects Effects: EC	21.10	**< .001**	**.07**
Political self-efficacy ($n = 283$)			
	(1, 281)		
Within-Subjects Effects: MP (self-efficacy for political competencies)	.125	.724	.00
Within-Subjects Effects: MP (self-efficacy for political competencies) * EC	.021	.885	.00
Between-Subjects Effects: EC	.149	.700	.00

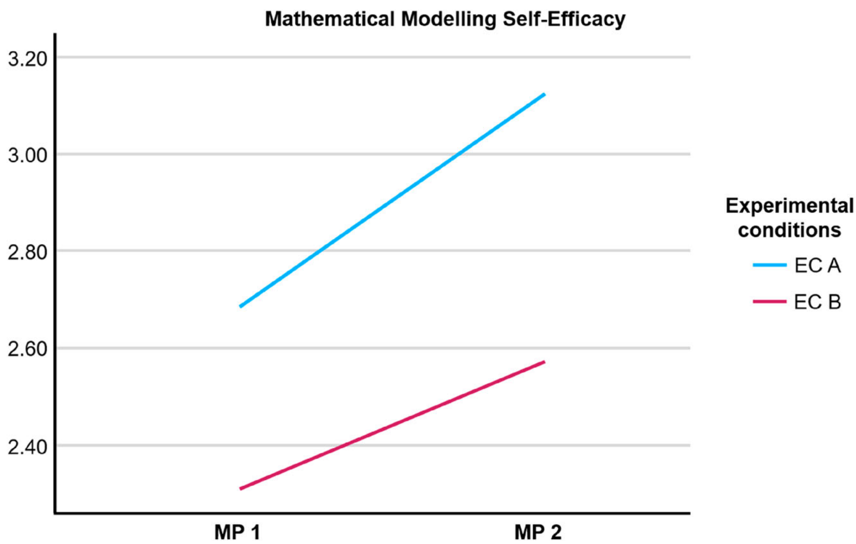

Figure 4. Trends in Mathematical Modelling Self-Efficacy over time.

mean of 2.57 on measurement point two ($p < .001$; $d = 0.61$) (see Table 1). The results of the repeated measures ANOVA show significant main effects of the measurement point ($p < .001$, $\eta^2 = .17$) and of the two different conditions (EC A being superior to EC B; $p < .001$, $\eta^2 = .07$). In addition, an marginally significant interaction effect of the measurement point and of the experimental condition can also be observed ($p = .053$, $\eta^2 = .01$) (see Table 3 and Figure 4). In other words, students in both experimental conditions were able to positively change their mathematical modelling self-efficacy over time (the first half year of studying at university), although students in EC A (participating in the seminar on mathematics and sustainable development) benefited more from the intervention.

In contrast to students' mathematical modelling self-efficacy, there were no significant changes in students' political self-efficacy in either of the two experimental conditions (see Table 1, Table 3, and Figure 5).

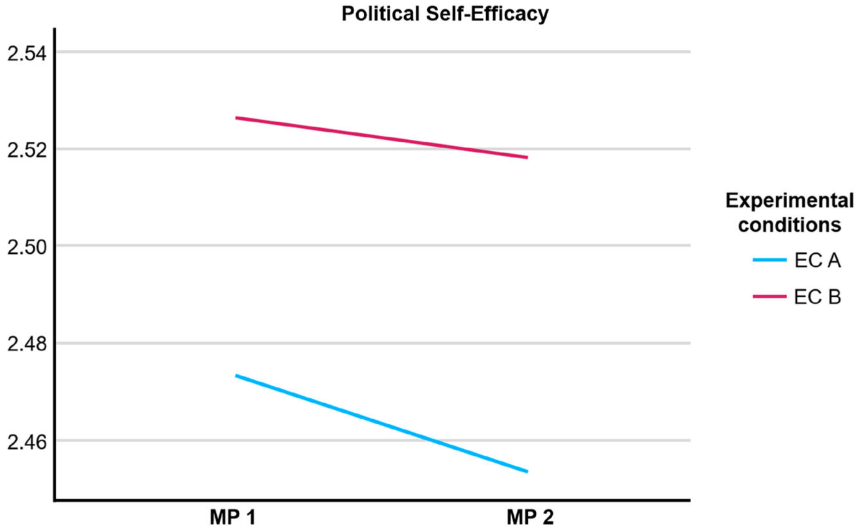

Figure 5. Trends in Political Self-Efficacy over time.

4. Discussion and implications

The present article comprises a conceptual and an empirical part. The results of both parts are critically discussed below to conclude the article. Finally, conclusions and implications are outlined explicitly.

4.1. Discussion and implications of the conceptual part: education for sustainable development and mathematical modelling in higher education

As it is often unclear what exactly is meant by ESD, both in general and in relation to specific education, the conceptual part is devoted to locating ESD before discussing its implementation. Thus, the article responds to explicit calls for concrete conceptualisations of ESD – particularly in mathematics education (Li & Tsai, 2021). A key outcome of the conceptual part is the proposed conceptualisation of ESD in the field of tension between instrumental and emancipatory approaches (Vare & Scott, 2007; Wals, 2011; Wals et al., 2008). From existing considerations, it can be deduced that ESD can be understood as an educational construct that enables students to become responsible citizens, able to judge independently but within a normative framework (democracy and human rights). A caveat, of course, is that although this is an innovative approach that can reduce the tensions described in the literature, it does not eliminate them. Thus, the aim of conceptualising ESD is to explicitly locate ESD in the field of tension and to understand it as a construct that can then be implemented; however, of course, it does not bring together all the ESD currents behind it. *The implications are simple yet crucial:* the conceptual appraisal highlights the 'fine line' along which ESD transitions between indoctrination and preparation for future sustainability challenges. These tensions should be acknowledged whenever considering the implementation of ESD, particularly in light of the emerging challenges facing democracies in the twenty-first century (Marouli, 2021).

Based on these considerations, the article furthermore demonstrates theoretically – focusing on the special example of mathematical modelling – that mathematics can not only contribute to ESD but, vice versa, must be seen as an indispensable part of ESD. Mathematical modelling is therefore important for successful ESD, especially in higher education, where future leaders should be empowered to meet the challenges of the twenty-first century. A review of current ESD competency models (Brundiers et al., 2021; Wiek et al., 2011) also indicates that ESD needs to be considered in an interdisciplinary manner and that mathematics, particularly mathematical modelling, should be viewed as a component of ESD higher education programmes. *This conceptual reappraisal implies once again:* Mathematical competencies are key competencies for the future lives of learners. Discussions about ESD must therefore also be discussions about the role of mathematics, the strengthening of the subject, and the question of how to support the learning of mathematics (Bakker et al., 2021; Coles et al., 2024; Li & Tsai, 2021).

4.2. Discussion and implications of the empirical part: exploratory research on the implementation of education for sustainable development through mathematical modelling in higher education

Limitations: Before interpreting the results of the empirical part of the study, the limitations must be outlined. Firstly, the students in experimental condition A (EC A) are a small and selective sample. They were not randomly selected, but rather registered to participate in the seminar based on their interest. As a result, a selection bias can be assumed, which is also reflected in the fact that the students in EC A have, on average, a slightly higher level of belief in the importance of mathematics for sustainable development and a slightly higher level of mathematical modelling self-efficacy than the students in EC B already in the pre-test. Furthermore, while the analyses provide variance relative to the pre-test measurement, the study's exploratory design does not yet consider additional background characteristics of the participants. Moreover, potential confounding variables should be acknowledged. For example, even with assurances of anonymity, social desirability effects may have shaped participants' responses. Additional influences – such as concurrent courses – have not yet been systematically assessed. It is also important to note that the empirical study initially focuses on self-reported beliefs and self-efficacy. The study has not yet assessed whether the targeted competencies are present in measurable form. Future research will require the collection of appropriate data using valid instruments for assessing such competencies. The results are therefore interpreted below with caution (as is usual with exploratory studies) in relation to the research questions.

Research question 1: The empirical results show that both the seminar group (EC A) and the comparison group (EC B) increased their belief in the importance of mathematics for sustainable development over time. However, the effect size of EC A is much bigger than the effect size of EC B (although this should be interpreted with caution, as the smaller sample size of EC A compared to EC B may affect the reliability of this effect size). In line with this, analysis of variance points out that changes in beliefs in the importance of mathematics for sustainable development can be explained by measurement points as well as by group (belonging to EC A), and a (marginally significant) interaction effect also exists.

Research question 2: The development of mathematical modelling self-efficacy is similar to that of belief in the importance of mathematical modelling for sustainable development:

There is an increase in both the seminar group (EC A) and the comparison group (EC B), but the seminar group is superior and, in this case, even has a large effect size. Once again, analysis of variance reveals that these effects can be attributed to both measurement points and group (belonging to EC B), with a marginally significant intervention effect. Effects on political self-efficacy could not be found.

With regard to the discussion on university teaching both in general (Fehlner, 2019; Žalėnienė & Pereira, 2021) as well as with respect to mathematics education in particular (Göller et al., 2017), the results once again highlight that well-designed interventions can contribute to changing beliefs and self-efficacy – and that specific (interdisciplinary) seminars (here: mathematics and ESD) are needed for successful teaching and learning mathematics at university (Nakakoji & Wilson, 2020; Winsløw et al., 2018). The results of the present study are also consistent with recent exploratory work in this area. For example, Çibik and Boz-Yaman (2025) showed that targeted interventions can have a positive effect on the sustainable development attitudes and mathematical self-efficacy of prospective teachers. In other words: If you want to teach something specific, you need specific interventions. Therefore, one should not expect a direct transfer from the general (mathematics) to the specific (ESD using mathematics); this is also evident in the moderate correlations between the constructs. *The implications are simple yet fundamental:* the fact that specific ESD learning goals necessitate targeted interventions makes curriculum development at universities indispensable. Expecting young people to develop ESD competencies without doing so is a form of reverie.

The findings on political self-efficacy support this need for curriculum development and highlight the complexity of the issue as well. Although the students feel more competent in the matter, they do not automatically feel more competent as citizens of a political society. *Implications are complex:* Achieving such a goal seems even more complex and fails 'incidentally', but requires recurring, complex, and challenging interventions.

These findings contribute to the growing body of work that seeks to understand how mathematics education can effectively support ESD. As Li and Tsai (2021) emphasise, 'more research into the integration of ESD into mathematics education will no doubt contribute further to an understanding of this highly complex and demanding area of education' (p. 2539). The empirical part of this study responds to this call by offering exploratory insights into the implementation of ESD through mathematical modelling in higher education.

4.3. Conclusion, implementation challenges and outlook

Overall, the article demonstrates that ESD is a complex and multifaceted concept that poses challenges for educational institutions, especially in higher education. On a conceptual level, it becomes clear that ESD is a 'fine line' between indoctrination and preparation for future sustainability problems and that it is indispensably dependent on mathematics as an interdisciplinary approach. On an empirical level, it is shown that specific ESD learning programmes are needed and that we cannot expect young people to simply develop ESD skills 'incidentally'. In future research, it may be particularly valuable to examine students with respect to their varying prior knowledge and diverse backgrounds.

However, such innovative implementations inevitably come with practical challenges. The further development of university study programmes is subject to many conditions, including personal, content-related, and structural ones (Campbell & Blankenship, 2020;

Chan et al., 2017). More specifically, several implementation challenges can be identified. Firstly, on the teaching level, the realisation of such interventions requires teaching teams capable of integrating interdisciplinary perspectives – in this case, combining mathematical work with the creation of a politically sensitive yet safe discursive space for sustainability issues. This presupposes a high level of didactic and moderative professionalism. Secondly, on the assessment level, evaluative frameworks must be designed to reflect the complexity of these interdisciplinary perspectives. Such innovative and interdisciplinary examination formats may conflict with established assessment practices that are primarily geared towards monodisciplinary approaches (Gao et al., 2020). Thirdly, on the student level, mathematical modelling processes presuppose sufficient basic knowledge of mathematics. Although such heterogeneity in students' mathematical prior knowledge can be addressed through differentiated task formats and supportive learning opportunities (Konstantinou-Katzi et al., 2013), this inevitably generates tensions between accessibility of the content on the one hand and mathematical depth on the other. While the seminar with 25 participants proved to be feasible both organisationally and didactically in the present case, it remains unclear to what extent such a concept can be transferred to larger cohorts.

The article thus underlines the already emphasised demand for more research into the successful implementation of ESD using mathematics in higher education (Karjanto, 2023; Lafuente-Lechuga et al., 2024). Theoretical concepts, practical development work, and accompanying research are needed for meaningful ESD so that future generations can face the challenges of the twenty-first century as responsible citizens, especially with the help of mathematics.

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Data availability statement

The data supporting the findings of this study are deposited in the Leuphana University research data repository at https://doi.org/10.48548/pubdata-3011. The data are available upon request via the repository's access procedure.

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