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FROM CLIMATE EDUCATION TO SUSTAINABILITY EDUCATION: PHYSICS EDUCATION ACROSS DIVERSE EDUCATIONAL CONTEXTS

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Sou professor a favor da liberdade contra o autoritarismo.
Sou professor a favor da luta constante contra qualquer forma de discriminação.
Sou professor a favor da boniteza de minha própria prática.

Paulo Freire

Alla mia famiglia e a tutte le persone meravigliose
incontrate in questo mio percorso

Abstract

This thesis investigates how science education, and particularly physics education, can contribute to sustainability education across different educational contexts, using with climate change as the main entry point. More specifically, the work explores how the understanding of climate-related physical phenomena can support broader educational approaches capable of engaging social, cultural, political, emotional, and epistemological dimensions of sustainability. The work began from the analysis of students' mental models, explored through drawings as a way to make visible how learners represent complex climate-related phenomena. Starting from this disciplinary perspective, the research gradually expanded toward a broader view of sustainability education. A central part of the work focused on the design and analysis of multidisciplinary teacher training course, aimed at supporting teachers in connecting scientific concepts with environmental, social, economic, and cultural dimensions. The international experiences further broadened this perspective. In Portugal, the work highlighted the importance of adapting sustainability education to specific educational and institutional contexts through interdisciplinary activities with pre-service teachers, while also opening a small comparative extension of the drawing-based methodology with younger students in a different educational setting. The mobility experience in Brazil opened a complementary reflection on epistemological plurality, social justice, and the role of different ways of knowing in science education, bringing greater attention to the cultural and political dimensions of sustainability. Alongside formal educational settings, the thesis also considers science theatre as a non-formal space where scientific issues can be explored through emotional, narrative, and participatory engagement. Taken together, these lines of work suggest that sustainability in science education cannot be addressed at a single level. It requires connecting conceptual understanding, teacher education, context-sensitive educational design, and broader reflections on how knowledge is constructed and shared. From this perspective, physics education becomes part of a wider educational project aimed at supporting more critical and transformative ways of engaging with global challenges.

List of publications

1. Fiorello, C., Di Mauro, M., Malgieri, M., Rosi, T., Toffaletti, S., Onorato, P., & Oss, S. (2025). Analyzing students' drawings of the greenhouse effect: Common features associated to the understanding of the phenomenon. *Journal of Physics: Conference Series, 2950*(1), 012033. https://doi.org/10.1088/1742-6596/2950/1/012033

2. Toffaletti, S., Di Mauro, M., Fiorello, C., Malgieri, M., Rosi, T., Tufino, E., Onorato, P., & Oss, S. (2024). Climate change: The physical basis of radiative phenomena for the study of the greenhouse effect. *Il Nuovo Cimento C, 47*(5), 342. https://doi.org/10.1393/ncc/i2024-24342-2

3. Toffaletti, S., Di Mauro, M., Fiorello, C., Malgieri, M., Rosi, T., Tufino, E., Onorato, P., & Oss, S. (2023). Some experiments to teach the physical bases of the greenhouse effect: Thermal emission and selective absorption. In *Book of Extended Abstracts of the GIREP-EPEC Conference 2023: Physics learning promoting culture and addressing societal issues* (p. 396). Košice, Slovakia. https://indico.cern.ch/event/1162406/attachments/2724005/4738517/2023GIREP-BookExtendedAbstracts.pdf

4. Salmoiraghi, A., Zamboni, A., Toffaletti, S., Di Mauro, M., Malgieri, M., Fiorello, C., Onorato, P., & Oss, S. (2025). Core of sustainability education: Bridging theory and practice in teaching climate science to future mathematics and physics teachers. *Sustainability, 17*(11), 5120. https://doi.org/10.3390/su17115120

5. Salmoiraghi, A., Toffaletti, S., Di Mauro, M., Fiorello, C., Rosi, T., Tufino, E., Onorato, P., & Oss, S. (2025). Effectively teaching the physical foundations of the greenhouse effect: Evolution of a TLS. In *Connecting Physics Education Research and Practice* (pp. 83–97). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-86609-8_6

6. Fiorello, C., Di Mauro, M., Toffaletti, S., Salmoiraghi, A., Onorato, P., & Oss, S. (2024). Integrating sustainability into secondary school teacher training: A multidisciplinary approach to promote active learning and behavioural engagement. In *Proceedings of the 4th World Conference on Physics Education 2024*. https://indico.cern.ch/event/1162407/contributions/5950196/attachments/2853668/5089357/192_P_revised_2.pdf

7. Toffaletti, S., Di Mauro, M., Fiorello, C., Malgieri, M., Rosi, T., Tufino, E., Onorato, P., & Oss, S. (2024). Instructing high school students in a teaching-learning sequence on the physical basis of the greenhouse effect: Preliminary results. In *Proceedings of the 4th World Conference on Physics Education 2024*. https://indico.cern.ch/event/1162407/contributions/5941588/attachments/2850449/5089355/191_P_2.pdf

8. Fiorello, C., Di Mauro, M., Salmoiraghi, A., Toffaletti, S., Onorato, P., & Oss, S. (2025). A multidisciplinary secondary school teacher training course dedicated to sustainability and scientific citizenship. *Il Nuovo Cimento C, 48*(4). https://doi.org/10.1393/ncc/i2025-25252-5

9. Fiorello, C., Lopes, B., & Piacentini, V. (2025). Da necessidade à possibilidade de conceber estratégias de formação inicial de professores de âmbito interdisciplinar e internacional: Um relato de experiência(s) focada(s) nas alterações climáticas. *Boletim AIA-CTS, 23*. https://aia-cts.web.ua.pt/wp-content/uploads/2025/09/Boletim_AIA_CTS_n23.pdf

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11. Fiorello, C., Di Mauro, M., Salmoiraghi, A., Toffaletti, S., Onorato, P., & Oss, S. (2026). Sostenibilità nella formazione secondaria degli insegnanti: Promuovere l'apprendimento attivo e l'impegno attraverso la multidisciplinarità. In C. Fiorello (Ed.), *International Scientific Workshop on Challenges of Sustainable Education.* Trento: Università degli Studi di Trento. ISBN 978-88-5541-147-9

12. Fiorello, C., Piacentini, V., & Lopes, B. (under review). Educação sobre alterações climáticas e educação para a sustentabilidade na formação de professores: Contributos de uma abordagem interdisciplinar e internacional. Submitted to the *Proceedings of the II International Conference on Science Education (IICIEC).*

13. Galano, S., Angeli, E., Bonino, R., Bottino, B., Carli, M., Carpineti, M., D'Alfonso, L., De Giorgi, M. L., De Luca, R., Fanti, V., Fazio, C., Fiorello, C., ... & Testa, I. (under review). Modeling physics identity profiles of freshmen physics students through person-centered analysis: Relationships with gender, academic motivation, engagement, anxiety and intention to drop-out. Submitted to *Physical Review Physics Education Research.*

Contents

Introduction

Climate change cannot be viewed as a distant or abstract problem. It is a complex reality that is already transforming environmental systems, societies, and everyday life. Nevertheless, it remains difficult to fully understand, as it involves deeply interconnected environmental, social, and economic processes.

In this context, addressing climate change is not only a scientific challenge but also an educational one [1, 2]. Education is, in fact, considered a fundamental element in helping learners make sense of the complexity of this phenomenon. However, teaching and learning about climate change is not so straightforward. Students frequently struggle to understand the underlying mechanisms, especially when these involve abstract processes such as energy balance and radiation [3, 4]. Within science education research, several studies have shown that students develop alternative conceptions of climate-related phenomena, particularly regarding the greenhouse effect. These ideas are often internally consistent and form what are commonly referred to as mental models, which students use to interpret and make sense of the phenomenon [5, 6]. Understanding how these models are structured can provide important insights into students' reasoning and support the design of more effective educational approaches.

At the same time, understanding how climate change works from a scientific point of view is not sufficient on its own. The topic also invites reflection on the human choices that contribute to it, the responsibilities connected to these choices, and the possible actions needed for the future. In this sense, climate change naturally opens the way to sustainability education, where scientific understanding is linked to critical reflection and the capacity to act. In this context, teachers play a crucial role. They remain responsible for conveying scientific knowledge, but also for creating learning environments in which students can engage with complex issues, and reflect on them. However, this requires support that goes beyond traditional disciplinary training, as teachers often deal with complex issues involving uncertainty and different perspectives [7].

From this consideration, this thesis explores the contribution that physics education can offer to sustainability education in different educational contexts.

Physics education represents a particularly relevant entry point into sustainability education because it provides the conceptual tools needed to understand climate-related phenomena such as the greenhouse effect, radiative balance, and energy transformations. Understanding these physical processes is fundamental for interpreting contemporary climate challenges and engaging critically with climate-related information.

Understanding climate phenomena, such as the greenhouse effect, is an important component of

climate education. However, the findings of this thesis suggest that scientific understanding alone is not sufficient to engage with the complexity of sustainability-related challenges. These issues extend beyond the scientific domain and involve social, cultural, political, emotional, and epistemological dimensions that shape how people interpret, experience, and respond to environmental problems. From this perspective, physics education can provide an important foundation for sustainability education, particularly when scientific knowledge is connected with reflection, dialogue, and action.

Starting from the analysis of students' mental models of the greenhouse effect, this thesis progressively expands its focus towards teacher education, interdisciplinary sustainability education, transnational educational experiences, epistemological plurality, and arts-based approaches to science communication. In doing so, the thesis investigates how physics education can contribute to sustainability education not as an isolated disciplinary domain, but as a starting point for developing educational practices.

The overarching research question guiding this thesis is therefore:

> How can physics education contribute to sustainability education by connecting the understanding of climate-related phenomena with the complexity of sustainability issues?

To address this question, the thesis follows a progressive research journey across different educational contexts and perspectives. Chapter 2 explores students' mental models of the greenhouse effect through the analysis of drawings, examining how learners represent and make sense of climate-related phenomena and what these representations can reveal about their understanding. Chapter 3 shifts the focus to teachers, examining how a sustainability-oriented teacher training programme can support more interdisciplinary approaches to sustainability education.

The inclusion of different educational and cultural contexts also helps explore how sustainability education is influenced by local cultures, social realities, educational traditions, and different ways of understanding environmental issues. In this way, the international dimension of this research not only broadens its scope, but also encourages exchange across different contexts.

Chapters 4 and 5 further expand the discussion through research experiences in Portugal and Brazil, exploring the influence of context, culture, and different ways of understanding sustainability. Finally, Chapter 6 considers science theatre approaches as opportunities to engage emotional and participatory dimensions of sustainability beyond formal educational settings.

Overall, the thesis proposes a progressive shift from a primarily conceptual focus on climate-related physical phenomena towards broader perspectives on sustainability education that integrate scientific, social, cultural, and emotional dimensions.

Chapter 1

Climate and Sustainability Education: key perspectives

Building on the general introduction of the thesis, this chapter outlines the theoretical framework underlying the study. This research relates to the field of physics education, with particular attention to climate education and sustainability education.

As discussed in the previous section, addressing climate change requires not only an understanding of the underlying scientific processes, but also the ability to deal with complex and interconnected dimensions. For this reason, the framework adopted in this work combines perspectives from physics education, climate education, and sustainability education.

The chapter is organised into two main parts. The first part focuses on climate education, with particular attention to the greenhouse effect as a key physical mechanism for understanding climate change. This includes both a scientific overview of the phenomenon and a discussion of the main difficulties encountered by students, especially in relation to the development of alternative conceptions and mental models.

The second part broadens the perspective to sustainability education, exploring how climate-related topics can be framed within a more comprehensive approach that integrates environmental, social, and economic dimensions. Particular attention is given to the role of education in supporting the development of competences related to sustainability.

By combining these perspectives, this chapter provides the conceptual basis for the empirical studies presented in the following chapters.

1.1 Climate education and greenhouse effect

Today, the climate crisis has become one of the most pressing challenges of our time. It is not only an environmental issue, but a complex phenomenon that affects societies at multiple levels, from ecosystems to economic systems and social structures. Rising global temperatures and their consequences pose a serious threat to human life, making climate change a problem that is both scientific and deeply societal.

To understand a challenge of this kind, a solid scientific foundation is essential. Indeed, scientific knowledge is fundamental to explaining the mechanisms underlying climate change and to interpreting data and models related to this phenomenon. However, knowledge alone is not enough. The climate crisis also requires the ability to make decisions and take action, which means that understanding must be accompanied by the ability to reflect and evaluate.

Within this framework, physics plays a central role. Many of the key processes involved in climate change, such as the Earth's energy balance and the interaction between radiation and matter, are grounded in physical principles. A physics-based understanding therefore provides the conceptual tools needed to make sense of climate phenomena. However, focusing only on the disciplinary dimension is not sufficient. Climate change is not just a physical process: its causes and consequences extend across environmental, social, and economic domains. This makes it necessary to adopt a broader perspective that takes into account the interconnected nature of these dimensions.

Education plays a fundamental role in addressing this crisis. It contributes not only to the dissemination of reliable scientific knowledge, but also to the development of attitudes, values, and skills that are necessary to deal with such challenges. In this context, we refer to climate education (CE), which includes educational approaches and content aimed at helping students understand the mechanisms underlying climate change, while also developing critical awareness and promoting sustainable behaviours [8–10]. Its main objective is to provide both theoretical knowledge and practical tools to interpret global warming and its multiple dimensions. Schools and universities therefore become key environments in which students can develop the competences needed to act as informed and active citizens, capable of addressing global challenges that require collaboration and a systemic perspective [1].

In this field, particular attention must be paid to the understanding of the physical mechanism underlying the greenhouse effect (GHE), which represents one of the key processes for explaining climate change. Climate models are based on the GHE, a natural mechanism in which greenhouse gases selectively absorb and emit radiation [11]. By regulating the Earth's energy balance, this process maintains temperatures within a range that allows life to exist [12]. Human activities, however, have altered this balance through the excessive emission of greenhouse gases, intensifying the greenhouse effect and accelerating global warming [13].

Understanding the greenhouse effect is therefore not only a scientific objective, but also an educational one. It represents a crucial step in supporting students in developing critical awareness and the ability to take action, which are central elements of climate education.

To understand why students often develop alternative or incorrect conceptions about the GHE, it is necessary to return to its basic physical mechanism, identifying which steps in the radiation processes may be conceptually challenging and therefore more prone to misunderstanding.

The greenhouse effect is a central process in Earth's climate system and an indispensable component of climate models, as it regulates surface temperatures and ensures habitability of the planet. This natural mechanism results from the interaction between electromagnetic radiation and greenhouse gases, especially when terrestrial energy is re-emitted as infrared radiation. While incoming solar energy, mostly in the visible spectrum, traverses the atmosphere with little attenuation and is absorbed by the Earth's surface, the subsequent infrared emission is partially absorbed by greenhouse gases. These gases then re-radiate energy in all directions, including back toward the surface.

This radiative feedback increases the mean surface temperature to approximately +15 °C, instead of the −18 °C that would be expected without an atmosphere [14]. Recent modeling efforts further validate the robustness of greenhouse gas-driven simulations, supporting the predictive accuracy of climate models for long-term warming trends [15]. For further information on the physical mechanism of the phenomenon, please refer to Chapter 2 in the paragraph "The greenhouse effect: physical description".

Although the natural greenhouse effect is vital for Earth's energy balance, human-induced emissions have significantly amplified this mechanism. The rising concentration of greenhouse gases in the atmosphere intensifies the re-emission of infrared radiation toward the surface, producing a measurable global temperature increase, a phenomenon commonly referred to as global warming. This anthropogenic greenhouse effect highlights the decisive role of human activity in contemporary climate change and is recognized as a primary driver of extreme climate events, including prolonged hot and dry periods across various regions of the globe [16].

Despite its scientific importance, teaching the greenhouse effect is often challenging. In many classroom contexts, the phenomenon is simplified to qualitative accounts that omit the underlying physics, such as the conversion of solar radiation into infrared energy and the selective transparency of gases to different wavelengths [17]. Research shows that students, from primary school through university, develop alternative conceptions of the greenhouse effect that differ from accepted scientific models [18–22].

These inaccurate notions often give rise to internally consistent structures, known as "mental models", which learners rely on when making sense of the greenhouse effect during instruction [5, 23]. Common difficulties include confusing the greenhouse effect with ozone depletion, misattributing warming to the trapping of incoming solar radiation rather than the re-emission of infrared radiation, or failing to distinguish among ultraviolet, visible, and terrestrial radiation. For example, interviews with 11–12-year-old students revealed erroneous ideas such as linking the greenhouse effect to seasonal variation or to the "ozone hole" [24–27].

Similar findings have emerged in the Italian context, where students struggle to connect heat and radiation concepts or to reason in terms of energy balance [28]. A large-scale Austrian study with grade 11 students confirmed that learners' knowledge of individual scientific concepts related to the greenhouse effect remains fragmented and incoherent, preventing them from forming accurate scientific explanations [29].

At the university level, research also documents persistent alternative frameworks. Surveys with both science and non-science majors revealed widespread confusion between greenhouse gases and ozone depletion, as well as misunderstandings about Earth's emission of radiation and the role of CO_2 [30–32]. Although targeted instructional interventions can reduce such inaccurate notions, for instance, by engaging students in data analysis tasks [32], many of these erroneous ideas remain resilient even after exposure to higher education.

As regards the Italian school system, topics related to climate change and the greenhouse effect already appear in secondary school curricula (9^{th} and 10^{th} grade, 14-15 years-old students), in natural sciences, and in the physics subject at 12^{th} grade.

The National Guidelines for both subjects emphasize the need to understand natural phenomena, atmospheric processes, and the Earth's energy balance, promoting an approach based on experiments and the analysis of real data [33]. However, these documents remain rather generic: they mention the importance of studying these processes without going into detail about the phys-

ical mechanisms that explain the GHE. This means that the way the topic is dealt with varies considerably depending on the school and the teaching choices of the teachers [3].

There are no common guidelines at national level in the university sector. However, several universities offer courses dedicated to climate physics, climate change or sustainability, especially at master's degree level.

Although climate education often starts from the understanding of physical processes such as the greenhouse effect, addressing climate change requires going beyond a purely scientific perspective. The climate crisis is inherently complex and cannot be reduced to a single dimension. It involves environmental processes, but also social inequalities, economic dynamics, cultural values, and political decisions, all of which are deeply interconnected.

Precisely because of this complexity, there are several challenges to be addressed. For example, climate-related phenomena occur on various scales, from the local to the global. Second, many of their effects are not immediately observable, but must be understood through abstract models and long-term projections. Third, the responsibility for addressing climate change is shared among multiple actors, including individuals, institutions, and governments, each of which plays a different role.

For these reasons, understanding climate change is not just a matter of acquiring knowledge, but also of developing the ability to navigate complexity, uncertainty, and multiple perspectives. This leads to the broader framework of sustainability education.

1.2 Sustainability education

Building on the role of climate education, it becomes necessary to consider educational approaches that address sustainability in a broader sense. Sustainability education extends this perspective by explicitly focusing on the interconnected environmental, social, and economic dimensions of the climate crisis.

1.2.1 Sustainability as a complex and normative concept

Sustainability is recognized as a complex and contested concept that cannot be reduced to a single definition. In fact, the literature shows that the term has multiple interpretations, often linked to different disciplinary fields and the historical transformations that have accompanied its development [34–37]. This plurality reflects both the richness of the concept and the difficulty of capturing the relationships between its different dimensions within a single framework.

In general, sustainability is described as a concept that cuts across multiple domains and cannot be understood without considering environmental, social, and economic dimensions together [34, 38]. Focusing exclusively on the environmental dimension risks oversimplifying the issue. Environmental challenges are deeply intertwined with questions of social justice and equity, while economic conditions influence the feasibility and long-term impact of sustainability strategies. For this reason, sustainable solutions need to be viable across all these dimensions.

A widely accepted definition is that proposed in the Brundtland Report, which describes sustainable development as the ability to meet present needs without compromising those of future generations [38]. From this perspective, sustainable development can be seen as the set of practices and policies through which the broader principle of sustainability is translated into action [39].

International initiatives such as Agenda 21 and, more recently, Agenda 2030 have contributed to operationalising sustainability, articulating it into the 17 Sustainable Development Goals, which today represent a key reference framework [40, 41].

Traditionally, sustainability has been described through three main dimensions: environmental, social, and economic. This framework remains useful for highlighting the interdependence between different domains and for emphasising the need for integrated approaches [42]. More recently, a cultural dimension has also been introduced, recognising the role of knowledge, values, and worldviews in shaping sustainable transformations [35].

When we talk about sustainability, it is not merely a matter of describing a phenomenon, but of engaging with a concept that is inherently normative. It involves making choices about what should be sustained, for whom, and according to which priorities, and is therefore inevitably subject to debate [39].

Achieving sustainability requires deep changes in values and goals at individual, societal, and global levels [41, 43, 44]. The current socio-ecological crisis calls for transformations not only in individual practices but also at collective and systemic levels [44]. These transformations are closely related to issues of power and knowledge, since not all perspectives are equally recognised, raising questions about whose knowledge is legitimised and whose remains marginalised [43, 45].

Achieving sustainability therefore implies processes of transformation that involve not only technological and policy changes, but also shifts in values, practices, and ways of understanding the world [44].

For these reasons, sustainability can also be seen as an educational issue, as it requires individuals to understand, question, and act upon complex and value-laden challenges.

1.2.2 The role of education in addressing sustainability

In this context, given the complexity, normative nature, and transformative implications of sustainability, education emerges as a key domain for addressing sustainability challenges [1, 41]. It is through education that individuals can develop the knowledge, values, and capacities needed to understand and engage with such complex and contested issues [7].

However, what it means to educate for sustainability is not univocal, and different perspectives can be identified. However, these different perspectives can be more clearly framed by referring to three main visions of science education, which reflect different ways of understanding its aims in relation to sustainability.

The first perspective, often referred to as *Vision I*, is based on a disciplinary approach. Here, the main goal is the transmission of scientific knowledge and the development of disciplinary understanding. Science is presented through its core concepts and structures, with a strong focus on accuracy and coherence within the discipline. This perspective mainly prepares students for further studies and for engaging with science in ways that reflect how knowledge is produced and validated within scientific fields [46].

Vision II represents a shift toward a broader understanding of science education. In this perspective, the focus moves from disciplinary knowledge to personal relevance and scientific literacy. Science is seen as a tool to understand everyday life and to engage with societal issues.

Approaches such as STSE, socio-scientific issues (SSI), and Education for Sustainable Development (ESD) reflect this shift, highlighting the importance of connecting science to real-world

problems and supporting informed decision-making [1, 47, 48]. Science education, therefore, becomes relevant for all students, not only for those who will pursue scientific careers.

However, several authors argue that this perspective is no longer sufficient to address current global challenges. Sustainability issues are complex, value-laden and closely connected to social and political dimensions, and therefore require a further step. This leads to *Vision III*, which emphasizes agency, values and transformation. In this view, students are not only expected to understand science, but also to critically reflect on societal issues and actively contribute to change. Science education is thus seen as a way to support participation, responsibility and action toward more sustainable futures [49, 50].

Within this perspective, learning is not only about acquiring knowledge, but also about changing how individuals think and relate to the world. Transformative learning approaches highlight the importance of questioning assumptions and engaging with complexity, uncertainty and ethical dimensions, especially in relation to sustainability [51].

Overall, these three visions represent different but complementary ways of understanding science education. Sustainability challenges highlight the need to move beyond a purely disciplinary or literacy-based approach, toward forms of education that support agency, critical thinking and transformative action.

In this sense, the relationship between sustainability and education is bidirectional: while sustainability challenges call for a rethinking of educational goals and approaches, education itself is also a key means to support and guide sustainability transformations.

In this context, the concept of *agency* becomes central. Agency can be understood as the capacity of individuals to act purposefully and responsibly in relation to complex socio-scientific issues, such as sustainability challenges.

In the context of sustainability education, this idea is often further developed through the notion of *action competence*, which emphasizes the practical dimension of agency. From this perspective, education is not limited to raising awareness, but aims at supporting learners in moving from understanding to action.

More broadly, agency can be seen as a capacity that it is shaped by past experiences, oriented toward future possibilities and enacted in present actions [52]. In this sense, agency is not fixed, but it is a process that develops over time and varies depending on the context.

1.2.3 Teacher education for sustainability

In this perspective, teachers can be seen as key agents of change. Teachers become central in mediating how sustainability is interpreted in educational contexts. Their role goes beyond the transmission of disciplinary knowledge, involving instead the capacity to engage with complex socio-scientific issues and to support students in making sense of them.

This shift, however, raises an important issue regarding disciplinary expertise. Asking science teachers to address the social, economic, or political aspects of sustainability may seem to push them beyond their area of competence, with the risk of oversimplification. This concern is particularly strong in science education, where solid disciplinary knowledge is considered essential. Rather than ignoring this tension, the literature suggests acknowledging it and reframing it. Sustainability education does not require teachers to become experts in all domains, but to be able to frame problems

as inherently complex, recognising that scientific, social, and ethical dimensions are intertwined [53, 54].

In this sense, disciplinary knowledge remains essential, but it takes on a different role. It shouldn't be seen as a limit, but it becomes a starting point for making connections.

For example, Ke et al. highlight the importance of using different types of models to help students understand complex issues: scientific models, which explain natural phenomena, and socio-scientific models, which connect science to society, politics, and values [55]. This means that teachers could be able to guide the use of these models in the classroom, creating learning environments that embrace complexity.

Research on socio-scientific issues also highlights that teachers need to go beyond disciplinary knowledge and support discussion, argumentation, and reflection in the classroom [48]. In this view, their role is less about providing answers and more about helping students engage with complex problems. This includes fostering skills such as argumentation, decision-making, and critical thinking [56].

These considerations highlight the central role of teacher education. If teachers are expected to deal with complexity, they need support that goes beyond disciplinary knowledge. This includes opportunities to develop more interactive teaching approaches, such as discussions, hands-on activities, and real-world applications [2, 57], and also the ability to reflect on broader connections between environmental, social, and economic systems [58].

It also points to the importance of collaborative and practice-based approaches, where teachers can work together and reflect on their own practice [59].

Engaging with sustainability also means recognising that teaching itself is not a neutral activity. Addressing issues that involve values and societal choices inevitably positions teachers within wider social and political contexts. In this sense, teaching involves shaping how knowledge is interpreted and used, rather than simply transmitting content [60].

This suggests that teacher education should go beyond knowledge and teaching strategies, and also help teachers reflect on the social and political aspects of science and education. In this way, teachers can be better prepared to deal with sustainability not just as a topic, but as an issue that involves questions of responsibility, justice, future choices, and issues of power.

In recent years, increasing attention has also been given to the role of digital technologies in supporting this kind of learning. Tools such as simulations and digital platforms can help represent cause–effect relationships, explore alternative scenarios, and analyse the impact of decisions across different dimensions of sustainability. These resources have been shown to support systems thinking and a more informed understanding of complex issues [61, 62].

Overall, these perspectives suggest that teacher education plays a crucial role in enabling teachers to act as agents of change in sustainability education.

Individual teachers are not expected to be experts in all fields related to sustainability, but the challenge lies in supporting them as they navigate this complexity, work collaboratively, and rethink their professional role in light of the global challenges that education is increasingly called upon to address.

Chapter 2

Students' mental models of the greenhouse effect for climate education

Understanding the greenhouse effect is important for climate education, but many students find it hard to understand how it really works. Looking at how students imagine and represent the greenhouse effect can therefore help us better understand how they think and learn about climate-related topics.

This chapter focuses on students' mental models and representations of the greenhouse effect, using drawings as the main research tool. The drawings produced by high school and university students are analysed through a quantitative approach, in order to identify recurring patterns and shared features in their representations.

2.1 Scientific and educational perspectives on the greenhouse effect

2.1.1 Physical description of the greenhouse effect

In order to correctly interpret students' mental models of the greenhouse effect, it is important to first explain the physical explanation of the phenomenon, paying particular attention to the essential radiative mechanisms and the simplest physical models used for teaching purposes.

The basic mechanism behind GHE can be explained in terms of radiative energy balance: on average, the energy absorbed from the Sun must equal the thermal radiation emitted by the Earth.

Solar radiation provides the primary source of energy for the Earth's climate system and drives atmospheric and oceanic circulation. When sunlight reaches the top of the Earth's atmosphere, part of it is scattered by the atmosphere back to space, another fraction is absorbed within the atmosphere and another one at the Earth's surface. The absorbed energy powers a variety of processes within the climate system. Ultimately, in order to maintain energy balance, the Earth

system must emit to space the same amount of energy it absorbs, mainly in the form of thermal infrared radiation.

The energy emitted by the Sun originates in its core, where hydrogen nuclei fuse into helium, releasing large amounts of energy. The total amount of radiative energy emitted by the Sun per unit time is known as solar luminosity $L_\odot = 3.83 \times 10^{26}$ W. While it is often treated as constant, it exhibits slight variations (about $\pm 0.06\%$) over the 11-year solar cycle associated with sunspot activity.

The radiation emitted by the Sun spreads outward in all directions through space. As it propagates away from the Sun, the total energy emitted per unit time remains constant. The same amount of radiative power crosses any spherical surface centred on the Sun. However, as the distance increases, this energy is distributed over a larger surface area.

For this reason, the amount of radiative energy crossing a unit surface area decreases with distance. The radiative energy passing per unit time through a unit area of a spherical surface located at a distance d from the Sun is given by

$$S = \frac{L_\odot}{4\pi d^2} \tag{2.1}$$

This quantity represents the radiative energy flux density, often referred to simply as the radiative energy flux, and it is measured in $\mathrm{W\,m^{-2}}$. This formula describes the flux on a surface perpendicular to the incoming radiaton.

The radiative energy flux incident on a surface is commonly referred to as *irradiance* or *insolation*. When the flux is evaluated at the mean distance between the Earth and the Sun, it takes a specific value known as the *solar constant* or *total solar irradiance*.

The mean distance between the Earth and the Sun is one astronomical unit (1 au), corresponding to 1.496×10^{11} m. Substituting this distance into Eq. (2.1), the solar radiative flux at the Earth's orbit can be written as

$$S_0 = \frac{L_\odot}{4\pi d_0^2} \approx 1360 \ \mathrm{W\,m^{-2}} \tag{2.2}$$

where d_0 is the mean Earth–Sun distance. Although often treated as constant, it actually shows small variations associated with changes in solar activity, fluctuating by about $\pm 0.8\ \mathrm{W\,m^{-2}}$ over the 11-year solar cycle.

Solar radiation consists of electromagnetic waves that span a broad range of frequencies and wavelengths. Most of the energy emitted by the Sun lies in the ultraviolet, visible and near-infrared regions of the electromagnetic spectrum.

Figure 2.1 shows the spectral distribution of solar radiation as a function of wavelength. The yellow curve represents the solar radiation spectrum at the top of the Earth's atmosphere (TOA). In this case the quantity plotted is the spectral radiative flux, meaning that the radiative energy flux is expressed as a function of wavelength. The maximum of the spectrum occurs in the visible region, close to green light.

The red curve represents the solar spectrum measured at the Earth's surface after the radiation has passed through a cloudless atmosphere under midlatitude conditions. As solar radiation travels through the atmosphere, several atmospheric constituents—including ozone, molecular oxygen, water vapour and carbon dioxide—absorb radiation in specific wavelength bands. Because of this absorption, the solar spectrum observed at the surface appears more irregular than the smoother spectrum present at the top of the atmosphere.

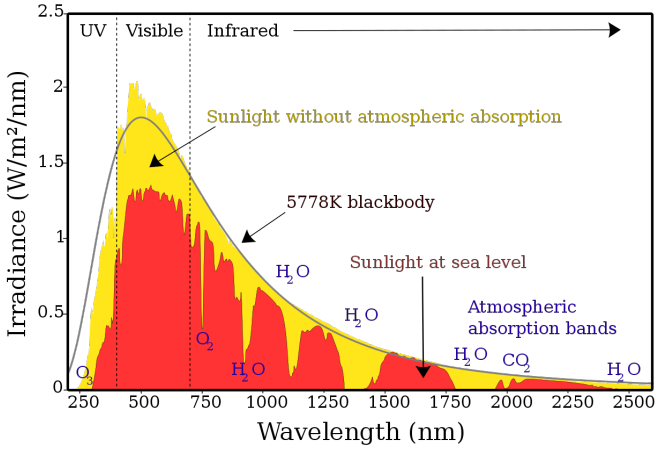


Figure 2.1: Solar spectral irradiance at the top of the atmosphere (yellow) and at the Earth's surface (red). Absorption bands due to atmospheric gases are visible in the surface spectrum.

In addition to absorbing solar radiation, the Earth's surface and atmosphere also scatter part of the incoming radiation, reflecting a fraction of it back into space. The fraction of incident radiative energy that is reflected by a body is called *albedo*. In general, albedo describes the reflectivity of a surface: the higher the albedo, the larger the fraction of incoming radiation that is reflected.

A perfect absorber has an albedo $\alpha = 0$, meaning that all incident radiation is absorbed, while a perfect reflector has $\alpha = 1$, meaning that all incoming radiation is reflected.

The albedo of a surface depends on several factors, including the material properties, the wavelength and the direction of the incoming radiation.

It is useful to define the *planetary* or Bond albedo, which represents the fraction of incoming solar radiation that is reflected back to space by the Earth system.

Satellite measurements of the incoming solar radiation and of the radiation reflected back to space allow the Bond albedo of the Earth to be estimated. Current observations indicate a value of approximately 0.290 ± 0.003. This means that, on average, about 29% of the incoming solar radiation is reflected back to space, while the remaining 71% is absorbed by the atmosphere and the Earth's surface. This absorbed energy represents the portion that ultimately drives the Earth's climate system.

Typical albedo values for different natural surfaces and atmospheric elements are reported in Table 2.1.

Surface	Albedo (%)
Fresh snow	70 - 90
Sea ice	50 - 70
Clouds	20 - 80
Desert	40
Deciduous forest	20
Evergreen forest	10
Ocean	3 - 40

Table 2.1: Typical albedo values for different natural surfaces and atmospheric elements.

The fraction of solar radiation that is not reflected by the Earth's atmosphere and surface is absorbed within the climate system. Part of the absorbed solar energy heats the Earth's surface. Another fraction is converted into kinetic energy associated with atmospheric motions. A further part is used to evaporate water from the surface. Through these processes, the absorbed solar energy changes the physical state of the materials involved and is eventually converted into thermal energy, often far from the location where the energy was initially absorbed.

In order to maintain the global energy balance, the Earth system must ultimately emit to space the same amount of energy that it absorbs from the Sun. This occurs through the emission of thermal radiation from both the Earth's surface and the atmosphere, commonly referred to as *terrestrial radiation*. Unlike reflection processes, which do not change the wavelength of the incoming solar radiation, the radiation emitted by the Earth is characterized by much longer wavelengths than the original solar radiation.

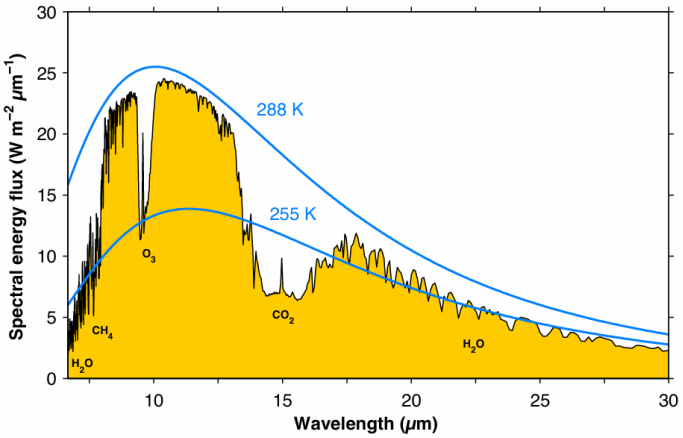


Figure 2.2: Spectral distribution of terrestrial radiation emitted by the Earth. Spectral distribution of terrestrial radiation in the infrared region. The black curve represents the outgoing longwave radiation measured at the top of the atmosphere, showing absorption features associated with atmospheric gases such as H_2O, CO_2, CH_4 and O_3. The blue curves correspond to ideal blackbody spectra at 288 K (the mean surface temperature of the Earth) and 255 K (the temperature the Earth would need to be in energy equilibrium with the Sun, without the greenhouse effect.).

The radiation emitted by the Earth has the following spectral characteristics. Because of the much lower temperature of the Earth's surface, terrestrial radiation contains no visible component and is emitted almost entirely in the infrared region of the electromagnetic spectrum. Most of the radiative energy is concentrated at wavelengths between approximately 4 and 50 μm.

The interaction of this radiation with the atmosphere plays a key role in the Earth's energy balance. Several atmospheric trace gases strongly absorb infrared radiation, including water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and ozone (O_3). These gases absorb radiation in specific spectral bands, reducing the radiative flux emitted to space at those wavelengths. An example is the strong absorption band of CO_2 around 15 μm.

There is a region of the infrared spectrum between approximately 8 and 13 μm where atmospheric absorption is much weaker. In this interval only ozone absorbs radiation in a relatively narrow band. For this reason, this spectral region is known as the *atmospheric infrared window*. Radiation emitted from the Earth's surface within this wavelength range can pass through the atmosphere and escape directly to space.

The spectral characteristics of solar and terrestrial radiation are substantially different. Almost all (about 99%) of the radiation emitted by the Earth occurs at wavelengths longer than 4 μm. In contrast, nearly all (about 99%) of the radiation emitted by the Sun is concentrated at wavelengths shorter than 4 μm.

Because of this clear separation in wavelength, it is convenient in climate studies to distinguish between two broad spectral ranges. The first is *shortwave radiation*, which refers to solar radiation reaching the Earth and is mainly associated with wavelengths shorter than 4 μm. The second is *longwave radiation*, which corresponds to the thermal infrared radiation emitted by the Earth's surface and atmosphere at wavelengths longer than 4 μm.

For practical purposes, the wavelength of 4 μm is commonly used as a boundary separating these two spectral regions.

When the incoming solar radiation is averaged over the entire surface of the Earth, the corresponding value is approximately 340 $\mathrm{W\,m^{-2}}$. This value is obtained by dividing the solar constant by 4, due to the ratio between the cross-sectional area and the total surface of the Earth. As mentioned above, a fraction of this radiation, about 30%, is reflected back into space. As a result, the mean solar energy absorbed by the Earth system is about 240 $\mathrm{W\,m^{-2}}$.

In order to maintain global energy balance, the Earth must on average emit back to space the same amount of energy that it absorbs from the Sun. The amount of radiation emitted by the Earth's surface depends on its temperature and can be described by the Stefan–Boltzmann law

$$E = \epsilon \sigma T^4 \tag{2.3}$$

where E is the radiative power emitted per unit area ($\mathrm{W\,m^{-2}}$), σ is the Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$), T is the absolute temperature (K), and ϵ is the emissivity of the surface, equal to 1 for an ideal blackbody.

A useful starting point for understanding the Earth's climate is to consider a highly simplified model of the planet without an atmosphere. In this simplified scenario the Earth's surface absorbs solar radiation and emits thermal radiation directly to space. By equating the absorbed solar flux (240 $\mathrm{W\,m^{-2}}$) with the emitted thermal radiation described by Eq. (2.3), it is possible to estimate the equilibrium temperature of the planet. For this purpose the Earth is approximated as an ideal blackbody, so that the emissivity can be taken as $\epsilon = 1$. Under this assumption, the balance between

absorbed and emitted radiation leads to an equilibrium temperature of about 255 K.

This temperature represents the effective radiative temperature of the Earth in the absence of an atmosphere. However, the observed global mean surface temperature is approximately 288 K, about 33 K higher than this value. This difference highlights the crucial role played by the atmosphere in modifying the Earth's radiative balance.

The presence of atmospheric gases that absorb and re-emit infrared radiation modifies this simple radiative balance, leading to a higher surface temperature. Certain atmospheric gases, such as CO_2, H_2O and CH_4, interact selectively with electromagnetic radiation: they are more transparent in the solar range than to radiation in the infrared range emitted by the Earth's surface, particularly at specific wavelengths.

The absorption bands of these gases are shown in Figure 2.3. Through this selective absorption and subsequent re-emission of infrared radiation, the atmosphere alters the Earth's radiative balance and increases the equilibrium surface temperature compared to a planet without an atmosphere. This mechanism is known as the *natural greenhouse effect*, and the gases involved are referred to as *greenhouse gases*.

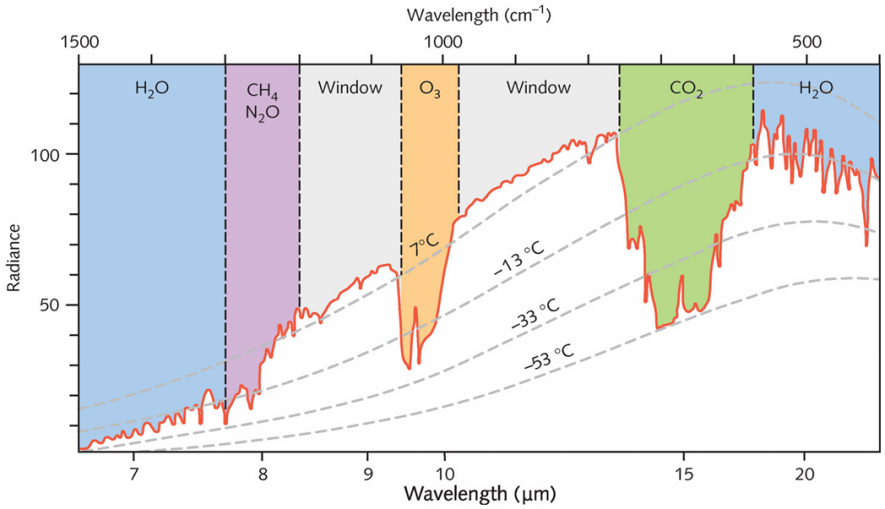


Figure 2.3: Outgoing longwave radiation spectrum measured at the top of the Earth's atmosphere. The red curve represents the observed spectral radiance, while the dashed curves correspond to blackbody spectra at different temperatures. The shaded regions indicate absorption bands of major greenhouse gases, including H_2O, CO_2, CH_4, N_2O and O_3. In the wavelength range between approximately 8 and 13 μm the atmosphere is relatively transparent, forming the so-called atmospheric infrared window through which radiation emitted at the Earth's surface can escape directly to space. Source: [63].

To better understand how the presence of the atmosphere modifies the Earth's radiative balance, it is useful to consider a simplified two-layer model consisting of the Earth's surface and a single atmospheric layer. In this model the surface has temperature T_X, while the atmosphere has temperature T_Y.

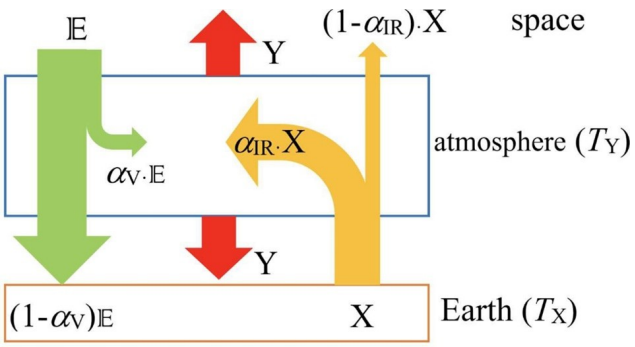


Figure 2.4: Simplified two-layer radiative model consisting of the Earth's surface and a single atmospheric layer. Source: [64]

.

E is the mean irradiance of the Earth's surface. A fraction α_V of this radiation is absorbed by the atmosphere, while the remaining fraction $(1-\alpha_V)E$ is absorbed by the Earth. The surface emits infrared radiation X, while the atmosphere emits infrared radiation Y both upward toward space and downward toward the surface. The parameter α_{IR} represents the fraction of infrared radiation absorbed by the atmosphere.

Under steady-state conditions the radiative energy balance must hold for both layers. Writing the energy balance for the surface and the atmosphere leads to the following system of equations:

$$\begin{cases} (1-\alpha_V)E + Y = X \\ \alpha_V E + \alpha_{IR} X = 2Y \end{cases} \tag{2.4}$$

The first equation represents the radiative balance at the Earth's surface. The surface receives solar radiation E and infrared radiation from the atmosphere Y, reflects a fraction $\alpha_V E$, and emits infrared radiation X.

The second equation represents the radiative balance of the atmosphere. The atmosphere absorbs a fraction α_{IR} of the infrared radiation emitted by the surface and re-emits radiation both upward and downward, represented by the two terms Y.

Solving this system yields the expressions for the infrared radiation emitted by the surface and by the atmosphere:

$$\begin{cases} X = E\frac{2-\alpha_V}{2-\alpha_{IR}} \\ Y = E\frac{\alpha_V + \alpha_{IR} - \alpha_V \alpha_{IR}}{2-\alpha_{IR}} \end{cases} \tag{2.5}$$

Using representative values for the Earth system, such as $E = 240\,\mathrm{W\,m^{-2}}$, $\alpha_V = 0.2$ and $\alpha_{IR} = 0.8$, we obtain

$$\begin{cases} X = 1.5E \approx 360\ \mathrm{W\,m^{-2}} \\ Y = 0.7E \approx 170\ \mathrm{W\,m^{-2}} \end{cases} \tag{2.6}$$

Using the fluxes obtained from the model and applying the Stefan–Boltzmann law, the temperatures of the surface and of the atmospheric layer can be estimated as

$$\begin{cases} T_X = \left(\dfrac{X}{\sigma}\right)^{1/4} \approx 280\,\mathrm{K} \\ T_Y = \left(\dfrac{Y}{\sigma}\right)^{1/4} \approx 250\,\mathrm{K} \end{cases} \tag{2.7}$$

The value obtained for the surface temperature is reasonably close to the observed global mean surface temperature of the Earth ($\approx 288\,\mathrm{K}$). This result shows that including the atmosphere in the radiative balance leads to a significantly better estimate of the Earth's surface temperature compared to the atmosphere-free model.

The two-layer model discussed above captures the essential mechanism through which the atmosphere modifies the Earth's radiative balance. However, the real climate system is considerably more complex.

A more detailed picture of the global energy balance of the Earth system is illustrated in Figure 2.5.

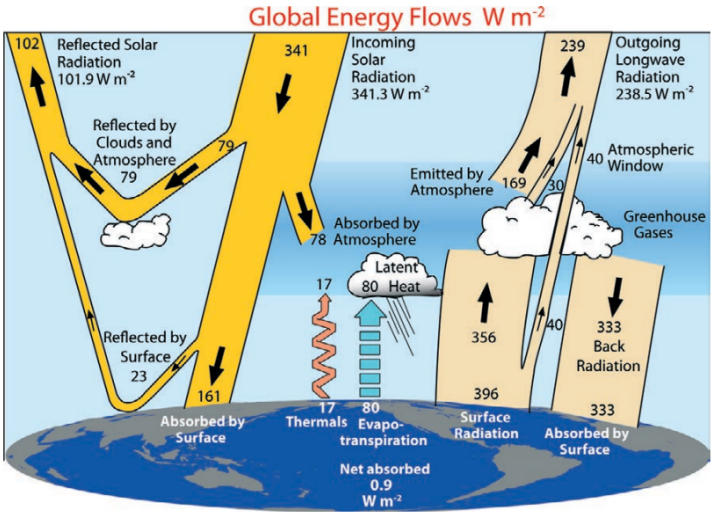


Figure 2.5: Global mean energy flows in the Earth–atmosphere system, showing the main radiative and non-radiative energy fluxes between the Sun, the atmosphere and the Earth's surface. Source: [65]

However, this representation also turns out to be too simplified. In fact, the atmosphere is still represented as a single homogeneous layer, whereas in reality it has a complex vertical structure with different temperatures and compositions. Nevertheless, this simplified approach is useful for illustrating the basic physical mechanism through which the atmosphere modifies the Earth's radiative balance and contributes to the greenhouse effect.

The greenhouse effect described above is called the 'natural greenhouse effect'. Without the presence of greenhouse gases in the atmosphere, the Earth's effective radiative temperature would

be about 255 K, significantly lower than the observed global mean surface temperature of approximately 288 K. The natural greenhouse effect therefore plays a crucial role in maintaining conditions that allow liquid water and life to exist on the planet.

However, since the beginning of the industrial era, human activities have altered the composition of the atmosphere by increasing the concentration of several greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These increases are mainly associated with the combustion of fossil fuels, deforestation, industrial processes and agricultural activities.

An increase in greenhouse gas concentration reduces the amount of infrared radiation that can escape directly to space. This temporarily disrupts the Earth's radiative balance, leading to a net energy gain in the climate system. The surface temperature therefore increases until the emitted thermal radiation again balances the incoming solar radiation. This process is commonly referred to as the anthropogenic greenhouse effect.

It is important to note that the anthropogenic greenhouse effect does not introduce a new physical mechanism; rather, it represents an intensification of the same radiative processes responsible for the natural greenhouse effect.

In summary, the greenhouse effect can be understood as the result of a radiative energy balance involving incoming solar radiation, outgoing radiation from the Earth's surface, and the selective absorption and re-emission of infrared radiation by atmospheric gases.

2.1.2 A teaching-learning sequence on the greenhouse effect

In recent years, our research group has devoted a significant part of its work to the design and development of Teaching-Learning Sequences (TLS) focused on understanding the physical fundamentals of climate change, particularly the greenhouse effect.

Analyses of the main textbooks used in Italian secondary schools have shown that the greenhouse effect is often presented in a partial and sometimes misleading way. In particular, some explanations overlook key aspects of the phenomenon, such as the selective absorption of radiation and the role of greenhouse gases in maintaining the Earth's thermal equilibrium [3]. These findings highlight the need to provide students with a well-structured educational pathway that can support a clearer understanding of this physical process.

To address these challenges, the group adopted an iterative approach inspired by the principles of Design-Based Research (DBR) [66] and integrated with established models such as Model of Educational Reconstruction (MER) [67]. In this way, TLS was developed in several stages, with each new version guided by the results obtained in the previous ones. An initial version of the sequence was developed more than fifteen years ago, and numerous revisions were made in the following years, each enriched by data collected during trials with students [18]. This cyclical process has enabled the TLS to be progressively improved, making it increasingly suited to educational needs.

In a previous version, tested between 2017 and 2021, the results obtained from the questionnaires administered throughout the sequence showed how many misconceptions persisted among students, for example regarding the selectivity of absorption or the idea of absolute transparency of matter. These difficulties led to the redesign of the TLS, which gradually introduced new experiments and a more functional order of topics [18]. A further update reinforced the role of tools such as FLIR thermal cameras, which are useful for making otherwise hidden phenomena visible, such as infrared emission or the dependence between spectrum and energy [4].

Currently, the sequence initially proposes activities dedicated to understanding the interaction between radiation and matter. The sequence is constructed using simple and accessible experiments, allowing students to gradually understand the physical principles governing the greenhouse effect and the Earth's energy balance. The aim is not to provide a purely qualitative description, but to enable understanding to emerge gradually through laboratory observations, modelling activities and data analysis [64]. Through the use of educational tools such as small spectroscopes built in the laboratory and infrared thermal cameras that can be attached to smartphones, students observe the differences between different light sources and and use thermal imaging to explore how the peak of emitted radiation changes with temperature, introducing Wien's law and the role of emissivity. Stefan–Boltzmann's law is instead addressed through the analysis of the radiation emitted by a light bulb. They are then related to practical experiments, for example with Leslie's cube or with measurements of the thermal equilibrium of irradiated black and white surfaces.

Subsequently, the topic of radiation-matter interaction is addressed during the TLS. In fact, thanks to the use of coloured filters and coloured aqueous solutions, or by observing the transparency of objects such as plastic and glass with IR cameras, students can observe how the transparency of a material depends on the wavelength of radiation. Through these activities and PhET simulations, students develop the concept of selective absorption, which is fundamental to understanding the role of greenhouse gases.

The construction of progressive climate models remains very important in the construction of the sequence. In the first model, a simplified model is proposed in which the Earth is considered to have no atmosphere: by calculating the balance between absorbed solar radiation and emitted infrared radiation, a much lower equilibrium temperature than the actual one (-18 °C) is obtained. Starting from this value, some considerations can be made to introduce a second, more realistic model, which includes the atmosphere as a single layer that selectively absorbs infrared radiation and re-emits it both towards space and towards the Earth's surface. Although this model is still simplified (0D) compared to the real one, it allows us to obtain values that are in good agreement with the observed average temperature and to highlight the crucial role of greenhouse gases in the planet's energy balance.

The sequence concludes with the construction and discussion of Earth–Sun–atmosphere energy flows, integrating experimental observations with the models developed. This concluding moment serves to consolidate the physical aspects related to the GHE phenomenon, but also stimulates critical reflection on climate change and the link between science and citizenship. The data collected show a clear improvement in the understanding of complex concepts and a reduction in recurring misconceptions [18, 64].

Students' initial representations of the greenhouse effect

Before beginning the sequence with the students, it was considered important to understand what initial representations the students had regarding the greenhouse effect. For this reason, a collection of drawings was started, conceived as a diagnostic tool to analyse pre-existing mental models.

Drawings can offer a broader picture of students' understanding, revealing not only what they already know but also the conceptual difficulties and partial ideas that often do not emerge through questionnaires or interviews alone. For this reason, the drawings were not used to evaluate students' skills, but rather to explore their initial conceptions of the phenomenon. Identifying this starting point helped guide the design of the TLS and make it more effective from a teaching perspective.

The relationship between the TLS and the study of students' mental models predates the present doctoral research. Previous iterations of the sequence were already informed by the analysis of students' responses and drawings, following a Design-Based Research approach in which evidence about students' understanding was used to progressively refine the instructional design. The study presented in Chapter 2 extends this line of research by analysing a larger dataset of students' drawings through quantitative methods, including factor and cluster analyses. This allowed a more systematic identification of recurring mental models and misconceptions related to key concepts.

2.2 Theoretical background and aims of the study

The use of drawings reflects one of the core methodological choices of the present research, where students' visual representations are used to access and analyse their mental models of the greenhouse effect.

2.2.1 Mental models

Mental models, or mental images, can be described as the individual and internalized representations that people construct to make sense of external phenomena and interpret the complexity of their surroundings [68]. These models constitute cognitive structures that allow individuals to organize their experiences and generate explanations or predictions about how a process or system functions [69]. In this sense, they act as internal structures through which reality is interpreted, understanding situations, concepts and problems that arise from personal and collective experiences [70].

Norman (1983) [71] emphasized that mental models are dynamic entities: they evolve as individuals interact with the system or phenomenon they are trying to understand, progressively adapting to achieve more effective and functional understanding. Although these models may often be partial, inconsistent, or even contradictory [71, 72], they remain essential tools for interpreting reality. Acting as cognitive filters, mental models support the organization and assimilation of new information and influence reasoning, decision-making, and behavioral responses toward the system under consideration [70].

In science education, focused on identifying students' existing mental models and helping them move toward more scientifically accurate understandings [73–75]. This perspective is also relevant in environmental education, where developing and refining mental models of environmental systems is considered essential for meaningful learning [76–78].

Many researchers have started using art-based methods, such as drawing, to better understand how people perceive their environment and what attitudes they have towards it [79–82]. Drawing allows students to express what they know without relying only on words. It is also useful for capturing spatial aspects and for understanding how students connect different concepts, which are often difficult to assess with traditional methods [83].

Several studies have examined students' mental models in different environmental contexts, from general topics such as sustainability and climate change to more specific environments like deserts or marine ecosystems [5, 6, 79, 84–86]. Analyzing these models helps educators better understand students' reasoning and support the development of more coherent and scientifically accurate ideas. Since mental models are internal and not directly observable, researchers infer them through external indicators. According to Gilbert et al. (2000), mental models can be studied

through the analysis of external representations, such as drawings, explanations, or diagrams, which offer insight into how individuals perceive and organize their understanding of reality [87].

In this study, we therefore interpret mental models as the patterns that emerge in how students visually represent the greenhouse effect.

Understanding students' mental models of the greenhouse effect through drawings

Building on this theoretical framework, several studies have explored students' mental models of the greenhouse effect through the analysis of drawings. Drawings are useful because they can show the complexity of students' ideas without limiting their reasoning to predefined categories.

For instance, Shepardson and colleagues (2011) conducted a qualitative investigation using a self-developed rubric that combined drawing analysis with written explanations to identify emerging conceptions [5]. Their findings indicated that a large proportion of students (33%) depicted the greenhouse effect using generic representations of solar radiation, without distinguishing between incoming and outgoing rays. A smaller group (12%) portrayed the atmosphere as an insulating layer that traps heat or solar rays, while others (13%) represented a real greenhouse or compared it explicitly with the atmosphere. Only a minor percentage (8%) included a hole in the ozone layer in their depictions.

Libarkin et al. (2015) used factor analysis as a tool to classify the mental models emerging from students' drawings [88]. This quantitative approach enabled the identification of recurrent representational patterns and the underlying cognitive dimensions not easily captured by purely qualitative methods. Their analysis revealed four main models. In the first (Model A), solar rays enter the atmosphere and reflect between Earth's surface and the atmospheric layer, which acts as a barrier. The second model (Model B) includes representations featuring plants, greenhouses, and emitted gases. In the third (Model C), the Sun's rays are shown as being absorbed or trapped before reaching Earth's surface. The fourth (Model D) excludes the Sun altogether, showing instead energy entering through ozone holes and sometimes including pollution sources.

Similarly, Harris and Gold (2017) applied a factor approach to examine drawings produced by 164 university students enrolled in an introductory course on oceans and atmospheres [73]. Their analysis led to the identification of seven distinct mental models. The first, called the *expert-like model*, represents longwave radiation emitted by the Earth, absorbed by greenhouse gases, and then re-emitted in all directions, with part of it returning to the surface. The second, or *simple reflection model*, shows a common misconception: solar energy is represented as bouncing off the Earth and then again off greenhouse gases, without distinguishing between different types of radiation. The third, known as the *trapping model*, depicts another widespread misunderstanding: greenhouse gases are portrayed as a barrier that traps or blocks radiation, causing all the energy to be redirected back toward Earth. The fourth, the *improved reflection model*, shows a partial understanding of the phenomenon: it includes both incoming solar radiation and outgoing longwave radiation, but still represents the process as reflection rather than absorption and re-emission. In the fifth, the *layer model*, greenhouse gases are represented as a distinct layer in the atmosphere that reflects radiation back toward Earth. The sixth, the *ozone model*, explains the greenhouse effect through the ozone layer, assuming that more solar radiation enters through "holes" in the atmosphere. Finally, the seventh model, called the *molecular details model*, introduces a more advanced representation at the molecular level.

Later, Liu (2021) applied a factor method to drawings from 130 Taiwanese university students [6]. The study also examines how the identified models are related to students' knowledge of climate change and their academic background. Four models were found. The *Textbook model* mirrors typical textbook depictions, showing solar radiation that reaches Earth, is re-emitted, and becomes partially trapped. The *Ozone Layer model* attributes the greenhouse effect primarily to the ozone hole. The *Sources model* emphasizes emission sources responsible for the effect. The *Simple Penetration model* represents sunlight passing through the atmosphere without being trapped, suggesting that the greenhouse effect is just due to the Sun's warming. Correlation analyses showed that the Textbook model was associated with higher climate knowledge, whereas no significant differences emerged between students from environmental and non-environmental majors.

2.2.2 Aim of the study

This research contributes to the expanding literature on students' mental models of climate change, focusing specifically on the greenhouse effect. Through the analysis of student-produced drawings, we aim to gain deeper insight into how learners conceptualize key physical processes, such as absorption and selective emission, that underpin climate change phenomena.

Although prior studies [6, 88] have adopted similar approaches, their coding schemes and analytical methods have not fully captured the complexity and diversity of students' representations. In contrast, our study adopts a combined use of factor and cluster analyses to achieve a more nuanced understanding of these models.

Furthermore, since previous research has predominantly examined university students, our study also includes high school participants to explore possible differences in understanding related to educational level.

This work is significant because understanding these representations can support the design of more effective teaching strategies and curricula, helping students develop a clearer view of the greenhouse effect and its role in climate change.

Based on these aims, the study was guided by the following research questions:

1. How can students' drawings of the greenhouse effect be used to explore and characterize their mental models of the phenomenon?
2. Which graphical elements in the drawings can be considered indicators of a coherent understanding of the physical mechanisms underlying the greenhouse effect?
3. Which computer-based analytical approach (factorial or cluster analysis) is most effective in identifying and grouping students' mental models from their drawings?
4. To what extent do the identified mental models vary according to the students' educational level and reflect the influence of external visual sources such as textbooks and online materials?

2.3 Methods

2.3.1 Sample and data collection

In this study, we analyzed drawings created by a total of 174 students. The convenience sample consisted of 80 high school students (mean age 16) and 94 university students (mean age 23) enrolled

in a master's program for future physics teachers.

The high school participants had completed courses in natural sciences during the 9th and 10th grades and studied physics in the 12th grade. The university participants had successfully passed an introductory physics course during the second year of their bachelor's degree. Therefore, it is likely that students already had some prior knowledge of the greenhouse effect, as outlined above.

In this study, drawings from both secondary school and university students were examined together. This choice aimed to include a wider range of graphical features, helping to better identify the different mental models in the sample. Combining the two groups also enhanced the statistical robustness of the analysis.

We collected our data through a 'draw-and-explain' task [6], with the following prompt: Draw a picture that explains the greenhouse effect on the Earth. Add labels and words to explain your diagram. The reason for asking to use both visual and verbal information was to facilitate the interpretation of the drawings and gain a more complete and detailed view of the mental models about greenhouse effect.

2.4 Data analysis

2.4.1 Grid-based analysis of key elements in students' drawings

In the preliminary stage of our research, we analyzed students' drawings to identify the most recurrent graphical and conceptual elements associated with their understanding of the greenhouse effect.

The analysis was based on a set of fundamental physical elements identified in the evaluation grid shown in Figure 2.6. These elements include the representation of solar radiation, the Earth, the atmosphere, greenhouse gases, and the interactions between them (reflection, absorption, emission, and transmission). The drawings were coded according to the presence and type of these elements, with particular attention to how the physical processes were represented graphically (e.g., through straight arrows, wavy lines, or fluxes).

ITEM	OPTIONS			
Model type	Energy budget	0-dimensional	Ingenous model	
Rappresentation Sun and Earth	Sphere	Dome	Layer	Straight line
Rappresentation Atmosphere and greenhouse gases	Sphere	Dome	Layer	Straight line
	Wavy line	Micro	Plume	
Radiation	Flux	Ray	Wave	Line
Interation with Earth	Reflection	Detached reflection	In/out	
Interation with atmosphere	Reflection	Reflection and transmission	Emission up and down	Emission in all directions
Theme variation	Ozone hole	Agricultural greenhouse	Anthropic elements	Heat

Figure 2.6: Fundamental physical elements used in the analysis of drawings. Source: [89]

The preliminary analysis revealed several common patterns and misconceptions in students' representations. A major finding was the lack of distinction between the atmosphere and greenhouse gases in a significant portion of the drawings.

As illustrated in Figure 2.7, about two-thirds of students did not differentiate between these two components, often depicting the atmosphere as a single, uniform layer surrounding the Earth.

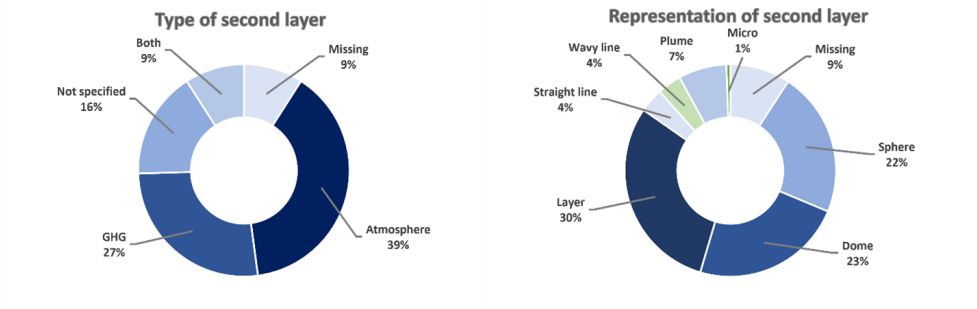


Figure 2.7: Percentage distribution of student responses on the type of second layer (Left) and its representation (Right). Source: [89]

Another relevant feature concerned how radiation was represented. As shown in Figure 2.8, most students (around 73%) used straight rays to depict radiation, while a smaller fraction employed arrows representing fluxes (17%) or wavy lines (10%). This suggests a prevailing tendency to associate energy transfer with simple directional motion, rather than with processes of absorption

and re-emission.

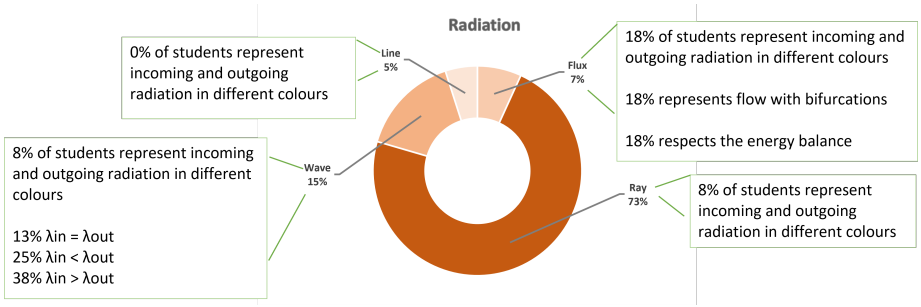


Figure 2.8: Percentage analysis of student responses on the type of radiation representation. Source: [89]

When analyzing the interactions with the Earth and the atmospheric layer (Figure 2.9), reflection emerged as the most frequently represented process (approximately 69% of the drawings). Fewer students included transmission or emission processes, indicating that many tend to interpret the greenhouse effect as a reflective phenomenon rather than one involving re-emission of infrared radiation.

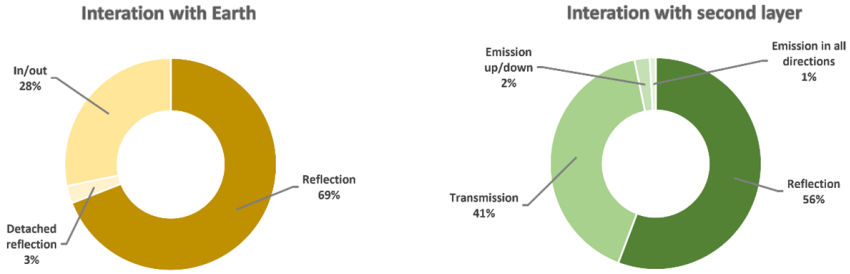


Figure 2.9: Results from students' responses on interaction with the Earth (Left) and the second layer (Right). Source: [89]

A correlation analysis between key items (Figure 2.10) revealed consistent associations between reflection on the Earth's surface and reflection on the second layer (correlation coefficient $r > 0.3$). This finding suggests that many students tend to use similar graphical logic to represent both processes, reinforcing the idea of a "mirror-like" conception of the atmosphere.

Finally, to explore possible external influences on students' drawings, we compared them with textbook images representing the greenhouse effect (Figure 2.11). Several visual analogies were identified, particularly in the use of arrows and in the depiction of the atmospheric layer, suggesting that students' visual models are often shaped by instructional materials.

	Flux	Ray	Wave	Line	Reflection	Detyached reflection	In/out	Reflection	Transmission	Emission up/down	Emission in all directions
Flux	1,00										
Ray	-0,50	1,00									
Wave	-0,13	-0,70	1,00								
Line	-0,06	-0,29	-0,08	1,00							
Reflection	-0,13	0,26	-0,10	-0,24	1,00						
Detached reflection	-0,05	0,10	-0,07	-0,03	-0,13	1,00					
In/out	0,12	-0,09	0,06	-0,10	-0,50	0,00	1,00				
Reflection	0,04	0,16	-0,08	-0,29	0,43	0,10	-0,09	1,00			
Transmission	0,07	0,13	-0,12	-0,19	0,27	-0,01	0,00	0,41	1,00		
Emission up/down	-0,03	-0,06	0,11	-0,02	-0,03	-0,02	0,06	-0,06	-0,12	1,00	
Emission in all directions	-0,03	-0,18	0,26	-0,02	-0,15	-0,02	0,06	-0,18	-0,12	-0,01	1,00

Figure 2.10: Correlation table between radiation, interaction with the Earth, and interaction with the second layer. Source: [89]

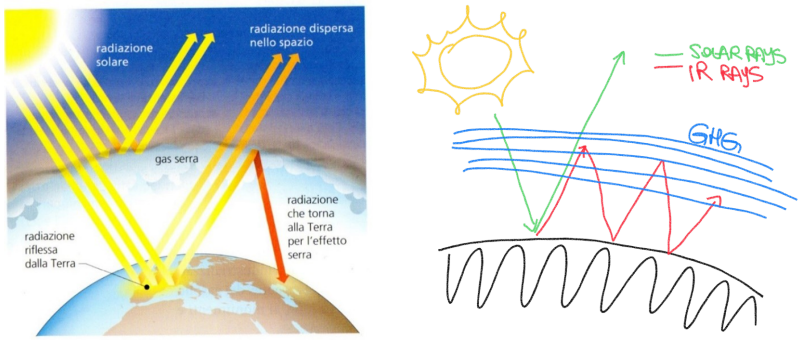


Figure 2.11: Comparison between a textbook image (left) and a student drawing (right). Both representations display similar visual conventions in depicting radiation and atmospheric layers. Source: [89]

This preliminary analysis offered a first characterization of students' drawings, highlighting common representational elements and areas of conceptual ambiguity. These insights were used to refine the analytical grid and to guide the following stages of the research, which aimed to examine the data in greater depth through quantitative and computer-based methods.

2.4.2 Identifying mental models through factorial and cluster analysis

Preliminary analysis - applying Liu's coding framework

At the beginning of our quantitative study, we aimed to replicate the findings obtained by Liu (2021) by applying the coding rubric reported in the paper [6]. The rubric, which in the context of the Liu (2021) study aimed to represent a list of "salient, relevant characteristics or features in students' conceptualization of this phenomenon" (p. 3003), was developed after several recursive rounds of independent analyses of the students' drawings carried out by two researchers first on a subset and then on the entire dataset.

The final rubric featured 16 distinct codes (Table 2.2).

	Drawing characteristic (DC)
1	Sun emitting something
2	Greenhouse gas present
3	Element absorbed or trapped by greenhouse gas
4	Incoming element is energy
5	Incoming element passes unchanged through atmosphere
6	Outgoing element to space
7	Incoming/outgoing element changed (above the Earth's surface)
8	Element reflected or absorbed by the atmosphere
9	Surface emitting something
10	Element reflected or absorbed by the Earth's surface
11	Rising temperature and its effects
12	Pollution and destruction
13	Organism emitting or absorbing gas
14	Ozone layer present
15	Hole in the ozone layer or atmosphere present
16	Element absorbed or trapped by ozone layer

Table 2.2: Drawing characteristics analyzed in the study. Source: [6]

We hence scored the drawings in our sample using the codes in Table 2.2. A first screening of our data led us to remove two codes, "Sun emitting something" and "Rising temperature and its effects", since they were present or absent in all drawings, respectively. Then, we performed a principal component analysis and retained an unrotated solution given that a drawing characteristics can correspond to more than one mental model [79]. The Kaiser-Meyer-Olkin measure of sampling adequacy yielded a value of 0.654, indicating adequacy for conducting factor analysis. Additionally, Bartlett's test of sphericity was significant (χ^2 (91) = 556, p < .001). The number of retained factors was decided by inspecting the scree plot and running a parallel analysis on random data. Four factors, A-D, were extracted.

As shown in Table 2.3, all four factors contained at least four items with the absolute value of loading greater or equal to 0.40.

The first factor explained 20.6% of the data variance, the second factor 14.3%, the third 11.5%, and the fourth 10%. The total variance explained by this four-factor solution for the 14 codes is 56.5%, suggesting that four underlying mental models dominated students' thinking about the greenhouse effect.

Drawing characteristics	A	B	C	D	Communalities
2	0.482				0.662
3			0.462		0.642
4			0.557		0.646
5	0.408	0.538			0.405
6	0.470		-0.479		0.502
7			0.407	-0.624	0.324
8	0.594	0.500			0.307
9			0.486	-0.480	0.449
10	0.654	0.463			0.349
12			0.445	0.476	0.528
13			0.497	0.460	0.438
14	-0.662	0.555			0.246
15	-0.711	0.480			0.249
16	-0.544	0.592			0.354

Table 2.3: Factor loadings and communalities based on a principal components analysis without rotation for 14 drawing codes (N = 174).

A higher loading suggests that a certain characteristic has a stronger association with the given model. A negative loading suggests that a certain characteristic is negatively associated with the given model, which means it is unlikely to be present in a drawing aligned with that model. The four models are reported in Figure 2.12.

By looking at factor loadings, it emerges that Factor A closely resembles a simplified conventional diagram found in textbooks describing the greenhouse effect. The drawings produced by students that align with this factor tend to illustrate an unchanged path of sunlight (DC5) reaching the Earth's surface (DC10), and it is then reflected back into space (DC6). Furthermore, these drawings illustrate how the greenhouse gases (DC2) trap some of this reflected light, causing it to remain in the earth's atmosphere (DC8). These drawings are also unlikely to feature any reference to ozone layer (DC14-DC16). Given the similarities with textbook illustrations, we called this factor the *Textbook Model* as in the Liu (2015) study.

In factor B, drawings feature graphical signs that represent the incoming elements passing through the atmosphere (DC5) and bouncing back and forth between the Earth and atmosphere strata (DC8, DC10). Moreover, they also include the ozone layer, the ozone hole, together with the representation of specific rays that are absorbed or trapped by the ozone layer (DC14-DC16). For such reasons, we called this factor *Ozone Layer Model*.

In factor C, drawings feature signs that represent incoming radiation or energy (DC4) that changes when it is emitted from the surface (DC7 and DC9). The radiation emitted from the Earth's surface is also completely trapped by the greenhouse gas (DC3) with no further emission in space (negative loading on DC6). There are also elements graphical elements depicting the sources of pollution, such as factories or vehicles that emit gases (DC12 and DC13). We called this composite factor *Flux Model*.

Finally, factor D features signs that only represent the sources responsible for greenhouse gas

emissions (DC12 and DC13) with no reference to incoming radiation or to Earth's surface emission (negative loadings on DC7 and DC9). We hence called this factor the *Source Model*.

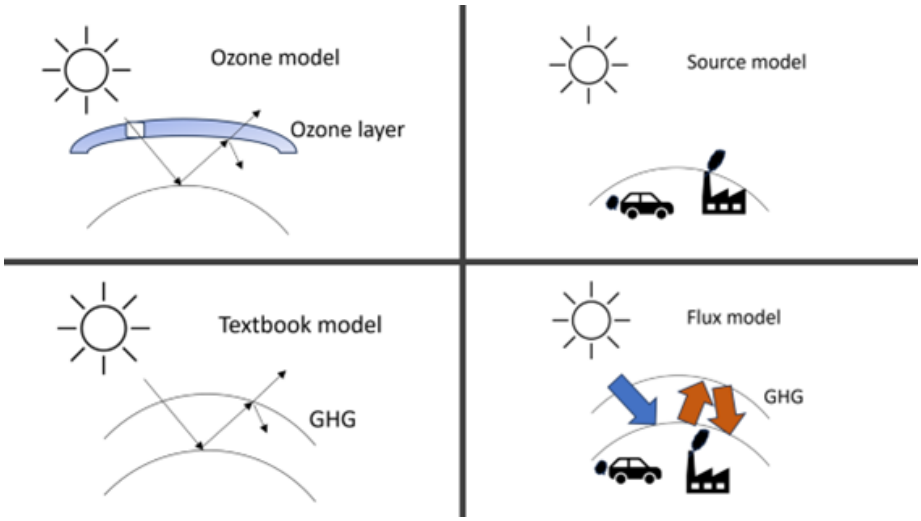


Figure 2.12: Factors emerging form the preliminary data analysis using the coding table in Liu (2021), with GHG indicating Greenhouse Gases in the drawings.

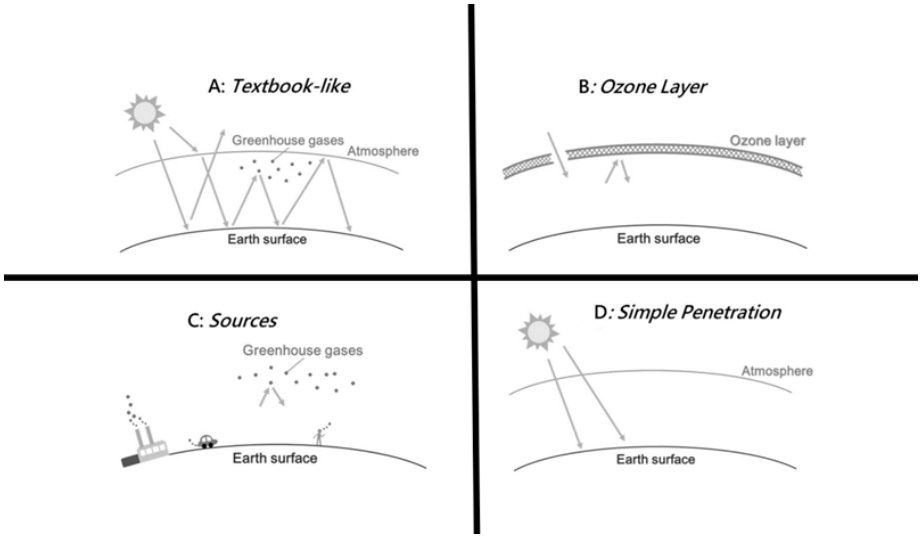


Figure 2.13: Four models identified by Liu through factor analysis applied to the attributes of drawings. Source: [6]

While two factors (*Ozone Layer Model* and *Source Model*) well aligned to the Liu (2021) study findings (Figure 2.13), the other two factors differed from the ones emerged in that study. Specifi-

cally, the *Textbook model* emerged in this study only partially corresponded to the *Textbook model* of the Liu (2015) study since it does not include graphical elements representing radiation that is absorbed or trapped by greenhouse gases or any reference to energy. The *Flux model*, on the other hand, is more complex than the *Simple Penetration model* since it included also characteristics related to how energy undergoes changes when it is emitted from the Earth's surface, namely there is explicit reference to Earth's surface emitted radiation that is different from the incoming one.

After assigning each drawing to a model based on the corresponding factorial scores, results showed that the great majority of drawings (80%) aligned with the *Textbook* Model, while only five drawings (3%) matched the Ozone Layer Model and four drawings (2%) the *Source* Model. They turn out to be unrepresentative of our drawings. Consequently, this result suggests us to exclude the 9 drawings associated with these models from our analysis and to eliminate the drawing attributes unique to them (e.g., Presence of ozone layer, Presence of hole in ozone layer or atmosphere, Element absorbed or trapped by ozone layer, Pollution, Organism emitting or absorbing gas) from the coding table.

This refinement process also highlighted some broader weaknesses in the rubric adopted from Liu (2021) [6]. In particular, it lacked explicit reference to the Earth's emitted radiation distinct from the incoming one, and many items were either redundant (e.g., "Sun emitting something"), too generic (e.g., "rising temperature"), or absent from the collected drawings (e.g., "pollution"). Similar shortcomings were observed in previous studies: Libarkin et al. (2015) [88] emphasized contextual rather than explanatory features (e.g., plants or pollution), whereas Harris and Gold (2017) [73] focused on molecular-level processes rarely represented by students. Overall, this preliminary analysis indicated that the rubric could not effectively discriminate between accurate and unsophisticated models of the greenhouse effect, nor capture essential aspects of understanding such as the dynamics of radiation absorption and emission.

Redesign of the coding table

Based on these results, we created a revised and more concise list of graphical features to analyze the drawings collected for this study. The updated rubric, shown in Table 2.4, is accompanied by a comparison with those used in previous research examining students' representations.

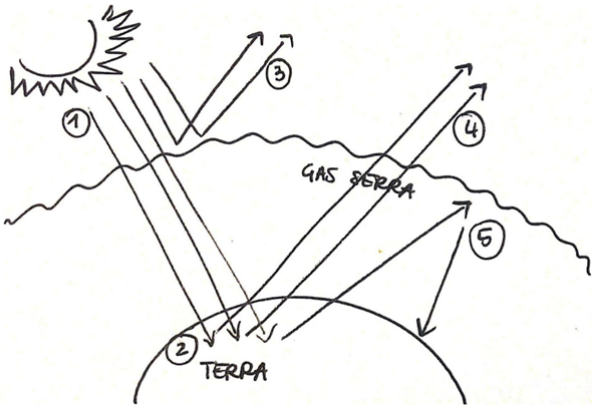
The revised rubric incorporates many of the elements already present in earlier coding schemes, such as trapped radiation and absorbed or re-emitted energy. At the same time, it introduces explicit distinctions between different graphical representations—such as straight segments, zigzag lines, or arrows—to differentiate whether solar radiation is depicted as a wave or as a simple incoming ray. For example, feature C4 refers specifically to radiation retained within the atmosphere, whereas feature C1 focuses on whether students represent only incoming light when illustrating the greenhouse effect. In addition, two separate features were defined to distinguish between radiation reflected by the Earth's surface and that reflected by the atmosphere (C2 and C3, respectively). These refinements made it possible to identify drawing elements that serve as strong indicators of a coherent understanding of the physical mechanism underlying the greenhouse effect.

Code	Graphical feature	Description	Comparison with previous rubrics
C1	Incoming radiation is a ray	A straight segment, a zig-zag line or an arrow is drawn from the Sun in the direction of the Earth's surface.	This item is related to the item *Incoming element is energy* in Liu (2021) and in Libarkin et al. (2015).
C2	Element reflected by the Earth's surface	A straight segment, a zig-zag line or an arrow is drawn from the Sun, reaches the Earth's surface and bounces unchanged away from the surface.	This corresponds to Harris & Gold (2017) items called *Earth's surface reflects incoming radiation* and partly to the item *Element reflected or absorbed by the Earth's surface* in Liu (2021) and the item *Element reflected unchanged by surface and/or atmosphere* in Libarkin et al. (2015).
C3	Element reflected by the atmosphere	A straight segment, a zig-zag line or an arrow reaches the atmosphere, represented as multiple arcs around the Earth, from which it is rebounded unchanged.	This item partly corresponds to the item *Element reflected or absorbed by the atmosphere* in Liu (2021) and item *Element reflected unchanged by surface and/or atmosphere* in Libarkin et al. (2015). This item is also similar to *GHGs that reflect or block radiation* in Harris & Gold (2017).
C4	Radiation is trapped by atmosphere	A straight segment, a zig-zag line or an arrow representing radiation cannot reach space because it is trapped within the atmosphere, represented as a single arc around the Earth, bouncing back and forth between the Earth's surface and the atmosphere.	This item corresponds to the item *Element absorbed or trapped by greenhouse gas* in Liu (2021), and the item *Barrier 'stops' something from escaping* in Libarkin (2015). It also partially corresponds to item *GHGs trap or block radiation* in Harris & Gold (2017).
C5	Incoming element passes unchanged through atmosphere	A straight segment, a zig-zag line or an arrow representing radiation passes through the atmosphere, represented by multiple arcs around the Earth.	This item corresponds to item *Incoming element passes unchanged through atmosphere* in Liu (2021).
C6	Incoming/outgoing element changed (above the Earth surface)	A straight segment, a zig-zag line or an arrow representing radiation is represented differently when arriving at the Earth's surface and when reflected away from it.	This item corresponds to item *Incoming/outgoing element changed (above the Earth surface)* in Liu (2021).
C7	Element absorbed by the Earth's surface	A straight segment, a zig-zag line or an arrow representing radiation stops at the Earth's surface.	This item corresponds to item *Earth's surface absorbs incoming radiation* in Harris & Gold (2017).
C8	Surface emitting something	An arrow or a wavy segment is drawn from the Earth's surface.	This item is explicitly featured in Liu (2021, *Surface emitting something*) and in Harris & Gold (2017), *Earth's surface gives off/emits radiation*).

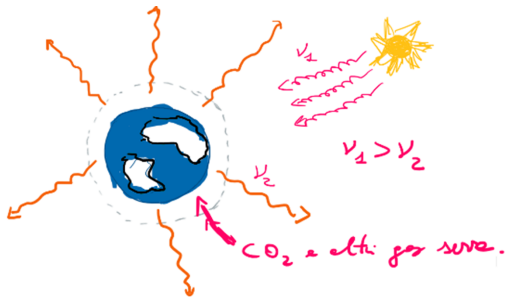
Table 2.4: List of graphical features used to code the drawings in the present study. Revised starting from Libarkin et al. (2015), Harris & Gold (2017) and Liu (2021). Source: [90]

Factor analysis with new coding table

The drawings were subsequently evaluated by the same two researchers using the refined coding rubric. The level of inter-rater agreement increased to a satisfactory value of 82%. Any remaining disagreements were jointly reviewed and discussed until a shared consensus was achieved. Two illustrative examples of the scoring process are presented in Table 2.5.



C1	C2	C3	C4	C5	C6	C7	C8
1	1	1	0	1	0	0	0



C1	C2	C3	C4	C5	C6	C7	C8
0	0	0	0	1	1	1	1

Table 2.5: Coding of two representative drawings of our sample using the list of graphical features in Table 2.2. Source: [90]

In the first drawing, radiation is depicted as an arrow (C1=1). It travels through the second layer without undergoing any change (C5=1), reaches the Earth's surface where it is reflected (C2=1), and remains unaltered in the process (C6=0). Some of the rays are reflected by the second layer (C3=1), whereas others escape into space without being retained (C4=0). The ray is not absorbed at the Earth's surface (C7=0), and no additional arrow, separate from the incoming one, is shown as being emitted from the surface (C8=0).

The second drawing complements the first. In this case, radiation is not represented by segments

(C1=0), but by a wave that neither reflects off the Earth's surface (C2=0) nor off the atmosphere (C3=0). No wave appears to be blocked by the atmosphere (C4=0). Instead, the radiation passes through the dotted arc representing the atmosphere without modification (C5=1), reaches the Earth's surface (C7=1), and changes its form in the process (C6=1). Additionally, wavy arrows originate from the Earth's surface (C8=1) and propagate outward into space.

We then conducted a principal component analysis and, in line with previous studies, retained an unrotated solution, as the features present in a drawing may relate to multiple mental models and simultaneously reflect both correct and incorrect conceptions. The suitability of the data for factor analysis was evaluated using the Kaiser–Meyer–Olkin measure of sampling adequacy and Bartlett's test of sphericity. The number of factors to retain was determined through inspection of the scree plot and by performing a parallel analysis on a randomly generated dataset.

The Kaiser–Meyer–Olkin measure of sampling adequacy was 0.613, which is considered suitable for factor analysis. Bartlett's test of sphericity was significant, χ^2 (28) = 556, p < .001.

Two factors were extracted by the principal component analysis performed on the 8 entries of the rubric (see Table 2.6).

Code	**1**	**2**	**Communalities**
1. Incoming radiation is a ray			0.162
2. Element reflected by the Earth's surface	-0.683	0.427	0.649
3. Element reflected by the atmosphere		0.674	0.563
4. Radiation is trapped by atmosphere		0.429	0.185
5. Incoming element passes unchanged through atmosphere		0.745	0.567
6. Incoming/outgoing element changed (above the Earth surface)	0.589		0.434
7. Element absorbed by the Earth's surface	0.911		0.856
8. Surface emitting something	0.897		0.848

Table 2.6: Factor loadings and communalities based on a principal components analysis without rotation for the new 8-code drawing rubric (N = 174). Source: [90]

The first component accounted for 33.2% of the total variance, while the second explained 20.1%. Together, these two components accounted for 53.3% of the variance, indicating that students' thinking about the greenhouse effect is largely characterised by two main underlying mental models. These two models are schematically illustrated in Figure 2.14.

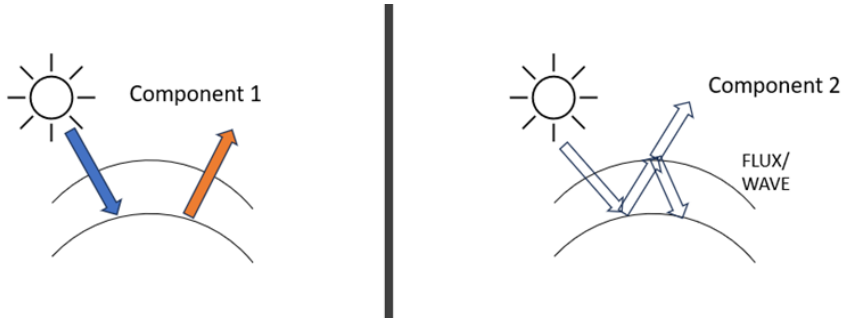


Figure 2.14: Representation of the two models obtained through principal component analysis of the drawings using the new coding rubric. Component 1: *Absorption/Emission Model*. Component 2: *Reflection/Trapping Model*. Source: [90]

The first extracted component is characterised by incoming radiation that undergoes a transformation after being re-emitted from the Earth's surface (C6 and C8). The radiation is also absorbed at the surface (C7), while reflection is not observed (as indicated by the negative loading of C2). For this reason, we refer to this component as the *Absorption/Emission Model*, as it captures the idea that the radiation entering the atmosphere differs from that leaving it.

The second component is characterised by incoming radiation that passes through the atmosphere without modification (C5) and is reflected by the Earth's surface (C2). Part of this radiation is retained within the atmosphere (C4), while another part is transmitted through it (C3), without any indication of transformation during the process. We therefore refer to this factor as the *Reflection/Trapping Model*, as it reflects the idea of radiation being repeatedly reflected within the system.

Overall, assigning students to the two models based on their factorial scores resulted in approximately 25% of the drawings being classified as *Absorption/Emission Model*, and about 75% as *Reflection/Trapping Model*. It is worth noting that item C1 does not load on either of the two components.

The revised set of graphical features used to analyse students' drawings resulted in the identification of only two factors, which we interpret as the main underlying structures shaping how students perceive and conceptualise the greenhouse effect. In the *Absorption/Emission* Model, radiation is understood as undergoing a transformation after interacting with the Earth's surface, where it is absorbed and subsequently re-emitted. In contrast, in the *Reflection/Trapping* Model, radiation is treated as unchanged and primarily described in terms of repeated reflections between the surface and the atmosphere. It is important to highlight that the *Reflection/Trapping* Model aligns with well-documented misconceptions in the literature, such as the notion of radiation being "trapped" or repeatedly reflected by the atmosphere. Conversely, the *Absorption/Emission* Model incorporates elements that are more consistent with the scientific explanation, although it does not explicitly account for the overall energy balance.

The two mental models identified in this study appear more parsimonious than those reported in previous research, as they capture more extreme and archetypal representations. For this reason, they may be considered more generalisable compared to earlier classifications. They retain several

features of previously identified models.

For instance, the *Absorption/Emission* Model incorporates elements of the *Expert-like*, *Improved reflection*, and *Molecular detail* models described by Harris and Gold (2017) [73], as it schematically represents outgoing radiation as different from the incoming one, thus reflecting a more scientifically coherent understanding of the greenhouse effect mechanism. Notably, a similar model did not emerge in the studies by Libarkin et al. (2015) [88] and Liu (2021) [6]. Furthermore, one additional aspect highlighted by our analysis is that the *Absorption/Emission* Model includes outgoing radiation that is partly transmitted and partly reflected. This feature, which is relevant for a more accurate representation of the physical mechanism of the greenhouse effect, was not identified in previous studies.

The *Reflection/Trapping* Model can also be related to earlier classifications. In particular, it shares key characteristics with Models a and c described by Libarkin et al. (2015) [88], in which solar radiation penetrates the atmosphere and is reflected by atmospheric layers, without any indication of transformation after interaction with the Earth's surface. Similarly, our model captures core aspects of the *Textbook-like* and *Simple Penetration* models identified by Liu (2021) [6], as well as the *Simple reflection*, *Trapping*, and *Layer Models* described by Harris and Gold (2017) [73]. All these models are based on the same underlying misconception, namely that radiation remains unchanged throughout processes of absorption and reflection.

Finally, we observe that the *Source* and *Ozone* models identified in Liu (2001) [6] and Harris and Gold (2017) [73], as well as Model d in Libarkin et al. (2015) [79], initially appeared in our factorial analysis. However, these models were later excluded, as they were not sufficiently representative of the overall sample. This result should not be interpreted as evidence that students in our study do not hold the ozone-related misconceptions reported in the literature [91]. Rather, it may be associated with the relatively limited emphasis placed in the Italian high school science curriculum on topics such as environmental pollution, the role of greenhouse gases in climate change, and ozone layer depletion, which also tend to receive marginal attention in textbooks. An alternative explanation may lie in students' limited understanding of the chemical processes underlying climate mechanisms [92].

Our analysis shows that factor analysis of students' drawings is a useful method for exploring mental models of the greenhouse effect, as it helps identify groups of related visual features that suggest underlying cognitive structures. However, a single drawing cannot fully represent an individual's mental model, since students may hold multiple, partially overlapping ideas at the same time. For this reason, it is difficult to assign each drawing to a single model. Within a purely factorial approach, drawings can only be described in terms of their similarity to the identified models, which makes the overall distribution of models across participants less clear.

To address these methodological constraints, we integrated a factor-analytic and a person-centered approach, offering a more comprehensive description of how students conceptualize the greenhouse effect and enabling stronger educational implications. Specifically, factor analysis was used to extract a set of representative mental models, while cluster analysis was employed to group individual drawings sharing similar visual and conceptual characteristics, thus showing how the extracted models are distributed within the sample.

From an item-centered to a person-centered approach

To implement the person-centered approach, we conducted a cluster analysis using the k-means algorithm [93]. First, we computed Z-scores for each student and each graphical feature of the revised coding rubric (Table 2.4). The Z-score for the i-th student and the j-th graphical feature, Z_{ij}, was calculated as:

$$Z_{ij} = \frac{x_{ij} - \bar{x}_j}{SD_j} \tag{2.8}$$

where x_{ij} represents the score of the i-th student for the j-th graphical feature (0 or 1), while $\bar{x}_j$ and SD_j denote the mean and standard deviation of that feature, respectively. By definition, Z_{ij} takes a positive value when $x_{ij} = 1$ and a negative value when $x_{ij} = 0$.

Students were then assigned to clusters based on the similarity of their Z-scores. The k-means algorithm was selected in order to identify clusters with high internal similarity. To determine the optimal number of clusters, we evaluated different solutions using the Dunn index [94], namely the ratio between the minimal distance between all the clusters considered in pairs (inter-cluster separation) to the largest distance between observations in the same cluster (intra-cluster separation). Higher values indicate better-separated clusters. We chose this index since it discriminates solutions with spatially more separated clusters, to the detriment of solutions having clusters though dense inside but with between-cluster "noise".

We also assessed cluster quality using the Davies–Bouldin Index (DBI), namely the ratio of within-cluster non-density to the distance between cluster centers. It can be obtained by taking the ratio of the average distance between points in a cluster and the centroid of the cluster to the distance between the centroids of the cluster and the nearest cluster. Lower values indicate more compact and well-separated clusters. This index was chosen as it performs well with clusters of different sizes. A post-hoc power analysis indicated that the sample size was adequate given the observed cluster separation [95].

Students were then assigned to a cluster based on the relative proximity of their data to the respective cluster centroids. Cluster distinctiveness was further examined using a one-way multivariate analysis of variance (MANOVA), with Z-scores of the graphical features as dependent variables and cluster membership as the independent variable. The sample size met the requirements for MANOVA, as each cluster included more than six cases and exceeded the number of dependent variables.

The assumption of linearity was evaluated using the Phi coefficient, appropriate for binary variables. Most coefficients ranged between 0.03 and 0.48, below the recommended threshold of 0.80. However, a high correlation was observed between C7 and C8 ($\phi = 0.95$), suggesting that emission from the Earth's surface is strongly associated with absorption of incoming radiation. For this reason, item C8 was excluded from the MANOVA.

Since the assumption of normality was not met due to the binary nature of the variables, we verified that the degrees of freedom for error exceeded the recommended threshold of 40, given the distribution of cases across clusters. As this condition was satisfied, MANOVA was considered appropriate [96]. To ensure robustness, Pillai's Trace was used as the test statistic, as it is less sensitive to violations of normality [97].

Finally, differences across school grades were examined using chi-square analysis. To meet the assumptions of this test, clusters were grouped according to their correspondence with the mental models identified through factor analysis.

Two solutions maximized the Dunn index (D = 0.73), one with 6 clusters, the other with 7 clusters. The 6-cluster solution explained 59% of the variance in the data, Pillai's Trace = 2.929, F(35; 785) = 31.708, p < 0.001, while the 7-cluster solution explained 42% of the variance, Pillai's Trace = 2.503, F(36; 948) = 18.850, p < 0.001. Moreover, Davies-Bouldin Index was lower for the 6-cluster solution than the 7-cluster solution (0.70 and 0.74, respectively). Therefore, we chose the 6-cluster solution (see Table 2.7 for the distribution of centroids in each of the six clusters). The six clusters are visually represented in Table 2.8.

A brief description of each cluster is also reported. Cluster 1 is the most predominant (about 40%), followed by cluster 2 and 6 (15%). The least frequent is cluster 3 (9%).

N(%)	**Cluster**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
61 (37)	Cluster 1	0.54	0.59	0.44	-0.51	0.44	-0.32	-0.60	-0.57
24 (15)	Cluster 2	-0.06	0.55	0.21	1.96	0.33	-0.16	-0.60	-0.57
15 (9)	Cluster 3	-1.85	0.16	0.14	-0.51	0.26	-0.08	-0.45	-0.57
19 (11)	Cluster 4	-0.97	-0.93	0.35	0.14	0.44	1.67	1.65	1.73
22 (13)	Cluster 5	0.21	-0.80	-1.16	-0.51	-1.89	-0.23	-0.60	-0.57
24 (15)	Cluster 6	0.44	-0.67	-0.64	0.01	-0.23	-0.07	1.65	1.54
η^2		0.556	0.428	0.337	0.717	0.602	0.374	0.971	0.940
p-value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 2.7: Distribution of centroids obtained from the k-means routine for the six clusters solution. Reported scores are Z-standardized. Source: [90]

Clusters 4 and 6, which together account for 26% of the drawings, are characterised by an absorption–emission mechanism, where the central idea is that the element entering the atmosphere differs from the one leaving it. Although both clusters capture the physical mechanism of the greenhouse effect, they differ in representation: in Cluster 6, radiation is depicted as a ray, whereas in Cluster 4 it is represented as a flux or wave. These clusters can therefore be associated with the *Absorption/Emission* mental model.

In contrast, Clusters 1, 2, 3, and 5, which account for 75% of the drawings, are all characterised by representations in which incoming radiation remains unchanged or becomes trapped after reflection from the Earth's surface. More specifically, Clusters 1 and 2 both depict a reflected ray, but with a key difference: in Cluster 1, the ray eventually escapes the atmosphere, whereas in Cluster 2 it remains confined, illustrating a typical example of the "trapping" idea, often reported as a misconception. Cluster 5 shows rays reaching the Earth without further interactions, while Cluster 3 differs by representing a reflected flux rather than a ray. These clusters can therefore be linked to the *Reflection/Trapping* mental model.

Note that the cluster distribution roughly confirms the one obtained from factorial scores, thus further validating the statistical findings.

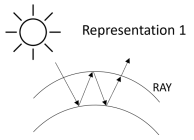
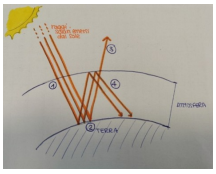
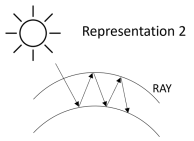
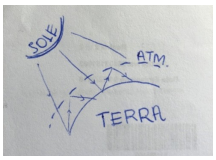
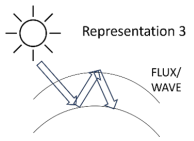
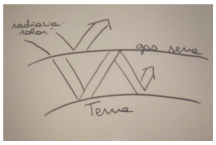
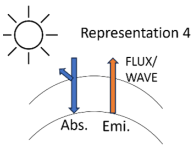
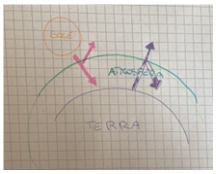
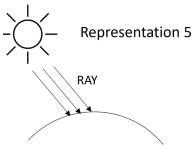
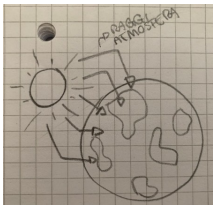
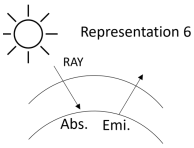
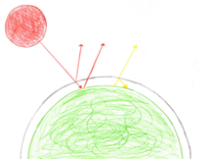
Cluster / Representation	Description	Example
	The representation shows the Sun emitting rays directed towards the Earth. The rays pass through the atmosphere, impinge the Earth's surface and are reflected back upwards. Some of these reflected rays bounce back between the surface and the atmosphere, while other exit towards space.	
	The representation shows the Sun emitting rays directed towards the Earth. The rays pass through the atmosphere, reach the Earth's surface and are reflected by bounching between the surface and the atmospheric layer without escaping.	
	The representation shows the Sun emitting flux of energy or a wave directed towards the Earth. The radiation passes through the atmosphere, reaches the Earth's surface and bounces back between the surface and the atmospheric.	
	The representation shows a flux of energy or a wave passing through the atmosphere and reaching the Earth's surface, indicated by 'Abs.' (absorption). A second flux of different nature is then emitted upwards from the Earth, denoted 'Emi.' (emission).	
	The representation shows the Sun emitting rectilinear rays directed towards the Earth's surface. The rays travel through space and strike the planet's surface, but no outgoing rays or interaction with the atmosphere is depicted.	
	The representation shows a solar ray passing through the atmosphere and reaching the Earth's surface, indicated by 'Abs.' (absorption). A second ray of different nature is then emitted upwards from the Earth, denoted 'Emi.' (emission).	

Table 2.8: Description of the six representations obtained from the cluster analysis. Source: [90]

The six identified drawing patterns not only reflect the core features of the two mental models extracted through factor analysis, but also show how these models are articulated in different ways across the sample. For example, both Cluster 1 and Cluster 5 depict light rays entering the atmosphere and undergoing multiple reflections between the Earth's surface and the atmosphere, similarly to common textbook representations. However, the analysis makes it possible to distinguish between cases in which some rays eventually escape into space and those in which they do not.

Although both representations are non-normative from a physical perspective, this distinction is meaningful: in Cluster 1, light can leave the atmosphere after several reflections, whereas in Cluster 5 it remains "trapped" between the Earth and the atmosphere, with no possibility of escape [24, 30].

In the first case, students may be reasoning by combining reflection and refraction laws from geometric optics, while in the second case their reasoning appears to rely solely on reflection. The use of reasoning strategies based on the more familiar light behavior instead of the more abstract energy flow processes confirms the difficulties that students have when explaining complex phenomena related to the Earth system [98].

This difficulty is also evident in Cluster 3, where incoming radiation is represented as energy rather than light, for instance through the use of thick arrows. However, even in this case, the energy does not change after interacting with the Earth's surface, suggesting that students still interpret the process mainly in terms of reflection.

Changes in the radiation emitted by the Earth are instead observed in Clusters 4 and 6. While Cluster 4 still relies on a ray-based representation and may indicate only a partial understanding of the mechanism, Cluster 6 points to a more coherent interpretation of the greenhouse effect, in which energy transformation through absorption and re-emission is explicitly represented. As highlighted in previous studies, this aspect is particularly challenging for students, who often confuse solar and terrestrial radiation [24] or struggle to understand emission processes from the Earth [30]. The fact that such a model did not emerge in earlier studies further supports the idea that this level of understanding is relatively uncommon.

Subdivision by school grade

Finally, we examined differences across school grades using a chi-square analysis. To satisfy the assumptions of the test, the identified clusters were grouped according to their correspondence with the mental models derived from the factor analysis.

The distribution of the six clusters for high school and university students is reported in Table 2.9.

	Reflection / Trapping model			**Absorption / Emission model**			**Total**
Group	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 5**	**Cluster 4**	**Cluster 6**	**Total**
High school	34	9	5	13	6	8	75
University	27	15	10	9	13	16	90
Total	**61**	**24**	**15**	**22**	**19**	**24**	**165**

Table 2.9: Distribution of students across clusters and models (Reflection/Trapping and Absorption/Emission). Source: [90]

After grouping the clusters according to their corresponding mental models, the chi-square analysis revealed significant differences between high school and university students' drawings, $\chi^2 = 8.678$, df = 3, $p < .05$. In particular, the majority of high school students' drawings (75%) were associated with representations in which incoming radiation remains unchanged after being reflected from the Earth's surface (Clusters 1, 2, 3, and 5). In contrast, approximately one third of

university students' drawings aligned with the more scientifically consistent *Absorption/Emission* mental model (Clusters 4 and 6).

The results indicate that both high school and university students generally lack a scientifically accurate understanding of the greenhouse effect, as most drawings in both groups correspond to incorrect representations in which penetration, reflection, or absorption of incoming radiation are considered separately. This suggests that the level of instruction has only a limited impact on students' mental models of the greenhouse effect. Cluster 1 emerged as the most frequent representation in both groups (45% of high school students and 30% of university students).

This pattern is in line with previous research showing that high school students often do not interpret the greenhouse effect in terms of energy balance [28], fail to distinguish between incoming and outgoing energy [24], or rely on explanations based on increased incoming solar radiation and reduced outgoing radiation [25]. These difficulties are also consistent with studies reporting that students struggle to understand the interaction between electromagnetic radiation and atmospheric gases, as well as the role of different types of radiation, which can lead to confusion between temperature increase and incoming radiation [99]. The presence of misconceptions among university students aligns with earlier findings showing that students have difficulties with concepts such as infrared emission from bodies [3] and the idea of energy being trapped in the atmosphere [30]. Overall, these results suggest that, in the absence of targeted instruction on the greenhouse effect, misconceptions tend to persist even at the university level [98, 100].

Despite these similarities, some differences between the two groups can be observed. In particular, drawings corresponding to Cluster 4, which include more accurate representations of energy flow and interactions with atmospheric gases, account for only 8% among high school students, compared to 14% among university students. This difference may reflect a greater familiarity among university students with concepts related to energy and radiation or, alternatively, a higher awareness of climate change and its associated risks [101].

2.5 Limitations of the study

This study presents several limitations that should be considered when interpreting the findings.

First, the use of a convenience sample may limit the representativeness of the participants included in the study. Although the sample involved both high school and university students, the findings cannot be generalized to all students within these educational levels. Future research involving larger and more diverse populations would be necessary to assess the generalizability of the identified mental models.

Second, although the sample size was sufficient to perform the factorial and cluster analyses, a larger dataset could have increased the robustness of the statistical procedures and potentially revealed additional patterns in students' representations.

A further limitation concerns the data sources considered in the analysis. While data collection included both drawings and written explanations, the analysis presented in this chapter focused exclusively on students' graphical representations. This choice was motivated by the aim of investigating the extent to which drawings alone could provide insight into students' mental models of the greenhouse effect. However, drawings and written explanations may capture different aspects

of students' understanding. Integrating the graphical and textual data could provide a richer and more comprehensive picture of students' reasoning and may help clarify ambiguities that arise when interpreting drawings alone. This integration will be explored in future work.

Finally, particular caution is required when interpreting the possible influence of external visual sources on students' representations. Previous studies conducted by our research group identified graphical features and misconceptions in textbooks that resemble several patterns observed in students' drawings [102, 103]. However, the present study did not collect information about the specific textbooks, online resources, or other visual materials previously encountered by the participating students. Therefore, although these similarities suggest a possible relationship between educational materials and students' visual representations, they do not provide evidence of a direct causal influence. Alternative explanations may include classroom instruction, media exposure, personal reinterpretations of scientific concepts, or the spontaneous use of intuitive visual analogies. Consequently, the influence of external visual sources should be regarded as a plausible interpretative hypothesis rather than a conclusion directly supported by the data.

In addition, the study did not consider other measures related to students' knowledge of the greenhouse effect or their attitudes toward climate change. Future research could address this aspect by combining the analysis of mental models with validated instruments measuring conceptual understanding and climate-related attitudes.

2.6 Conclusions

This chapter analyzed drawings produced by high school and university students to investigate their mental models of the greenhouse effect and the underlying physical processes. Based on a sample of 174 students (80 from high school and 94 from university), the study combined qualitative and quantitative tools to explore students' representations in depth.

In the preliminary phase, a coding grid was used to identify the most recurrent graphical and conceptual elements, such as how the Sun, the Earth, and the atmosphere were represented, and how different types of radiation were depicted. This initial step showed that drawings can be a valuable tool to explore students' mental models while also revealing the influence of external visual sources, such as textbook or online images.

Subsequently, an initial factor analysis using Liu's coding scheme produced models partly consistent with those found in the literature. However, this scheme was not sufficient to capture the nuances of students' understanding. For this reason, we developed a revised and more concise rubric, focusing on the key physical processes of the greenhouse effect. A second factor analysis based on this new framework led to the identification of two main mental models.

To capture finer distinctions among the drawings, a cluster analysis was then conducted, revealing six typical representations that could be grouped under the two overarching mental models previously identified. The analysis by educational level showed that most students, regardless of grade, do not have an accurate understanding of the greenhouse effect. Their drawings often depict the penetration, reflection, or absorption of incoming radiation as separate processes, without reference to the Earth–atmosphere energy balance. These misconceptions, consistent with previous research, appear at both levels of instruction, though university students tend to produce slightly

more coherent representations of energy flows and gas–radiation interactions.

One of the main limitations of this study concerns the use of a convenience sample, which may not be representative of the two target populations. As a result, the findings cannot be generalized to all students. Future research should involve larger and more diverse samples, including different educational backgrounds and school levels, to obtain more robust results and a broader understanding of students' conceptions of the greenhouse effect.

Furthermore, this study relied only on students' drawings to investigate their mental models. Including additional data sources, such as verbal explanations or written responses, as done in previous studies [21, 23], could offer a more complete picture of students' reasoning. This aspect could be further investigated in future studies.

Finally, the study did not consider other measures related to students' knowledge of the greenhouse effect or their attitudes toward climate change. Future work could address this by validating an Italian version of the three-level diagnostic questionnaire developed by Arslan, Cigdemoglu and Moseley (2012) [104], as well as the five-item scale on "Attitudes towards Global Warming" proposed by Lewandowsky et al. (2019) [105].

One key implication of this study is that teaching sequences on the greenhouse effect should better clarify the underlying physical mechanisms. In particular, greater attention should be given to concepts such as energy balance and the difference in wavelength between incoming solar radiation and outgoing terrestrial radiation. A Teaching–Learning Sequence (TLS) focusing on these aspects is currently being developed and validated [64].

In line with previous research [6, 106], our results also suggest that common textbook representations of the greenhouse effect may include ambiguous graphical elements. For example, arrows are often used to represent both radiation and energy flows, without a clear distinction. For this reason, the design of visual representations in climate education should more carefully consider graphical conventions and how students interpret them.

Overall, this study shows the value of combining variable-centered and person-centered approaches to better understand students' mental models of the greenhouse effect. While the results confirm that misconceptions persist even among university students, they also offer useful directions for designing targeted teaching strategies. In particular, these strategies can support students in interpreting visual representations more accurately and in developing a more scientifically grounded understanding of the physical mechanisms underlying the greenhouse effect.

The findings presented in this chapter reinforce the importance of climate science education and highlight the need to support students in developing a coherent understanding of key climate-related phenomena. Both the literature and our broader research experience suggest that conceptual understanding alone is not sufficient to address the challenges posed by climate change and sustainability. While understanding the physical basis of the greenhouse effect represents an essential foundation, sustainability-related issues also involve social, cultural, economic, psychological, and civic dimensions that extend beyond disciplinary knowledge.

For this reason, the next chapter moves from the analysis of students' understanding to the professional development of teachers. The focus shifts from how students conceptualize climate-related phenomena to how teachers can be supported in designing educational experiences that engage with the multidimensional nature of sustainability and promote meaningful participation in addressing complex societal challenges.

Chapter 3

Promoting sustainability through multidisciplinary teacher training

3.1 Introduction

This chapter presents the development of a teacher training programme on sustainability designed within a Design-Based Research (DBR) framework [107]. The iterative nature of the DBR process supported the progressive refinement of the training programme and also contributed to broadening the educational perspective underlying this research, moving from a primarily disciplinary focus towards more multidimensional and context-sensitive understandings of sustainability education.

This chapter revisits and reworks the studies already presented in previous contributions, listed at the beginning of the thesis, on teacher training in relation to sustainability and scientific citizenship. The contents of these articles have been reorganised, expanded and integrated into a unified framework for the purposes of this doctoral thesis.

Our work starts from a teaching sequence (TLS) on the greenhouse effect already mentioned in the previous chapter, developed to support teachers in introducing the physical principles underlying the phenomenon [4]. The studies presented in Chapter 2 highlighted the importance of helping students develop a scientifically coherent understanding of climate-related phenomena and revealed the persistence of several misconceptions regarding the greenhouse effect.

However, both the literature on climate change education and our experience with the TLS suggested that conceptual understanding alone is not sufficient to address the educational challenges posed by sustainability issues. While understanding the physical basis of climate change represents an essential foundation, sustainability-related challenges also involve social, economic, cultural, psychological, and civic dimensions. Promoting informed participation and enabling learners to engage with complex sustainability problems therefore requires educational approaches that go beyond disciplinary knowledge alone.

For this reason, the focus of our research progressively expanded from the teaching of climate science towards broader forms of sustainability education, leading to the development of the multidisciplinary in-service teacher training programme presented in this chapter. It is developed in collaboration with Provincial Institute for Educational Research and Experimentation (IPRASE)

and involving university lecturers from different departments. The course combined theoretical contributions with laboratory activities, collaborative tasks and moments of co-design, encouraging teachers to connect different dimensions of sustainability and translate them into meaningful classroom activities.

As mentioned above, the entire project was structured according to iterative DBR cycles. The first cycle allowed us to test an initial version of the course and gather evidence about its strengths and limitations. Based on the results obtained, a second cycle was redesigned, with greater emphasis on collaboration and interdisciplinary integration. A timeline of these phases is presented in Figure 3.1.

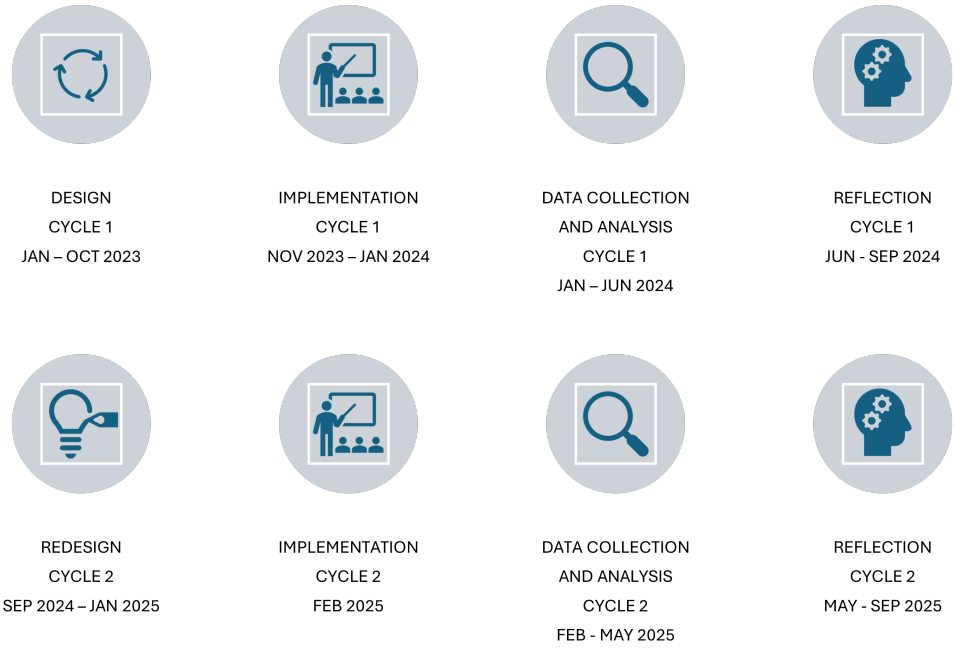


Figure 3.1: Schematic representation of the Design-Based Research cycles, showing the timeline of the design, implementation and refinement of the teacher training programme on sustainability.

The development of the training programme was guided by the broad research questions:

- How can a teacher training programme be designed to reflect the complexity and multidimensionality of sustainability, moving beyond a discipline-based perspective?
- How do teachers translate this multidimensional perspective on sustainability into the design of classroom activities?

3.1.1 Physical and conceptual foundations

In designing the two training cycles, physics expertise played a central role both in presenting the content and in guiding the design of the teaching activities.

The course was conceived as a multidisciplinary programme, but in order to function effectively, it had to maintain a continuous link to scientific concepts, mainly to support rigorous teaching design. In particular, understanding the physical mechanisms of the greenhouse effect was fundamental to rigorously addressing issues related to climate change and sustainability.

The topics covered are based on complex physical phenomena, the understanding of which is essential to avoid simplistic interpretations.

Among the scientific topics covered are the distinction between different types of radiation, the energy balance of the Earth-atmosphere system, the role of greenhouse gases, and the limitations of commonly used analogies. More broadly, the course addresses phenomena such as energy production and consumption, climate modelling, and the analysis of mitigation scenarios.

In addition to the content covered, physics also helped guide the teaching choices made in the two training cycles. Physics was not only included in the course as subject content, but also served as a guiding criterion for teaching choices. In designing the activities, attention was paid to the way in which phenomena were presented, avoiding conceptually incorrect simplifications and selecting models and representations consistent with the underlying scientific mechanisms. In this way, teachers were supported in designing accessible and scientifically accurate activities.

3.1.2 Teacher education, civic education, and sustainability in the Trentino context

In the Italian school context, sustainability education is increasingly approached as a cross-curricular theme that cuts across different subjects and requires the development of competences, rather than the simple transmission of content knowledge. Sustainability-related themes are mainly addressed within areas such as science, geography, and civic education, where aspects such as systems thinking, participation, and the capacity to act responsibly become particularly relevant [108].

An important turning point in the Italian context was the reintroduction of civic education through Law No. 92/2019, which made it compulsory across all school levels. The law explicitly frames civic education as a way to foster responsible and active citizenship, promoting informed participation in civic, cultural, and social life. This framework was further specified by Ministerial Decree No. 35/2020, which issued the national guidelines and identified three main conceptual areas: constitution, sustainable development, and digital citizenship. Within this structure, sustainable development is not treated as a separate environmental topic, but as one of the core dimensions through which schools are expected to connect disciplinary learning with social responsibility, wellbeing, and participation.

Since the 2020–2021 school year, the new subject has been introduced under the name Civic and Citizenship Education (CCE).

The data collected in the Autonomous Province of Trento by IPRASE during the first years of implementation show that, among the themes most frequently developed by schools, sustainable development and the environment appear prominently, together with issues related to rights and legality [109]. This suggests that, in the Trentino context, sustainability is already understood not only as an environmental issue, but as part of a broader approach to citizenship education.

Teacher education is a particularly relevant aspect in this context. The monitoring activities carried out by IPRASE show that schools still face recurring difficulties, especially in building a

shared curriculum, defining common assessment criteria, and translating the cross-curricular nature of CCE into everyday practice. The most recent monitoring data confirm that these challenges remain relevant even after the initial three-year implementation phase, particularly with regard to competence-based teaching and interdisciplinary collaboration across subjects [110]. To respond to these needs, the Province progressively developed a support system for teachers and school coordinators.

It is within this framework that the present research is situated. The collaboration with IPRASE is embedded in a context where Trentino schools have already recognized the value of cross-curricular approaches, competence-based design, and the connection between disciplinary knowledge and socially relevant issues. In this sense, the teacher education pathway developed in this research builds on a need that had already emerged at the system level, while specifically exploring the contribution that sustainability education can offer to science education and citizenship.

3.2 The first cycle

This section describes the first cycle of the training programme (flyer in Figure 3.2), developed in collaboration with IPRASE and aimed at lower and upper secondary school teachers from different disciplinary backgrounds in the Autonomous Province of Trento, Italy. The course took place between November 2023 and February 2024 and included eleven meetings, each lasting approximately three hours.

Figure 3.2: Flyer of the teacher training course, developed in collaboration with IPRASE (Trento, Italy). Source: IPRASE training platform.

The main objective was not to provide an exhaustive overview of all aspects of sustainability education, but rather to offer participants conceptual and methodological tools to integrate sustainability into their teaching practice, promoting an interdisciplinary and scientifically grounded approach.

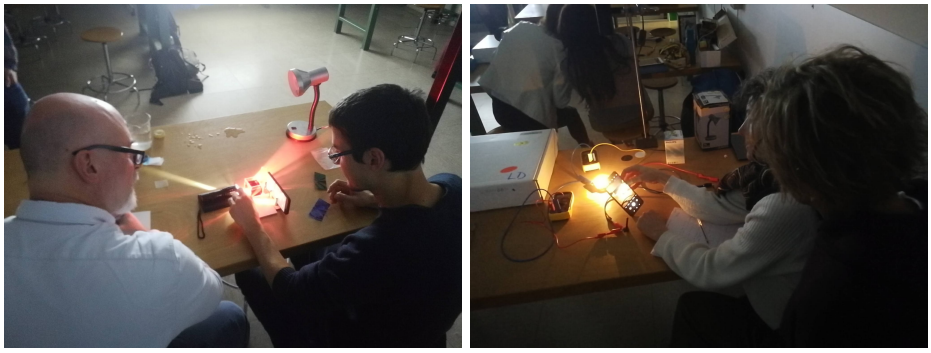


Figure 3.3: Some of the activities proposed during the first cycle of the training programme.

3.2.1 Theoretical framework

Since the aim of the sustainability course was to go beyond the purely physical dimension and address the issue in all its multidimensionality and complexity, contributions from other fields were incorporated, particularly from climate psychology.

In fact, the course was designed using as its theoretical framework the psychological factors identified in the literature as fundamental for stimulating pro-climate behaviour. Pro-climate action is not considered to be the result of a single factor; but it is influenced by emotional, identity-related, cognitive and social dimensions. In the field of climate psychology, studies have analysed the processes that promote or inhibit action against the climate crisis, highlighting the determining factors for environmental commitment [111].

The emotional dimension is in fact very important for activation. *Emotional Engagement*, such as feeling personally affected by the climate crisis, feeling empathy towards those who suffer its consequences, or feeling indignation at political inaction, can be a significant driver of commitment [112–115]. In this sense, emotion is a component that guides and supports choices, not in opposition to the rational part.

To move from emotion to action, it is necessary to feel that one can really influence the situation. This concerns both *Self Efficacy*, or confidence in one's own ability to act [116], and *Collective Efficacy*, or the belief that shared action can bring about concrete change [113]. Feeling that "I can" and "we can" make a difference is crucial to prevent awareness from turning into a sense of powerlessness.

A further aspect concerns the way in which people imagine the process of social change. The *Theory of Change* does not refer to the perception of personal effectiveness, but to beliefs about where and how meaningful transformation can originate: whether from local and community initiatives or from institutional and political decisions [117, 118]. Believing that change can also emerge from the bottom up values educational practices as a driver of broader transformation.

However, having positive intentions is not enough. The literature emphasises the importance of *Implementation intentions*, i.e. the ability to translate intentions into concrete, planned steps [119].

The social context also influences individual choices. *Social norms* also influence behaviour, for

example when people perceive that significant individuals in their environment would approve of the action taken or are already moving in the same direction [120].

However, the *Personal Identity* plan remains fundamental: recognising oneself as a person committed to protecting the environment strengthens the consistency between values and behaviours [121]. Environmentalist identity helps to stabilise commitment over time, making it an integral part of one's self-definition.

A further dimension is that of *Imagination*. The ability to envisage alternative future scenarios (what would happen if nothing changed, or if change were possible) broadens the horizon for action and makes transformation conceivable [122]. In this sense, imagination is not a way of escaping reality but a way of creating possibilities.

Finally, *Trust in institutions* affects the perception of having a say in decision-making processes and of being listened to when changes are requested [123].

The factors described above were identified, together with the psychology expert involved in the course design, as the most relevant to focus on within the training programme and to discuss with participating teachers.

Based on this literature, the teaching sequence was expanded and adapted to the Trentino context. Each module was designed to promote both the acquisition of scientific knowledge and an understanding of the psychological and social dynamics that can support changes in attitudes and educational practices.

3.2.2 Course structure

The course was organised into several thematic modules in Figure 3.4 designed to alternate frontal lessons with moments of reflection and active experimentation.

In fact, each session included workshops, debates and opportunities for peer discussion to encourage dialogue and the sharing of professional experiences.

The sequence of activities was designed to encourage critical reflection on the complexity of sustainability and the interconnections between its environmental, economic, social and cultural dimensions.

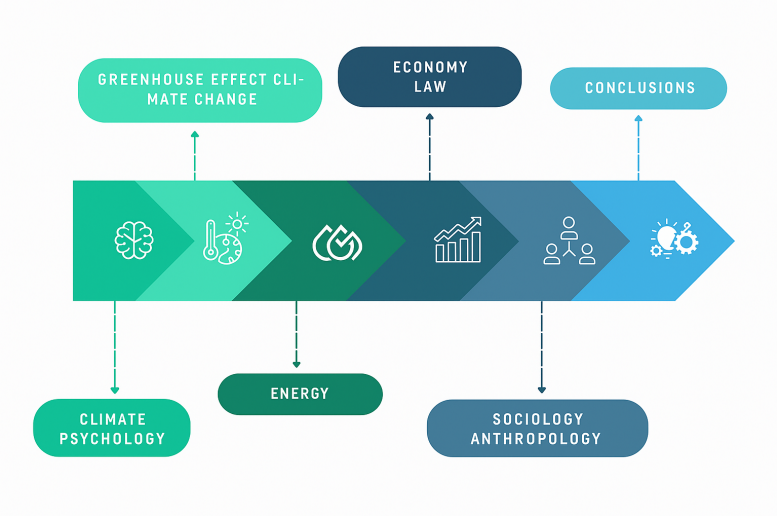


Figure 3.4: Division of the training course into modules.

Physics was presented as a universal language for understanding the scientific principles underlying environmental phenomena and as a tool to analyse sustainability issues from a quantitative and systemic perspective.

To overcome a purely disciplinary view, the course also integrated contributions from other domains, including climate psychology, law, economics, and socio-anthropology, that broadened the perspective and enabled a multidimensional exploration of sustainability.

The course was organised around five main thematic areas:

1. **Climate psychology**, introducing the psychological factors that sustain individual and collective climate action;
2. **Greenhouse effect and climate change**, focusing on the physical mechanisms underlying atmospheric phenomena and the role of science in understanding the climate crisis;
3. **Energy**, exploring the relationships among energy consumption, ecological transition, and civic responsibility;
4. **Law and economics**, analysing the normative and financial mechanisms that underpin sustainability policies;
5. **Socio-anthropology**, addressing the cultural and collective representations of the environmental crisis and their impact on education.

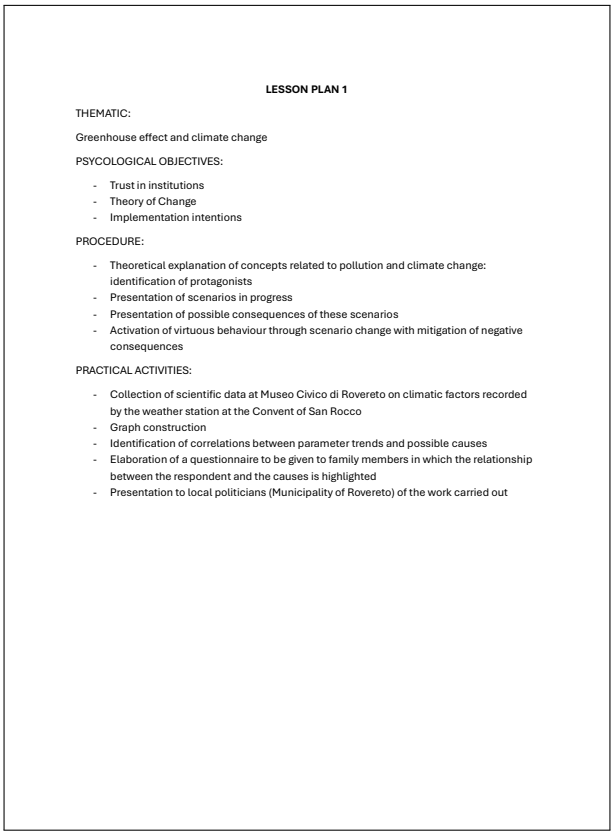
Table 3.1 summarises the overall structure of the course and the distribution of the thematic modules.

Module	**Topic**	**Objectives / Methods**
Climate psychology	Critical thinking, scientific method, and communication	Support teachers in addressing complexity and promoting change through critical thinking and the scientific method, while fostering student motivation for sustainability via psychological and communicative dimensions. *Methods:* Discussion, practical examples.
GHE and Climate Change	Scientific foundations of climate change	Provide teachers with scientific tools to introduce the concept of climate change. *Methods:* Explanations, group work.
Energy and Decarbonization	Fossil and renewable energy; decarbonization	Understand the importance of energy and decarbonization strategies. *Methods:* Case analysis, debates.
Law and economics	Linear and circular economy; role of institutions	Explain economic models and the role of institutions in sustainability. *Methods:* Case studies, practical examples.
Socio-anthropology	Systemic change and sustainable policies	Examine how local change can trigger global sustainable policies. *Methods:* Group discussions, analysis.
Conclusions	Psychology and critical thinking in activist communication	Integrate all components into a comprehensive framework of activist communication and critical thinking. *Methods:* Synthesis, final reflections.

Table 3.1: Summary of the course structure divided by modules, including the main topics, objectives, and applied teaching methods.

In the final meeting, teachers were asked to create a teaching unit based on sustainability. They were guided in compiling teaching activities by filling in a form with the topic to be addressed in the lesson plan, the psychological factors they wanted to enhance, the lecture part and the workshop activities.

Another assessment tool for our course was a satisfaction questionnaire completed at the end of the course. It consisted of open-ended questions and Likert scale questions, grouped into the following macro-areas: organisation of the training activity, satisfaction with the content, feedback on the trainers, and perceived usefulness and impact of the training.



LESSON PLAN 1

THEMATIC:

Greenhouse effect and climate change

PSYCOLOGICAL OBJECTIVES:

- Trust in institutions
- Theory of Change
- Implementation intentions

PROCEDURE:

- Theoretical explanation of concepts related to pollution and climate change: identification of protagonists
- Presentation of scenarios in progress
- Presentation of possible consequences of these scenarios
- Activation of virtuous behaviour through scenario change with mitigation of negative consequences

PRACTICAL ACTIVITIES:

- Collection of scientific data at Museo Civico di Rovereto on climatic factors recorded by the weather station at the Convent of San Rocco
- Graph construction
- Identification of correlations between parameter trends and possible causes
- Elaboration of a questionnaire to be given to family members in which the relationship between the respondent and the causes is highlighted
- Presentation to local politicians (Municipality of Rovereto) of the work carried out

Figure 3.5: Example of activities suggested by teachers.

3.2.3 Results and discussion

In line with the DBR approach, this first cycle of the training course was designed as an exploratory phase. The main objective was to assess how teachers rework the information obtained during the training course to transform it into teaching activities.

A total of 23 secondary school teachers enrolled in the full training course, but attendance at individual sessions was uneven. Teachers who attended at least 75% of the course sessions were able to complete the final evaluation questionnaire, for a total of 10 participants. Of these, 7 teachers were present at the final session, during which they were asked to individually design and present a lesson plan based on sustainability-related topics. These seven lesson plans form part of the analysis in the first design cycle. The group included teachers from both lower and upper secondary education, with one teacher from lower secondary school and six from upper secondary school. Their disciplinary backgrounds were diverse, including mathematics and physics (n=3), natural sciences (n=1), English (n=1), philosophy and human sciences (n=1), and technology (n=1).

The data collection therefore consists of the lesson plans produced by the participants, sum-

marised in Table 3.6. For a complete overview of the lesson plans and the qualitative feedback, please refer to Appendix 1 e 2.

Topic	**Psychological Objectives**	**Procedure / Practical Activities**
Greenhouse effect and climate change	Trust in institutions, Theory of Change, Implementation intentions	Theory on pollution and climate scenarios; activate virtuous behaviour. Data collection; graphing; questionnaire; presentation to politicians.
Energy and decarbonization	Trust in institutions, Efficacy, Imagination	Explain Ecological Footprint, consumption; present policies. Footprint calculation; CO2 budget game; discussion; quiz.
Energy and decarbonization	Social Norm, Efficacy, Imagination	Energy sources, sector use, diesel equivalent; plant capacity. Energy calc. with jerry can; group footprint calc. simulating ministers.
Energy and decarbonization	Social Norm, Theory of Change	Graphs on energy demand, CO2, sources. Footprint calc.; group discussions; logbook; publicity campaign.
Energy and decarbonization	Personal identity	Material degradation times; sustainable materials discussion. Outdoor practical activity.
Energy and decarbonization	Personal identity, Imagination, Efficacy	Consumption breakdown; energy savings; decarbonisation pros/cons. Research and discussion on energy production, pollution, legislation.
Energy and decarbonization	Implementation intentions, Emotional Engagement, Theory of Change	Climate change basics; Overshoot Day; action discussion. Surveys; Jigsaw with talks; word cloud; footprint calc.; awareness product.

Table 3.2: Summary of the seven lesson plans produced by the teachers, showing the main topic, targeted psychological objectives, and corresponding procedures or practical activities.

Analysis of the teaching programmes shows that teachers chose to develop scientific topics such as the greenhouse effect, climate change and energy transition.

Physics is therefore perceived as a fundamental discipline for addressing sustainability in a scientifically sound manner.

In addition to the scientific component, some of the active and participatory methodologies presented during the course were integrated into the lessons, such as ecological footprint calculation, group discussions and debates.

This indicates that teachers recognised the importance of combining scientific knowledge with more cross-cutting dimensions, such as critical thinking, imagination and civic engagement.

Several lesson plans explicitly extended learning beyond the classroom. For example, Lesson Plan 1 proposed the collection of climatic data at the Museo Civico di Rovereto, the administration of questionnaires to family members, and the presentation of students' findings to representatives of

the Municipality of Rovereto. Lesson Plan 4 included the development of a school-wide awareness campaign, while Lesson Plan 6 encouraged students to reflect on citizens' rights and duties and on possible forms of interaction with political institutions. These examples suggest that teachers did not frame sustainability exclusively as a scientific issue, but also as a social and civic one requiring engagement with actors beyond the school context.

The teaching plans also show how the psychological factors proposed in the theoretical framework of the course are implemented.

For example, the factor "Trust in institutions" was associated with activities such as the presentation of students' work to representatives of the Municipality of Rovereto (Italy); "Imagination" was stimulated through reflections on future scenarios based on human choices regarding greenhouse gas emissions; and "Social norms" were promoted through initiatives such as internal school campaigns encouraging sustainable behaviour.

These examples demonstrate how teachers not only addressed scientific content, but also adopted a multidimensional perspective consistent with climate psychology, with the aim of activating climate-friendly attitudes and behaviours among students.

The lesson plans also showed a strong emphasis on the use of data and evidence-based reasoning. Lesson Plan 1 involved the analysis of climatic data collected from a local weather station and the construction of graphs to identify correlations between variables. Lesson Plan 4 required students to construct and interpret time-series graphs relating energy demand and CO_2 emissions, while Lesson Plan 7 included the analysis of graphs on Earth Overshoot Day and global CO_2 emissions. These activities suggest that teachers sought to connect sustainability issues with the interpretation of empirical evidence and scientific data.

Some activities were explicitly contextualised within local realities. For example, Lesson Plan 1 involved the collection of climatic data from a local weather station and the presentation of findings to representatives of the Municipality of Rovereto, while Lesson Plan 2 referred to consumption patterns in the Trentino region. At the same time, several lesson plans addressed broader issues such as global energy demand, Earth Overshoot Day and CO_2 emissions (Lesson plan 2, 3 and 4). This combination of local and global references suggests an attempt to connect sustainability challenges across different scales.

The feedback questionnaires provided additional evidence on the perceived effectiveness of the course. Overall, teachers expressed a very positive evaluation: they appreciated the course organisation, the quality and clarity of the materials, and the trainers' competence.

The majority of participants (90%) agreed that they had learned new things and found the course stimulating and valuable; 80% reported an increased interest in the topics, and 90% indicated that what they had learned was transferable to their teaching practice, with many already implementing new ideas in class.

These results confirm that the course was not only well received but also perceived as relevant and applicable to professional practice.

Teachers also reported improvements in transversal skills, such as the ability to synthesise information from multiple sources (70%), to communicate ideas effectively (60%), and to identify solutions to emerging problems (60%).

However, the development of collaborative skills appeared less evident, with only 30% of teachers reporting substantial improvement in this area. This aspect, identified as a limitation of the first

cycle, will be explicitly addressed in the design of the second cycle — consistent with the iterative nature of the DBR approach — by including more opportunities for group work and co-design among teachers.

3.2.4 Conclusion and perspectives

This first cycle of research, developed according to the design-based research approach, allowed us to observe how a multidisciplinary training programme can support teachers in designing educational activities on sustainability that integrate scientific, psychological and civic dimensions.

The results show that participants reworked the proposed content, demonstrating their ability to translate it into teaching programmes. The topics are physical in nature, but the approaches and activities proposed also demonstrate the implementation of other dimensions of sustainability. The use of real data and the adoption of active methodologies support participatory and evidence-based teaching practices.

Furthermore, the integration of psychological factors into lesson planning suggests that teachers recognised the importance of activating emotional and motivational components in their students, thus promoting pro-climate behaviours.

However, this first cycle also highlighted some critical issues, in particular the need to strengthen collaborative skills and peer co-design practices.

Another aspect to consider concerns the disciplinary framing of the programme. Since the first design cycle originated from previous work on the greenhouse effect and climate-related physical mechanisms, it is possible that the strong presence of climate science and energy-related topics in the lesson plans was influenced not only by teachers' interests, but also by the structure and emphasis of the course itself. From this perspective, the lesson plans developed during the first cycle should be interpreted in relation to the disciplinary framing of the programme.

These findings provide a foundation for the design of the second cycle. In this sense, the first cycle fully fulfilled the exploratory function typical of the DBR approach, offering essential insights for refining the design.

3.3 The second cycle

The design of the second cycle of the teacher training programme on sustainability was based on the experience of the first edition. Collaboration with IPRASE was maintained in this cycle as well.

The redesign did not focus on expanding the content, but retained what had worked best previously, while offering a more concentrated and collaborative format.

The multidisciplinary spirit of the course was maintained, with activities designed to help teachers connect the scientific part with everyday practices and broader issues related to sustainability.

The following paragraph explains in more detail how the insights from the first cycle guided the redesign of this second edition.

Figure 3.6: Flyer of the teacher training course, developed in collaboration with IPRASE (Trento, Italy). Source: IPRASE training platform.

3.3.1 From the first to the second cycle

The transition from the first to the second cycle of teacher training represented a moment of reworking of the programme.

While in the first cycle the theoretical framework focused mainly on the psychological factors that promote climate-friendly behaviour, in the second cycle we decided to adopt GreenComp, the European framework for sustainability competences, which offers a broader and more integrated perspective. This choice allowed us to maintain our focus on both psychological aspects and scientific content, placing them in a broader framework that also emphasises the social and action-oriented dimensions of sustainability.

From an organisational point of view, the course format was revised to make participation more accessible and sustainable for teachers. The first cycle was divided into several meetings over a period of several months. This approach highlighted some difficulties in ensuring regular attendance by teachers.

To overcome this problem, the second cycle was condensed into two consecutive days: one dedicated to theoretical and multidisciplinary input and the other to collaborative lesson planning. The planning phase on the second day was organised according to a trialogical learning approach, which values collaborative work among teachers through the construction of shared artifacts, such as lesson plans. This new structure facilitated teacher attendance on both days and peer collaboration.

Furthermore, the course remained aimed at secondary school teachers from different subject areas, but was also extended to primary school teachers. This decision stemmed from the idea that education on sustainability and scientific citizenship requires a consistent vertical approach and that having a shared space for reflection and co-design can benefit teachers at different school levels.

The GreenComp Framework for Sustainability Competences

On 2022 the Joint Research Centre (JRC) of the European Commission published GreenComp [124], a reference framework that defines the competences needed to address sustainability challenges in a systemic way.

GreenComp is designed as a learning framework that can be adapted to a variety of educational contexts, and is conceived as a reference tool to support educational programmes that aim to develop sustainability as a key competence.

It divides sustainability competence into four closely interrelated areas: 'embodying sustainability values', 'embracing complexity in sustainability', 'envisioning sustainable futures' and 'acting for sustainability'. Each area includes three interconnected competences that are considered equally important.

All twelve competences are interrelated and complementary, and should be considered as integrated parts of a coherent whole.

Area 1, *Embodying sustainability values*, is linked to the values aspect of sustainability. This area concerns the ability to critically reflect on one's own values and worldviews, recognising how these can support or hinder sustainability pathways. In this context, the importance of the principles of equity and justice between present and future generations is emphasised, as well as the recognition that human beings are part of the natural systems on which they depend.

It includes three main competences:

1.1 *Valuing sustainability*, which encourages critical reflection on one's own values in light of sustainability principles, and recognition that these may differ between individuals and change over time;

1.2 *Supporting fairness*, which encourages justice between present and future generations, while also valuing the lessons of the past;

1.3 *Promoting nature*, which consists of recognising that human beings belong to nature and respecting the rights of other species and ecosystems.

The second competence area *Embracing complexity* in sustainability refers to the ability to understand the complexity of sustainability challenges through systemic and critical thinking. This competence involves recognising the interconnections between environmental, economic, and social phenomena and interpreting problems by considering the different actors involved and the multiple scales of the issue. Sustainability education therefore helps learners identify these relationships and understand how issues that may appear unrelated can in fact be part of the same sustainability challenge.

It consists of:

2.1 *Systems thinking*, which helps to interpret phenomena by relating different scales (local, national, global) and environmental, social, economic and cultural dimensions;

2.2 *Critical thinking*, which includes a set of advanced cognitive skills needed to interpret and evaluate information related to sustainability issues;

2.3 *Problem framing*, which consists of recognising and identifying current or potential sustainability issues and describing them, taking into account their complexity and the actors most involved.

The area of *Envisioning sustainable futures* concerns the ability to imagine sustainable future scenarios and identify possible actions to achieve them. This also requires knowing how to deal with uncertainty and considering the compromises that are often present in choices related to sustainability, using creative approaches that are open to different perspectives.

It is also composed of three competences:

3.1 *Futures literacy*, which refers to the ability to imagine and develop one's own vision of a sustainable future, by fostering the knowledge, skills, and attitudes needed to view the future as a range of possible alternatives;

3.2 *Adaptability*, which refers to the ability to deal with change and uncertainty by evaluating different options and making decisions even when sustainability challenges involve trade-offs between environmental, social, and economic dimensions;

3.3 *Exploratory thinking*, which encourages creativity to imagine alternative future scenarios by integrating perspectives from different disciplines, traditions, and cultures in a transdisciplinary way.

The last competence area is *Acting for sustainability.* It encourages learners to take action, both individually and collectively, to contribute to building more sustainable futures. It also promotes an active attitude, encouraging learners to call on institutions and decision-makers to take concrete action to support change.

4.1 *Political agency*, which refers to the ability to encourage policymakers to take action, having understood the context and identified the actors who can be involved in the process of change towards sustainability;

4.2 *Collective action*, which consists in working together with others to promote sustainability, recognising the contribution of communities and civil society organisations;

4.3 *Individual initiative*, which which refers to recognising one's potential to support sustainability and actively contributing to improving the future of the community and the planet.

In the first cycle of the course, the project focused primarily on research in the field of climate psychology, which highlights the psychological factors that can promote or inhibit climate-friendly behaviour. In the second cycle, the course adopted the GreenComp framework to provide a broader educational perspective on sustainability.

The two frameworks look at the same issue from different perspectives. Climate psychology explains the motivational processes that can lead people to act, while GreenComp provides an educational framework describing the competences needed to engage with sustainability challenges.

Several of the psychological dimensions previously considered can therefore be recognised within the competences described in GreenComp. Table 3.3 illustrates some of the conceptual correspondences between the motivational factors discussed in the first cycle and the sustainability competences proposed in the GreenComp framework used in the second cycle.

Psychological factor (cycle 1)	**Related GreenComp competence(s) (cycle 2)**
Emotional engagement	Emotional engagement, such as concern about the consequences of the climate crisis or empathy towards affected communities, can support students' motivation to address sustainability issues. In GreenComp, the emotional side of learners is highlighted in particular in relation to values linked to sustainability and future scenarios, connecting in particular with **1.1 Valuing sustainability** and **3.1 Future literacy**.
Self-efficacy and collective efficacy	The belief that individuals or groups can successfully tackle climate challenges is closely related to the action-oriented dimension of sustainability competences. It can therefore be associated with **4.3 Individual initiative** and **4.2 Collective action**, which emphasise the importance of recognising one's own ability to contribute to sustainability and working collaboratively to promote change.
Theory of change	Beliefs about how meaningful social transformation can occur, whether through grassroots initiatives or institutional processes, can be related to the competence **4.1 Political agency**. This competence involves understanding governance structures and recognising the actors involved in transitions towards sustainability.
Implementation intentions	The ability to translate intentions into concrete actions can be linked to the competence **4.3 Individual initiative**. This competence encourages individuals to recognise their own potential and to make it available to the community and the planet.
Social norms	Perceiving that people in one's social environment support or adopt sustainable behaviours can encourage participation in collective sustainability efforts. This dimension can be related to point **4.2 Collective action**, which emphasises the importance of collaboration in transitions towards sustainability.
Personal identity	Recognising oneself as a person committed to environmental protection is closely linked to the reflection on personal values promoted by **1.1 Valuing sustainability**, which includes consideration of how individual beliefs and values shape attitudes towards sustainability.
Imagination	The ability to imagine alternative future scenarios connects strongly with **3.1 Futures literacy** and **3.3 Exploratory thinking**. These competences encourage envisioning sustainable futures and exploring different pathways to achieve them.

Psychological factor (cycle 1)	**Related GreenComp competence(s) (cycle 2)**
Trust in institutions	Trust in institutions includes the perception that collective decisions and governance processes can support transitions towards sustainability. This dimension can be linked to point **4.1 Political agency**, which emphasises the importance of understanding decision-making processes and the involvement of institutional actors.

Table 3.3: Conceptual relationship between the psychological factors considered in the first cycle of the course and sustainability competences from the GreenComp framework used in the second cycle

In this sense, the use of GreenComp in the second cycle did not replace the previous approach, but rather provided a more comprehensive educational structure in which the psychological dimensions previously considered can be situated and further developed.

While the first cycle already involved contributions from multiple disciplines, its focus on climate change and energy-related issues may have influenced the types of sustainability topics addressed by participants. The adoption of GreenComp provided a broader framework through which additional environmental, social and economic dimensions could be explored.

The Trialogical Approach to collaborative lesson design

The Trialogical Learning Approach (TLA) [125, 126] offers a powerful framework for rethinking teaching and learning in collaborative and productive ways.

It combines the individual (monological) and social (dialogical) dimensions of learning with a third element: the intentional creation of shared and meaningful knowledge artifacts [126].

Learning, in this view, is not limited to acquiring information or participating in social exchanges, but involves building concrete, useful objects that embody collective knowledge and can circulate across contexts as boundary objects [127].

The TLA is based on six design principles that guide its implementation in educational contexts [126]:

1. organising activities around shared objects;
2. supporting interaction between individual and collective levels;
3. promoting long-term processes of knowledge advancement;
4. emphasising creativity and reflection through transformation;
5. encouraging the hybridisation of practices and disciplines;
6. providing flexible mediating tools that sustain collaboration and reflection.

In educational settings, these principles translate into authentic, multidisciplinary and collaborative learning activities, where students and teachers co-create artifacts, such as conceptual maps, lesson plans, or digital resources, that have meaning beyond the immediate learning context. Digital technologies play a crucial mediating role, enabling the externalisation, sharing, and continuous refinement of ideas in shared spaces.

Within the teacher training programme, the TLA was used to guide the co-design phase. Participants were divided into mixed-discipline groups and worked on the design of educational activities inspired by the GreenComp framework.

Each group, supported by the instructor, developed teaching proposals that can be applied in real classrooms, transforming the conceptual and methodological content covered during the course into practical results. This training session was based on discussion, peer feedback and reflection, and encouraged collaboration and creativity.

3.3.2 Methods

The second cycle of the teacher training course, as already mentioned, took place over two intensive days to make participation more accessible, while maintaining its multidisciplinary nature.

The first day focused on lectures with conceptual and methodological input. It was divided into four thematic sessions: an introduction to the GreenComp framework, a session on environmental sustainability, one on social sustainability and one on economic sustainability.

Session	Main contents
Introduction to GreenComp	Presentation of the European framework for sustainability competences (GreenComp): its four competence areas, systemic approach, and emphasis on futures thinking, agency, and collective action. Discussion on how GreenComp can guide educational practices and lifelong learning for sustainability.
Environmental sustainability	Scientific background on climate change and decarbonisation. Analysis of global and Alpine-scale climate data (temperature, precipitation, snow cover) and the physical basis of greenhouse gas effects. Discussion on energy production and consumption, renewable sources, and the decarbonisation of the chemical industry as key challenges for sustainability.
Social sustainability	Reflections on social and cultural dimensions of sustainability. Legal and anthropological perspectives on community-based governance and the concept of "territories of life" in mountain areas. Exploration of human–environment relations, rights and responsibilities, and the role of collective domains in ensuring dignity, justice, and long-term coexistence.
Economic sustainability	Introduction to economic indicators for sustainability and the multidimensional nature of sustainable development. Analysis of ecological footprint, biocapacity, and the dynamics of the Earth Overshoot Day. Discussion on consumption patterns, global inequality, and strategies for reducing humanity's environmental impact.

Table 3.4: Structure and main topics of the first day

The second day was devoted to a practical workshop, during which participants worked collaboratively in mixed groups to design educational activities inspired by the GreenComp framework. Each group produced a lesson plan, for a total of 3 plans. This was achieved through a trialogical approach, translating the conceptual content into an educational proposal that could be implemented in the classroom.

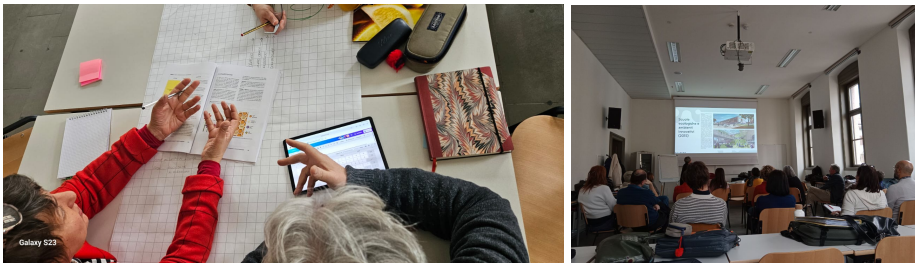


Figure 3.7: Some of the activities proposed during the second cycle of the training programme.

Data were collected through two main sources: (1) a satisfaction questionnaire, identical to that used in the previous cycle, aimed at collecting teachers' perceptions of the course's organisation, content, and relevance; and (2) the teaching plans developed by the working groups.

The qualitative analysis of the teaching plans focused on how the various dimensions of sustainability (environmental, social, economic) were integrated and on the presence of elements linked to the GreenComp framework.

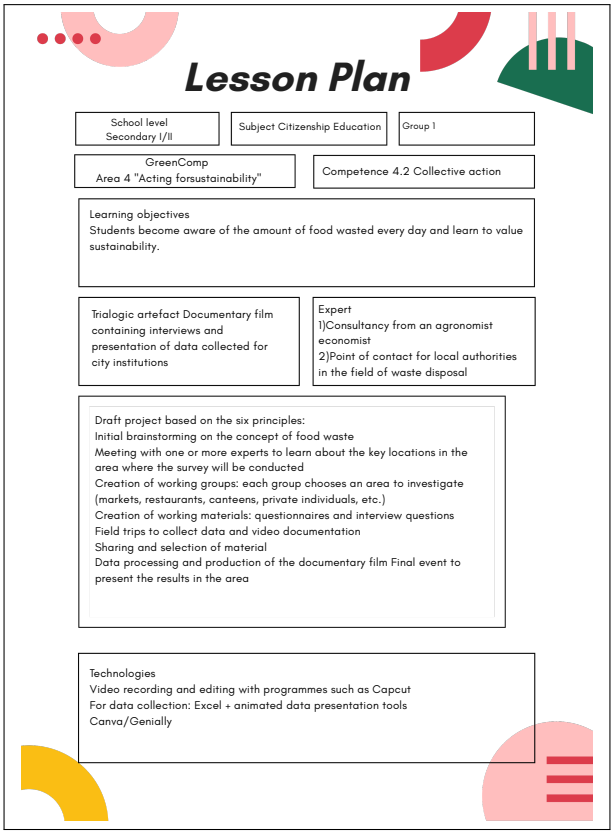


Figure 3.8: Example of activities suggested by teachers.

The questionnaires were analysed qualitatively to examine recurring comments, suggestions and critical reflections that emerged from the open questions, with particular attention to teachers' perceptions of co-design opportunities and collaborative work.

3.3.3 Results and discussion

As with the teaching proposals developed in the first cycle, in this second edition we have also analysed how the lesson plans developed by teachers integrate the multidimensionality of sustainability, in this case also in light of the GreenComp competences framework.

The aim is to understand how the course content is reworked in order to translate it into concrete teaching proposals on sustainability.

A total of 14 teachers participated, representing different school levels and subject areas. Participant profiles are summarised in Table 3.5.

Educational level / role	**Disciplinary background**
Primary school (n = 5)	Mathematics, science, and technology (n = 2); Italian language (n = 2); English (n = 1).
Lower secondary school (n = 3)	Mathematics and science (n = 1); Technology (n = 1); Mathematics and physics (n = 1).
Upper secondary school (n = 5)	Mechanical sciences and technologies (n = 1); Literary subjects and Latin in German-language high schools (n = 1); Literary subjects, Latin, and Greek (n = 1); Textile science and technology laboratories (n = 1); Electrical and electronic sciences and technologies (n = 1).
Non-teaching participant (n = 1)	Educational support.

Table 3.5: Profile of participants involved in the second design cycle lesson plan development

Before analyzing the teaching programs in detail, it is important to emphasize that the activities developed during the second cycle do not always refer explicitly to physics topics. However, several elements reflect forms of scientific reasoning typically associated with physics teaching. Data collection, interpretation of quantitative information, and analysis of everyday phenomena can still be recognized as part of a scientific approach to sustainability issues.

Analysis of the lesson plans

An overview of the proposals developed by the teachers is presented in Table 3.6. For a complete overview of the lesson plans, please refer to Appendix 3.

Lesson plan	Main contents and artifact
Group 1 — Food waste (lower/upper secondary, citizenship education)	Brainstorming on food waste; identification of local contexts to investigate (markets, restaurants, canteens, households); design of questionnaires and interviews; field data collection; selection and analysis of results; creation of a short documentary to communicate findings to the community. **Artifact**: documentary on food waste.
Group 2 — Everyday energy saving (primary/lower secondary)	Analysis of students' everyday behaviours related to energy use; class discussion of possible improvements; collaborative construction of a "good practices" list to promote energy saving at school and at home; dissemination of the final document within the school community. **Artifact**: digital energy-saving decalogue.
Group 3 — Fast fashion and textile supply chain (lower secondary, civic education)	Data collection on students' wardrobes (number of items, frequency of use); graphical representation of the data; reflection on environmental and social impacts of the textile industry; activities aimed at raising awareness of personal consumption habits; creation of a traffic-light tool to guide more responsible clothing purchases. **Artifact**: traffic-light decision tool.

Table 3.6: Summary of the lesson plans developed by participating teachers

A general analysis of the teaching plans shows that the theoretical framework proposed in the course is interpreted differently by the various groups, both in terms of the multidimensional nature of sustainability and GreenComp competences.

The first project focuses on food waste, with a programme that leads students to analyse this phenomenon on a local scale. It begins with a brainstorming session on the concept of food waste. This initial phase can highlight the issue of sustainability linked to food waste and can be traced back to the skill of **problem framing (2.3)**.

Subsequently, the activity involves dividing the students into working groups to organise a real investigation in the local area, involving different contexts such as markets, restaurants and families. The design of questionnaires and interviews, and the collection of data and video material, allows students to explore the phenomenon from multiple perspectives and understand the role of the various actors involved. In this sense, the project promotes the development of elements of **systems thinking (2.1)**, as students are led to consider the relationships between different elements of the food system.

The work is mainly carried out in groups, with moments dedicated to sharing and discussing the collected results. This collaborative dimension represents one of the central aspects of the project and relates to the competence of **collective action (4.2)**, as students are required to coordinate and work together in order to better understand the phenomenon.

The final stage of the project involves the production of a documentary bringing together the interviews and the data collected during the investigation. The video is conceived as a way to share

the outcomes of the work with the local community and institutions. In this way, students also take an active role in raising awareness within the community, engaging in concrete forms of civic participation In this perspective, it is possible to read elements related to **individual initiative (4.3)** and **collective action (4.2)**. The presentation of the collected data to local institutions also introduces a dimension of participation in the local public debate. This element can be related to **political agency (4.1)**.

Overall, the project addresses the environmental, social and economic dimensions of sustainability by involving students in a survey conducted in their local context. Field research and data collection highlight the **environmental impacts** of food waste. Interviews with local actors and the analysis of everyday practices also bring forward its **social implications** within the community, while discussions about consumption habits and food management practices allow students to reflect on its **economic dimension**.

The second lesson plan focuses on energy saving and is designed to be more oriented towards everyday behaviour. This approach combines an initial phase of self-analysis of personal practices with a final result oriented towards the group and the dissemination of responsible behaviour within the school.

An initial moment of sharing about participants' everyday behaviours is planned, with the aim of discussing possible more sustainable alternatives. This step can be linked to the competence of **valuing sustainability (1.1)**, as it encourages reflection on the values that guide individual choices.

The definition of good practices takes place collaboratively: students share ideas and proposals, discuss possible solutions, and contribute to the development of the final decalogue. This process reflects the dimension of **collective action (4.2)**, as the strategies identified emerge through discussion and collaboration among peers.

From the perspective of the multidimensional nature of sustainability, the project mainly addresses the **environmental dimension**, which emerges in the discussion on reducing energy waste. It also touches upon the **social dimension**, as the document produced aims to promote shared practices within the school community. The economic dimension is not explicitly addressed, but reducing energy consumption may also indirectly relate to **economic aspects**, such as potential savings in household energy use.

The third lesson plan addresses the environmental and social impacts of the textile industry, with particular attention to the phenomenon of fast fashion. The project begins with a data collection activity in which students analyse their own wardrobes, reflecting on the number of garments they own and how frequently they are used.

The competence of **valuing sustainability (1.1)** emerges particularly in the activities that invite students to reflect on their consumption habits. In particular, asking students to evaluate whether a purchase is really necessary and designing a tool to guide purchasing decisions encourage them to connect their consumption choices with sustainability values.

The graphical representation of the collected data allows students to observe their consumption habits from a different perspective and discuss them together in class. This activity encourages a more critical reflection on consumption patterns and their implications, bringing out elements related to **critical thinking (2.2)**.

The discussion of the environmental and social impacts of the textile supply chain also connects the topic of fast fashion to broader questions of social justice and global sustainability, aspects related to **supporting fairness (1.2)**, as students are invited to consider the social implications

of production and consumption systems.

By analysing both consumption habits and the production chain, students are encouraged to recognise the connections between individual practices and wider environmental and social impacts, thus engaging in processes related to **problem framing (2.3)**.

Finally, the project includes the creation of a "traffic light" to consult before buying new clothes. The lesson plan does not define fixed quantitative parameters for the traffic-light system. The idea is that students construct their own criteria after analysing the textile supply chain and reflecting on their personal consumption habits. In this sense, the tool functions mainly as a reflective device that supports discussion about more conscious purchasing choices. The aim is to encourage more conscious consumption choices. This activity can be interpreted as encouraging **individual initiative (4.3)**. It can also be interpreted as opening a space for **futures literacy (3.1)**, since students are invited to consider how their future consumption choices could be different.

In terms of sustainability, the project begins by identifying critical points related to both the **environmental** and **social impacts** of the textile industry. It also opens up a reflection on the **economic dimension** of sustainability. By inviting students to evaluate whether a purchase is really necessary, the activity encourages a more conscious use of financial resources.

Project	**Focus**	**Sustainability dimensions activated**	**GreenComp competences activated**
1 – Food waste	Local context, community, public inquiry	Environmental, social, economic	2.1, 2.3, 4.2, 4.3
2 – Energy saving	Everyday practices and school community	Environmental, social, indirectly economic	1.1, 4.2
3 – Fast fashion and supply chain	Critical consumption, global systems, personal agency	Environmental, social, economic	1.1, 1.2, 2.2, 2.3, 3.1, 4.1, 4.3

Table 3.7: Overview of project focus, activated sustainability dimensions, and related GreenComp competences.

The analysis presented so far has focused on the competences that emerge from the activities designed by the teachers. However, it may also be interesting to complement this perspective with a comparison between the different projects, in order to observe how each lesson plan "carves out" and puts the GreenComp framework into practice.

In the first project, which focuses on food waste, the way the GreenComp framework is interpreted becomes visible already in the keywords used to describe the project. The teachers explicitly state that the aim is to expand competences related to action, yet the learning objectives formulated in the lesson plan refer more clearly to the dimension of valuing sustainability ("Students become aware of the amount of food wasted every day and learn to value sustainability."). This suggests that, although the project is framed in terms of action, it also involves a strong reflection on the values underlying everyday practices. Another relevant expression appears in the description of the final artifact, which is presented as a trialogical product intended for local institutions ("Documentary film containing interviews and presentation of data collected for city institutions").

The third project, focused on fast fashion and the textile supply chain, follows a different logic. In this case, keywords are not explicitly highlighted in the description of the project. Instead,

the way the GreenComp framework is used becomes visible through the structure of the activities themselves.

Another interesting type of analysis can be found in how the individual and collective dimensions are addressed.

The first project begins with a general reflection on the concept of food waste, introduced through an initial brainstorming activity. The focus then shifts to the local context through meetings with experts and the identification of local organisations where the investigation can take place. The project concludes with the production of a documentary intended for local institutions. In this sense, the project follows a clear progression: **general issue → local territory → community**, presenting sustainability as a public and collective matter.

The third project begins at an individual level, through the analysis of students' personal wardrobes, and gradually expands towards a broader perspective that considers the production chain of the textile industry. In this way, the project connects personal experiences with a more systemic view of the phenomenon. At the same time, the process eventually returns to the individual level through the design of a tool intended to guide purchasing decisions. Unlike the first project, the final output is not conceived as a form of communication to the community, but rather as a support for students' everyday choices. In this sense, the project follows a different progression: **personal experience → production system → personal choices**. Sustainability is therefore framed primarily as a reflection on individual consumption practices.

The comparison between these two projects highlights two different ways of engaging with sustainability. While the first project frames sustainability as a public and territorial issue involving the local community, the third project places greater emphasis on individual consumption practices and their connection with wider production systems.

The second project, centred on energy saving, provides fewer elements for this type of analysis. The activities mainly focus on students' daily practices and on the collaborative construction of a set of good practices. While the project highlights the collective dimension of sustainable behaviours within the school community, the lesson plan offers fewer indications of how the GreenComp framework is interpreted at a broader level.

A direct comparison between the lesson plans developed during the first and second cycles is not entirely possible. In the second cycle, the template used for lesson plan design was revised and the focus of the course shifted from psychological factors related to climate action to sustainability competences described in the GreenComp framework. Nevertheless, some general considerations can still be drawn.

The lesson plans developed during the first cycle show a strong focus on scientific topics related to climate change and energy transition, such as the greenhouse effect, decarbonisation and energy consumption. In this sense, physics is positioned as a key discipline for addressing sustainability issues through a scientifically grounded perspective.

Compared to the first cycle, the lesson plans developed during the second cycle show a broader pedagogical perspective. While scientific understanding remains an important component, teachers begin to connect these topics more explicitly with students' everyday experiences and with the social and cultural dimensions of sustainability. Issues such as food waste, energy saving, and fast fashion are therefore addressed not only as environmental challenges, but also as situations linked to students' own practices, consumption habits, and everyday choices. This suggests that physics-based understanding provides the conceptual foundation upon which broader sustainability

competences can be developed.

In the projects analysed, several elements typical of scientific reasoning can still be recognised. The project on energy saving directly engages with issues related to energy consumption and efficiency, while the fast fashion project involves the statistical representation and interpretation of collected data. In the food waste project, the collection and processing of field data introduces elements of data-driven inquiry.

These examples suggest that, although physics is no longer the explicit focus of the projects, it still supports several activities related to sustainability.

Analysis of the questionnaires

The analysis of the questionnaires, reported in Appendix 4, completed at the end of the second cycle, shows a generally very positive picture.

Overall, participants rated both the organization and the overall quality of the course positively. Almost all teachers considered the course to be well structured and well planned, with clear objectives and carefully prepared materials: more than half of the participants said they "strongly agreed" with each of these aspects, while the rest still gave a positive assessment.

The content offered was also highly appreciated. All participants said that the course was interesting and motivating, and about 70% said they had learned "many" new things. The trainers were also evaluated positively: most of the teachers found them very engaging and clear in their explanations, and no one expressed negative opinions. This is an important element of continuity with the first cycle, where the quality of the trainers had already emerged as a strong point.

The results are also very positive with regard to professional impact. Almost all participants recognized the full applicability of the topics covered to their school practice, and 100% indicated that what they learned could be used in their work. The perception of usefulness for professional growth is also very high, as is that relating to increased interest in the topics covered. The fact that the vast majority of teachers said they had already put some of the ideas into practice or intended to do so is a clear indicator of the course's usefulness.

The questionnaire responses were primarily analysed as feedback on the second cycle of the course rather than as a direct comparison with the first cycle. However, one aspect deserves particular attention. During the first cycle, opportunities for collaboration among participants had emerged as a potential area for improvement. For this reason, the item related to the development of collaborative skills was considered with particular interest.

In the second cycle, most participants reported that the course contributed to strengthening their ability to work in groups and collaborate with others in their professional role: 12 out of 14 teachers declared that they agreed or strongly agreed with this statement, while only two expressed a lower level of agreement. Although the number of respondents is limited, this result may suggest that the changes introduced in the second cycle helped to foster a stronger perception of collaboration among participants.

In the open comments, several people also emphasized how the second day, which was more workshop-based and focused on shared planning, was engaging and useful. This indicates that the changes introduced during the redesign phase worked, directly addressing the critical issues previously identified.

Overall, the comments confirm that the course was well received. Some participants suggested dedicating even more time to the design phase, while a recurring suggestion was to focus more on source verification, a topic that is particularly important in teaching practice.

3.3.4 Conclusions and perspectives

Overall, the analysis of the lesson plans and questionnaires from the second cycle provides useful insights into how teachers interpret and translate sustainability into educational planning after participating in the training course. The lesson plans show that teachers are able to reinterpret the theoretical framework proposed during the course and transform it into concrete classroom activities addressing different aspects of sustainability.

The projects highlight different approaches to sustainability in teaching. The food waste project frames sustainability as a collective issue linked to the local community and institutions. The fast fashion project, on the other hand, focuses more on individual practices and consumption habits, inviting students to reflect on the relationship between personal choices and broader environmental and social systems.

In projects, different GreenComp competences appear together within the same activities. For example, discussions about sustainability values are often linked with reflections on complex systems and possible actions. This suggests that teachers tend to approach sustainability through integrated learning experiences rather than through isolated competences.

Because the course structure changed between the two cycles, the lesson plans cannot be directly compared. However, they still offer some insights into how sustainability is addressed in the projects. In the first cycle many lesson plans were strongly anchored in scientific topics related to climate and energy. In the second cycle, the projects more often connect these themes with students' everyday experiences and consumption practices. Sustainability therefore appears less as a topic to be explained and more as a lens through which everyday practices and broader systems can be explored.

However, it is possible to recognize elements typical of scientific reasoning in the activities presented: analysis of energy consumption, data collection and representation, interpretation of quantitative information. From this perspective, physics can be seen not as the explicit focus of the activities, as was the case in the first cycle, but rather as a support for the study of sustainability topics in class.

The questionnaire responses show that participants rated the course very positively and found it useful for their professional practice. In particular, teachers appreciated the time devoted to collaborative planning and reported greater confidence in designing teaching activities related to sustainability.

Overall, these elements suggest that multidisciplinary teacher training can support teachers in translating sustainability from an abstract concept into concrete classroom practices. Future iterations of the course could further strengthen opportunities for collaborative design and encourage deeper reflection on the sources and information used when addressing sustainability topics in school contexts.

3.4 Final considerations

In this chapter, we have reconstructed the process that guided the design, implementation, and revision of the teacher training course on sustainability. Starting from a TLS focused on the greenhouse effect and students' conceptions, we gradually broadened the focus to develop a course that reflected the multidimensionality of sustainability, integrating scientific, social, economic, and psychological dimensions. The collaboration with IPRASE and the involvement of university professors from different fields allowed us to build a structured training program, capable of combining disciplinary contributions and laboratory activities oriented towards educational design.

The adoption of a Design-Based Research approach has enabled continuous improvement of the course. The first cycle provided information on the overall effectiveness of the course, on the appreciation of the content, and on the difficulties encountered by teachers, highlighting in particular the need to strengthen the collaborative dimension and the ability to translate the concepts addressed into integrated teaching practices.

The second cycle, redesigned on the basis of this evidence, made it possible to further refine the structure of the course and to explore how teachers integrated the different dimensions of sustainability into their teaching proposals, as reflected in the lesson plans developed during the course.

In light of the results obtained, we can now return to the questions that guided our work.
(i) This study suggests that a teacher training programme can address the complexity of sustainability when it brings together different disciplinary perspectives and combines theoretical contributions with moments of collaborative educational design. In this case, the iterative structure of the course, guided by a Design-Based Research approach, made it possible to progressively refine the programme over the two cycles.
(ii) The analysis of the lesson plans developed by the participants provides some indications of how teachers tried to translate this multidimensional perspective on sustainability into their teaching proposals. In several cases, the activities designed by the teachers connect scientific concepts with social, psychological and value-related aspects of sustainability. Many of these proposals also invite students to reflect on their everyday practices, discuss possible alternatives, and engage more actively with sustainability-related issues.

Beyond the specific outcomes of the two design cycles, the findings also contribute to the growing literature on teacher professional learning for sustainability. Consistent with previous studies [53, 54], teachers were able to engage with sustainability as a multidimensional issue that extends beyond disciplinary boundaries. The lesson plans frequently connected environmental concerns with social and economic dimensions, supporting the development of more systemic perspectives on sustainability [58]. Furthermore, the collaborative design activities adopted during the second cycle align with research emphasising the importance of practice-based and community-oriented approaches to teacher professional learning [59]. Finally, many of the proposed activities reflected characteristics commonly associated with socio-scientific issue approaches, including discussion, argumentation, reflection and decision-making [48, 56].

Overall, the experience described in this chapter shows that a multidisciplinary training program can help teachers approach sustainability as a complex and interconnected topic, providing them with concrete tools to translate this into meaningful teaching activities.

However, some aspects could be further developed in future implementations of the course and in subsequent research. In particular, the study did not include interviews with participating teachers, which could have provided insights into how teachers with different disciplinary backgrounds interpret sustainability skills and integrate them into their teaching practices.

Another important aspect concerns the implementation of the proposed activities in real school contexts. In fact, the present study mainly focused on the design phase, analysing the lesson plans developed by teachers at the end of the course. Future research could therefore investigate how these activities are implemented in the classroom, exploring the challenges teachers face during implementation and how these activities may influence students' understanding of sustainability and their attitudes towards environmental issues.

Chapter 4

Dialogue between educational contexts and research: Experiences in Portugal

4.1 Introduction

This chapter presents the research experiences carried out abroad during the PhD, with a particular focus on the research periods spent in Portugal, at the University of Porto and at the University of Aveiro. These international experiences allowed the research projects developed in Italy to be further expanded and adapted in new educational contexts.

During the period spent in Porto, the research built on previous work using drawings as a primary investigative tool, but shifted the focus towards children's imagined representations of possible future scenarios. In particular, pupils were asked to draw the world as they imagine it would be if pollution were to continue, and alternatively if it were to be reduced or avoided. The experience in Aveiro was instead connected to another central line of the PhD research, focused on teacher education for sustainability. In this context, a teacher training course previously designed and implemented in Italy was adapted to a new setting: a pre-service teacher education course. This adaptation required a careful analysis of the local context and territory to better fit the new audience and educational objectives.

Overall, the research experiences in Portugal created a dialogue between different educational contexts and research practices. They also strengthened the international dimension of the PhD and showed the importance of adapting research and educational activities to each context.

4.1.1 The portuguese educational context

The Portuguese education system is organised into different levels.

The educational pathway begins with pre-school education, which is optional and attended by children between the ages of 3 and 6. Compulsory schooling continues with Basic Education, which is divided into three consecutive cycles: a first cycle lasting four years (ages 6–9), a second cycle

lasting two years (ages 10–11), and a third cycle lasting three years (ages 12–14). Within Basic Education, different types of pathways are offered, including general education, artistic courses, and education and training programmes.

After Basic Education, students move on to Secondary Education, which lasts three years and is generally attended between the ages of 15 and 17. This level includes different tracks, such as scientific-humanistic, vocational, and artistic pathways, which prepare students either for further studies or for entry into the labour market.

After completing secondary education (usually around the age of 17), the Portuguese education system offers both post-secondary non-university pathways and short-cycle higher education programmes, before access to university in the strict sense. These pathways are mainly technical and professionally oriented.

Finally, higher education follows the Bologna process and includes bachelor's, master's, and doctoral programmes.

Within this educational framework, sustainability is mainly addressed through Citizenship and Development (*Cidadania e Desenvolvimento*), which aims to support students in understanding their role as active members of society.

Education for sustainable development and environmental education are part of this area throughout compulsory schooling, from primary to secondary education. Sustainability is not taught as a separate subject, but it is approached in a cross-cutting way and linked to broader social issues, such as human rights, equality, and intercultural understanding.

In primary education, Citizenship and Development is integrated into everyday classroom activities. In lower secondary education, it may be offered as a specific subject, depending on the organisational choices made by each school. In upper secondary education, sustainability-related topics are usually addressed through interdisciplinary activities and projects involving different subjects.

Schools have a certain degree of autonomy in how Citizenship and Development is implemented. As a result, sustainability may be addressed through dedicated lessons, interdisciplinary work, or whole-school projects, often using participatory and project-based approaches.

In science subjects such as Biology and Geology, sustainability is explicitly addressed through subject-specific content.

For example, in Biology and Geology, students explore topics such as ecosystems, biodiversity conservation, natural resource management, and the impacts of human activity on the Earth system. These subjects provide a scientific foundation that supports students' understanding of sustainability and reinforces the interdisciplinary approaches developed across the curriculum.

Initial teacher education in the Portuguese context

Within this broader educational structure, the preparation of future secondary science teachers in Portugal generally combines disciplinary training with a subsequent phase of pedagogical specialization. Students interested in teaching subjects such as Biology, Geology, or Physics typically begin with a bachelor's degree in their disciplinary field, which provides the scientific foundations of the subject area.

This is usually followed by a teaching-oriented master's programme, where disciplinary knowl-

edge is integrated with educational and didactic preparation. In this phase, future teachers engage with issues related to curriculum design, classroom practices, assessment, and the teaching of scientific concepts in school settings. An important component of this pathway is the practicum carried out in schools, which allows pre-service teachers to progressively connect theoretical preparation with real teaching situations. This process typically culminates in the development of a research project conducted within the context of pedagogical practice, which is publicly defended as part of the completion of the master's degree.

4.2 Exploring children's drawings of future environmental scenarios: the Porto study

4.2.1 Theoretical framework

Children's drawings are increasingly recognized in science and environmental education research as valuable tools to access how young learners interpret the world around them. drawings provide access not only to what children know, but also to what they consider salient and emotionally relevant. This is particularly important in early and primary education, where verbal language may not always fully capture the richness of children's thinking [128–130].

Through drawings, children use the visual resources available to them to communicate what they find important. This is especially relevant when exploring environmental issues, since children's understanding is often influenced by everyday experiences, media, school activities, and the local context in which they live [130].

Within environmental education research, drawings have been used to investigate children's perceptions of their environment and of environmental change. Previous studies have shown that drawings allow researchers to capture both descriptive and affective dimensions of children's relationships with their surroundings, including elements of attachment, belonging, concern, and responsibility [128, 131, 132].

The local dimension is relevant, as children's ideas about environmental futures are often shaped by the relationship they develop with the places around them. What children imagine is closely connected to what they see and recognize as part of their everyday world. However, even when they live close to environmentally significant places, they may not automatically perceive them as meaningful spaces that deserve care, unless educational activities help make this connection explicit [131]. This highlights the relevance of place-based perspectives in sustainability education, as they support connections between broader environmental challenges and the future of familiar places.

A further relevant dimension concerns children's ability to imagine possible futures. The representation of contrasting environmental scenarios supports early forms of futures-oriented reasoning, as it invites children to connect present actions with long-term consequences and to consider that different choices may lead to different environmental trajectories. Recent studies suggest that children's visual representations of future environmental scenarios often oscillate between catastrophic and hopeful visions, revealing not only their understanding of environmental change but also their sense of possibility and agency [132, 133].

In this sense, the use of contrasting future scenarios can also be interpreted as a pedagogical

opportunity to foster early forms of sustainability agency. Rather than reinforcing exclusively fear-based narratives, this approach creates opportunities to explore the consequences of choices and to imagine desirable alternatives. This perspective aligns with research in early sustainability education that emphasises the importance of supporting hopeful, action-oriented, and emotionally meaningful engagements with environmental issues from the first years of schooling [134, 135].

Overall, this theoretical perspective views children's drawings of future environmental scenarios as meaningful representations through which it is possible to explore how children perceive environmental change, relate to places, imagine the future, and begin to develop a sense of agency toward sustainability.

4.2.2 Study design and research procedures

During my three-month research stay at the University of Porto, I worked under the supervision of Professor Clara Vasconcelos, Professor at the Faculty of Sciences, affiliated with the Department of Geosciences, Environment and Spatial Planning and with the Unit of Science Teaching. Her research focuses on science education, environmental education, and sustainability, with particular attention to students' conceptions and the use of visual and qualitative methods in educational research. I carried out a study aimed at exploring primary school pupils' mental models of environmental change through the analysis of drawings. The study involved primary school pupils aged 7–9 and focused on how they imagine possible future scenarios related to pollution and environmental degradation.

The activity was designed as a guided drawing task. To introduce the topic in an age-appropriate way and to establish a shared reference frame, pupils were first shown a short cartoon addressing global warming and its main causes (see Figure 4.1). After this introductory phase, they were asked to complete a drawing activity using a structured worksheet specifically developed for this study.

As shown in Figure 4.2, the worksheet consisted of a single sheet printed on both sides. On the front, pupils were provided with written instructions in Portuguese, inviting them to imagine how a landscape might change if pollution continues and how it might look if pollution were to stop. The instructions explicitly encouraged pupils to consider different elements of nature (such as water, sky, land, and living beings), to use colours, and to label the elements included in their drawings. The back of the worksheet presented a drawing template divided into two sections, labelled "With pollution" and "Without pollution", which pupils were asked to complete.

The drawings were analysed using a coding grid developed on the basis of key elements identified in the literature on children's conceptions of environmental issues and climate change. The grid was applied independently by two researchers. The coding results were then compared and discussed to assess agreement and to resolve discrepancies through consensus, thus enhancing the reliability of the analysis. The coding grid used for the analysis is reported in Table 4.1.

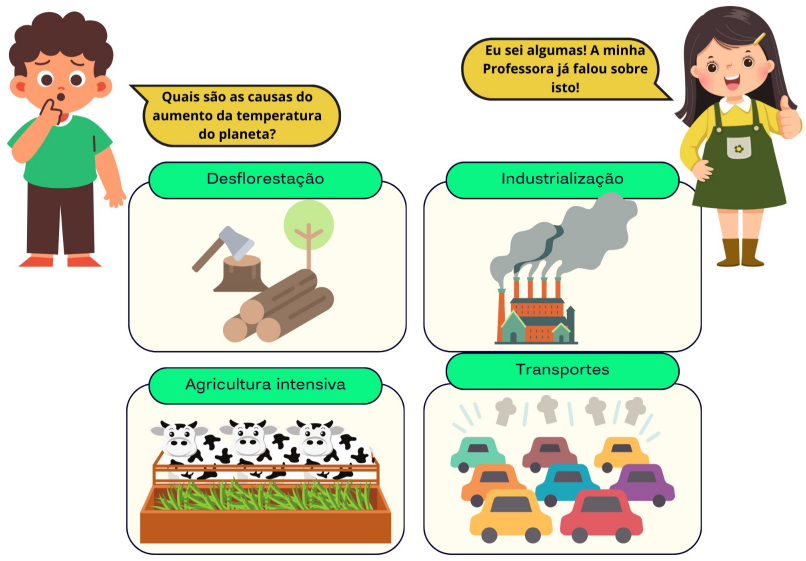


Figure 4.1: Cartoon used as an introductory stimulus before the drawing activity. The original text in Portuguese was as follows: "What are the causes of the increase in the planet's temperature?" — "I know some! My teacher has already talked about this!" The causes presented in the cartoon are labelled as *Deforestation, Industrialization, Intensive agriculture, and Transport.*

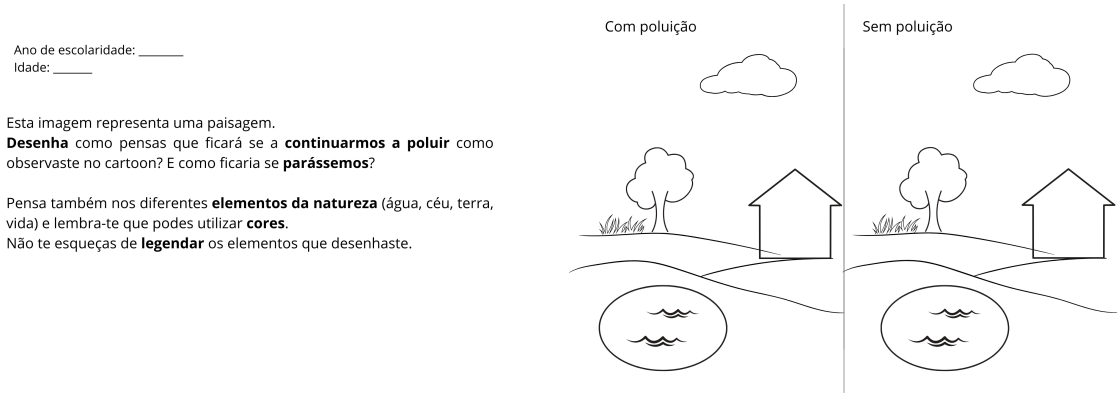


Figure 4.2: Front and back of the worksheet used for the drawing task with primary school pupils. Instructions (translated from Portuguese): "This image represents a landscape. Draw how you think it will look if we continue to pollute, as shown in the cartoon, and how it would look if we stopped. Think about the different elements of nature (water, sky, land, life), use colours, and label the elements you draw." The drawing template includes two scenarios: *With pollution* and *Without pollution.*

Category	Subcategory	Description
A. Environmental Condition	A1. Presence of polluted air (smog, dark clouds)	Sky depicted with grey or dark tones, or industrial smoke
	A2. Clean atmosphere (blue skies, white clouds)	Clear sky, use of light or blue colours
	A3. Presence of water pollution (dark rivers, floating waste)	Water bodies shown with waste, dark or brownish colouring
	A4. Clean water (clear rivers/lakes, visible aquatic life)	Blue, clean water with visible aquatic life
B. Natural Elements	B1. Healthy vegetation (green trees, grass, flowers)	Signs of lush vegetation, flowers, or sunflowers
	B2. Degraded vegetation (burnt, dead, or no trees)	Absence of plants or depiction of destroyed flora
	B3. Presence of animals in harmony with the environment	Animals depicted as active and healthy
	B4. Impacted fauna (dead fish, sad or sick animals)	Fauna depicted as affected by environmental degradation
C. Anthropic Elements	C1. Industrial pollution sources (factories, chimneys)	Factories or visible emissions from industrial infrastructure
	C2. Responsible human behaviour (playing, recycling)	People coexisting positively with nature (e.g., recycling, biking)
	C3. Wildfires	
	C4. Domestic or human-caused fires	
D. Sustainability Elements	D1. Renewable energy (solar panels, wind turbines)	Presence of clean energy technologies
	D2. Recycling systems (bins, ecopoints)	Recycling bins and colour-coded waste separation
	D3. Sustainable transport (bicycles, walking)	Use of bicycles or walking, absence of cars
E. Emotional Representation	E1. Positive emotions (happy sun, smiling clouds)	Anthropomorphised nature with positive expressions
	E2. Negative emotions (sad sun, crying clouds)	Elements expressing sadness or distress due to pollution
F. Colour Use	F1. Dominant bright colours (greens, blues, yellows)	Use of bright colours associated with healthy environments
	F2. Dominant dark colours (greys, blacks, browns)	Use of dark tones to represent pollution and degradation

Table 4.1: Coding grid used for the analysis of pupils' drawings.

Although the full interpretative phase of the data analysis is still ongoing, this research experience provides initial indications that may contribute to broadening the methodological perspective of the doctoral work, by extending the use of drawings as a research tool to younger learners and to future-oriented environmental scenarios. The study also lays the groundwork for a possible shared coding framework that could support future comparative analyses across different educational levels and cultural contexts. In this sense, the Porto experience points towards a strengthening of the international and methodological dimension of the thesis, and suggests a possible further line of research on children's visual representations of environmental futures.

4.3 Teacher education for sustainability in Aveiro

During my PhD, I carried out a two-month research stay at the Universidade de Aveiro, within the CIDTFF – Centro de Investigação Didática e Tecnologia na Formação de Formadores and the Departamento de Educação e Psicologia. This experience took place under the supervision of Prof. Betina Lopes and Prof. Valentina Piacentini, both active in the field of science education and teacher training.

The research period in Aveiro extended the work previously developed in the Italian context on multidisciplinary teacher education for sustainability into a Portuguese pre-service teacher education setting. This experience made it possible to further develop a transdisciplinary perspective, connecting physics, biology, and geology with social, cultural, and environmental dimensions of sustainability. Particular attention was given to the Aveiro context, where local environmental and cultural specificities offered a meaningful way to relate local issues to broader global sustainability challenges.

Figure 4.3: Moments from the teacher training intervention.

4.3.1 Methods

These reflections were then developed into a teaching intervention within the Portuguese context of pre-service teacher education. Designed through a Science–Technology–Society perspective, the intervention addressed sustainability as a topic that combines scientific knowledge with social, cultural, and technological dimensions.

The intervention was implemented within the course *Didática e Desenvolvimento Curricular de Biologia e Geologia II*, part of the Master's degree in Teaching Biology and Geology. Participants were pre-service teachers preparing to teach in lower (students aged 12–14) and upper (students aged 15–17) secondary schools. To encourage collaboration and shared planning, students worked in small groups throughout the activities.

The main aim of the intervention was to support future teachers in understanding how the environmental, social, economic, and cultural dimensions of sustainability are interconnected, and in designing interdisciplinary teaching activities on sustainability.

The intervention was structured into several phases:

1. Introduction to sustainability, focusing on its multidimensional nature and on the concept of sustainable development, drawing on the Brundtland Report [38] and the Sustainable Development Goals [41].

2. Critical analysis of scientific data related to climate change. Students worked in small groups to interpret graphs and datasets, reflecting on data sources and scientific reliability.

3. Discussion of educational frameworks, comparing how sustainability and citizenship education are addressed in Italian and Portuguese curricula [136].

4. Introduction to the Smart Knowledge Garden (SKG) [137, 138], a Science Garden, opening a discussion on outdoor educational spaces, non-formal learning contexts, and their role in sustainability education.

5. Exploration of digital tools, with a specific focus on the climate simulator En-ROADS.

6. Design of interdisciplinary lesson plans, where groups developed teaching proposals on sustainability, integrating scientific content with social, economic, and cultural aspects.

A key element of the intervention was the use of the En-ROADS simulator, developed by *Climate Interactive* in collaboration with *MIT Sloan*. The tool allows users to explore different climate mitigation scenarios by modifying variables such as energy production, emissions, land use, and economic growth.

The simulator provides immediate feedback on how these choices affect the projected global average temperature by 2100.

During the session, En-ROADS was used to support discussion on the links between climate policies, environmental impacts, and social and economic consequences. The simulator was also integrated into the design process of the lesson plans, rather than used only as a demonstration tool. This approach provided an opportunity to examine how students used the tool when developing interdisciplinary proposals on sustainability.

This study aims to understand how a training activity focused on sustainability can support pre-service teachers in designing interdisciplinary teaching proposals on climate change. In particular, the study addresses two main research questions:

1. To what extent do the teaching proposals developed by the students integrate the environmental, social, and economic dimensions of sustainability?
2. How did the use of En-ROADS support students in connecting the environmental, social, and economic dimensions of sustainability?

The study contributes in two main ways. First, it offers insights into initial teacher education within an international and multidisciplinary context. Second, it explores the potential of digital tools to support the design of sustainability-oriented teaching activities.

Data collection included the interdisciplinary lesson plans produced by the student groups at the end of the intervention, as well as observations collected during group work and the final collective discussion. The data were analysed using a qualitative content analysis approach, with the aim of examining how the different dimensions of sustainability were integrated into the lesson plans and how the En-ROADS simulator was used during the design process.

The analysis followed several steps. First, all materials were read in their entirety to gain an overall understanding of the proposals developed by the groups.

Subsequently, analytical categories were defined in relation to the research questions, focusing on the integration of the environmental, social, and economic dimensions of sustainability and on the different ways the simulator was used.

The lesson plans were then re-analysed according to these categories, allowing similarities, differences, and specific features across the groups to be identified.

4.3.2 Results and discussion

A summary of the teaching proposals developed by the groups is presented in Table 4.2, highlighting the objectives, structure and way in which the simulator was integrated into the activity of each proposal.

It is possible to observe that the five proposals share several common features. Although their objectives are diverse, they all aim to connect disciplinary content (such as biology, geology, and energy) with realistic decision-making processes. Students followed the instructions provided for the use of the simulator, and across all proposals the pre-service teachers used it as a tool to guide pupils in evaluating mitigation strategies through the interpretation of graphs and the exploration of future scenarios.

In addition, all proposals included the division of the class into groups with different roles (e.g., ministries, entities, countries, or productive sectors), highlighting that climate change is a complex phenomenon that requires the consideration of multiple perspectives in decision-making. Overall, the proposals reflect a view of learning that emphasizes active student engagement and the comparison of different choices.

Based on this initial reading, it was possible to further analyse how the different dimensions of sustainability were integrated across the proposals. The main elements emerging from the analysis are presented in Table 4.3.

Aim of the proposal	Activity structure	Use of En-ROADS	Final products / assessment
Understanding how pollution, deforestation, fires, and invasive species affect ecosystems.	Theoretical introduction; division of the class into small groups; assignment of a country and a specific environmental issue; identification of mitigation measures related to the assigned problem.	Testing the proposed measures in the simulator; comparison of predicted impacts on temperature and other indicators.	Final group presentation including the environmental issue addressed, the proposed measures, and their impact on the projected temperature increase by 2100.
Analysing policy decisions and trade-offs in climate crisis scenarios.	Storyline ("going back to 2001"); division into four teams (energy, economy, nature, society); successive decision-making rounds with whole-class discussion.	Constrained use of the simulator, with each team allowed to modify only specific parameters; joint observation of graphs and discussion of consequences.	Final discussion on changes in the graphs, the impacts obtained, and the justifications provided by the teams.
Interpreting data on the exploitation of geological resources and their impacts on Earth systems.	Division into five "ministries" (energy, transport, agriculture, economy, population); guided inquiry; recording of decisions and analysis of simulator indicators.	Justified decision-making on the platform; interpretation of relevant variables; reflection on environmental, economic, and social impacts.	Final poster including three key proposed measures, two simulator graphs, and a conclusion on the impacts of the policies adopted by the ministries.
Inferring future scenarios related to global warming and evaluating energy strategies.	Division into four entities (Government, NGO, Forestry Industry, Energies PT); definition of specific goals; activity including a competitive component between groups.	Simulation based on predefined parameters for each entity; comparison of different strategies and their effects on global temperature.	Assessment based on which group proposes the most effective measures to achieve the defined goal, leading to a lower temperature increase by 2100.
Distinguishing types of energy resources and evaluating realistic climate-change mitigation policies.	Role-play activity in which students act as world leaders; selection of three policies per group; comparison and discussion between groups.	Testing selected policies in the simulator; comparison of results across groups; joint integration of final measures into a shared scenario.	Final discussion on the realistic possibility of reducing the temperature increase to 2 °C compared to the initial 3.3 °C scenario.

Table 4.2: Summary of the five lesson plan proposals developed by the pre-service teachers.

The analysis of the developed activities shows the presence of the three dimensions of sustainability (environmental, social, and economic), although not in a homogeneous way.

The environmental dimension emerges as the most solid and systematic across the proposals. All groups used the simulator to explore the effects of different measures in terms of CO_2 emissions and removals, deforestation, and energy use on the increase in global average temperature.

However, the proposals differ in the specific environmental aspects addressed. For example, some groups focused on the links between the exploitation of geological resources and impacts on Earth subsystems (Group 3), while others concentrated on the effects of specific energy policies (Groups 4 and 5). Overall, the proposals show a good ability to connect environmental changes with simulation outcomes and with the interpretation of graphs.

The social dimension appears through several of the issues addressed, for instance through references to differences between countries (Group 1), impacts on populations (Group 5), or the role of actors such as governments, NGOs, and industries (Group 4). This dimension is also reflected in the attention given to human vulnerability in situations of resource scarcity or extreme events (Group 2), as well as in trade-offs between different productive sectors and social groups, such as energy, agriculture, and transport (Group 3). These elements indicate an awareness of the social implications of climate change and of the importance of integrating a climate justice perspective into educational activities.

The economic dimension, by contrast, is not explicitly addressed in all proposals. In some groups, it is linked to economic measures such as taxes, investments, and changes in fossil fuel prices (Group 2), or to evaluations of trade-offs between economic growth and environmental protection (Group 3). In other proposals, this dimension is only marginally present through general references (Group

Group	Environmental dimension	Social dimension	Economic dimension
1	Impacts of pollution, deforestation, and fires; use of the simulator to propose mitigation measures.	Differences between countries; impacts on populations.	Dimension not explicitly addressed.
2	Environmental changes (deforestation, energy) and interpretation of climate effects.	Teamwork; human vulnerability due to lack of resources and extreme temperatures.	Adjustments in coal use, energy efficiency, resource pricing, and justified economic decisions.
3	Sustainability of geological resource exploitation and impacts on Earth subsystems.	Trade-offs between sectors (energy, agriculture, transport) and social impacts.	Economic measures (taxes, investments, growth); evaluation of trade-offs.
4	Impacts of energy-related decisions on temperature and global warming.	Social actors with different objectives (Government, NGO, Forestry Industry, Energies PT).	References to economic implications, but not explored in depth, resulting in a weakly represented dimension.
5	Effects of mitigation measures on emissions, CO_2 removals, and global temperature.	Collective discussion on choices and social consequences.	Dimension not explicitly addressed.

Table 4.3: Summary of the sustainability dimensions integrated into the lesson plan proposals.

4), or not addressed at all (Groups 1 and 5). This suggests that the economic dimension may require further support within teacher education.

Regarding the use of the En-ROADS simulator in the activities, the proposals reveal five distinct ways in which the simulator was used:

- Simulation as validation of pre-designed strategies: students formulate hypotheses based on the problems assigned to different countries and use the simulator to test the effectiveness of their proposed strategies (Group 1).
- Simulation as verification of previously argued decisions: choices are first discussed and justified, and only afterwards their quantitative effects are examined using the simulator (Group 2).
- Free exploration followed by interpretation: students are initially allowed to explore the tool freely, and the results are then collectively interpreted and discussed (Group 3).
- Constrained simulation: the use of the simulator is restricted by limiting the parameters that can be modified (Group 4).
- Policy comparison: the simulator is used to compare the results obtained under different policies and to discuss the strategies adopted by the groups (Group 5).

The results show that the proposed activities were designed to create different groups in order to support collective discussion, data-based arguments, and an understanding of the trade-offs between political, economic, and environmental choices.

The overall analysis indicates that the pre-service teachers were able to include the three dimensions of sustainability—environmental, social, and economic—in ways that are generally consistent with Education for Sustainability and the principles of the 2030 Agenda [1, 139], even though the three dimensions were not integrated to the same extent. In particular, the economic dimension was included in a more uneven way across the proposals. Nevertheless, all groups attempted to connect disciplinary content with real-world problems, involving social actors and considering the consequences of different decisions.

Pre-service teachers showed that they were able to link data, impacts, and choices, moving beyond an approach in which disciplines are treated as separate subjects.

Their ability to connect environmental changes with social and economic implications suggests the development of early forms of systems thinking [140] and interdisciplinary attitudes that are useful for dealing with complex socio-scientific issues [141].

The use of the En-ROADS simulator supported a broader and more systemic view of sustainability, in line with previous studies [61, 62]. The proposals also show an intention to support students' agency [142], by encouraging learners to make informed decisions, compare different scenarios, and reflect on the consequences of their choices in everyday contexts. Overall, this suggests that pre-service teachers are beginning to see sustainability not only as a scientific topic, but also as an educational practice connected to participation and social responsibility.

In addition to these results, some qualitative aspects are worth highlighting. For example, in Group 4, the final presentation was delivered in two languages, Italian and Portuguese (in the Figure 4.4, to support communication in my the presence. This choice is not only practical, but also reflects attention to inclusivity in teaching practices. This suggests that training activities involving different countries or cultural contexts can offer valuable opportunities to reflect on multicultural and inclusive education, which is increasingly important in today's schools.

Figure 4.4: Example of a bilingual presentation (Group 4).

Other interesting aspects also emerged in other groups. In Group 1, participants explicitly stated that they revisited a previous activity developed in the course Biology, Society and Environment, reinterpreting it through the use of the En-ROADS simulator. This shows that the training did not only introduce new tools, but also helped give new meaning to already familiar practices, supporting continuity between past and new learning experiences. A similar aspect emerged in Group 5, where participants explained that the main topic of their proposal was chosen based on an interest previously expressed by the class. This indicates that the pre-service teachers planned their activities by taking into account the educational context and students' interests, linking theory with concrete classroom experience.

4.3.3 Conclusions

The analysis of the five lesson plan proposals developed by the pre-service teachers makes it possible to answer the research questions and to draw some conclusions about how sustainability was

understood and integrated into the designed activities.

The results show that all groups attempted to link disciplinary content (biology, geology, and energy) with real-world problems, including environmental, social, and economic elements. However, the three dimensions were not addressed to the same extent. The environmental dimension was the most developed and was closely connected to the results of the simulations. The social dimension emerged through references to communities and involved social actors, while the economic dimension, although present in some activities, was less developed and appears to be the area that requires further support in teacher education. Overall, the proposals reflect an interdisciplinary view of sustainability and suggest an educational approach in which future teachers are able to connect natural phenomena, social aspects, and policy-related implications.

The analysis also highlights that the En-ROADS simulator can support more systemic forms of thinking. The ways in which the simulator was used varied across groups—such as validating designed strategies, verifying previously discussed decisions, free exploration, restricted use of parameters, or comparison between policies—but in all cases the simulator was used as a tool to read data, interpret graphs, and explore future scenarios. This use of the simulator helped make visible the interconnections between energy choices, climate effects, and social and economic implications. It also supported students in reflecting more carefully on their decisions and in recognising necessary trade-offs, which are important aspects of developing systems thinking and climate citizenship.

Finally, some qualitative elements emerging from the proposals, such as attention to multicultural aspects in the work of Group 4, the reworking of previously developed activities in Group 1, and the choice of topics relevant to students' contexts in Group 5, indicate a growing sensitivity towards sustainability education that takes into account real-world contexts, students' prior learning experiences, and classroom needs.

These results also represent a positive example of how encounters between different cultures (Italian and Portuguese) and between different disciplines (biology, geology, and physics) can stimulate new educational perspectives that go beyond disciplinary boundaries and promote more informed scientific citizenship. In this sense, the training experience offered students and future teachers the opportunity to gain experience in increasingly multicultural professional contexts, supporting the development of educational practices that value different perspectives.

In conclusion, while this intervention has shown meaningful results, its value also lies in its potential to strengthen international and intercultural collaboration. The creation of networks that support the sharing of research and educational practices, with the aim of building more inclusive educational pathways and preparing students to become citizens aware of the global challenges of sustainability, emerges not only as a necessary strategy, but also as a feasible one.

This also invites a closer look at what it means to "value different perspectives", and at when different forms of knowledge are actually recognised as legitimate within educational contexts. These questions are developed in the following chapter.

4.4 Final considerations

The experience described in this chapter can be understood as part of the broader research trajectory presented throughout this thesis. In fact, these experiences do not provide a direct comparison

between the Italian and Portuguese contexts, but contributed to the research through a process of mutual enrichment between different research practices and perspectives on sustainability education.

The studies conducted in Italy had initially focused on students' understanding of climate-related phenomena and on the design of sustainability-oriented teacher education programmes. The experience in Portugal did not seek to replicate the same studies in a different context, but rather offered opportunities to expand and complement them. For example, the collaboration with Portuguese researchers contributed to extending the investigation of drawings to primary school students, a population that had not been included in the earlier Italian studies. It also encouraged greater attention to qualitative approaches and interpretative dimensions that were less central in the initial phases of the research.

Similarly, the work on teacher education benefited from being situated within a different educational and cultural context. While the Italian programme had emphasised interdisciplinarity and sustainability competences, the Portuguese experience highlighted the relevance of Science–Technology–Society perspectives and the importance of connecting sustainability issues with local realities. Discussions around the territory of Aveiro, local environmental challenges, and existing community initiatives offered examples of how sustainability education can be grounded in contexts that are meaningful for future teachers and their students.

From this perspective, the value of the Portuguese experience lies not in the comparison of results across countries, but in the dialogue that emerged between different ways of approaching sustainability education. This dialogue contributed to broadening the scope of the research and reinforced the idea that understanding climate-related phenomena, while important, represents only one element of a more complex educational process that also involves cultural, social, contextual, and methodological dimensions.

Chapter 5

Dialogue between educational contexts and research: Perspectives from Brazil

The mobility experience in Brazil helped to further contextualise a question that had already emerged within sustainability education itself.

In the earlier stages of the research, the main focus was on designing and analysing educational approaches to sustainability, especially in relation to competences, multidisciplinarity, and the connection between scientific knowledge and real-world contexts. The work carried out in Italy, and later extended to the Portuguese context, had already shown that sustainability education cannot be understood simply as the transmission of disciplinary content. More broadly, it involves educational pathways that can support wider forms of social transformation.

What became clearer was a question that had remained more implicit until that point: if sustainability education aims to contribute to more just and sustainable futures, then it also requires asking sustainability for whom.

This question brings into focus issues of social inequalities, unequal participation, power relations, and access to decision-making processes. The Brazilian context offered a particularly meaningful space for reflecting on how sustainability challenges are deeply intertwined with colonial histories, North–South inequalities, racialised forms of exclusion, and unsustainable models of development.

As discussed in the literature, knowledge production cannot be considered neutral or universal, but is always shaped by historically situated power relations [43, 45, 143]. In Brazil, these dimensions are not only part of theoretical debates, but are often explicitly present in educational practices, where science education is closely linked to citizenship, human rights, environmental justice, and broader processes of social transformation, in continuity with Freirean traditions of popular education [144, 145].

This context made visible some assumptions that had remained more in the background during the earlier phases of the research, especially those concerning the role of science and the ways in

which knowledge is framed and legitimised within sustainability education.

The mobility took place in Rio de Janeiro, under the supervision of Professors Giselle Faur de Castro Catarino and Glória Regina Pessôa Campello Queiroz, within the PPCTE doctoral programme at the Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, in collaboration with the Universidade do Estado do Rio de Janeiro.

During the mobility, these reflections were closely connected to the activities carried out within the host institutions. Alongside the PPCTE doctoral programme at CEFET/RJ, one of the most meaningful aspects was the opportunity to engage with different research groups across CEFET and UERJ, where science education was discussed through historical, cultural, and socio-political lenses [146, 147].

During a research meeting held at UERJ in July 2025, I presented a series of questions that emerged from my previous encounters with Freirean pedagogy and decolonial perspectives. These questions concerned the relationship between science, culture, and coloniality, including whether science should be understood as a universal form of knowledge or as a historically situated tradition associated with Western modernity. The discussion that followed did not lead to a single answer. Instead, it revealed the existence of multiple positions regarding the meaning of decolonising science, the role of indigenous knowledge systems, and the relationship between scientific and non-scientific forms of knowledge. This encounter highlighted the complexity of these debates and motivated the subsequent readings that informed the reflections presented in this chapter.

Following these discussions, I was introduced to a number of readings that further expanded my understanding of the relationship between knowledge, culture, and power. These included works on Yanomami knowledge systems [148], indigenous cosmologies, the history of Western knowledge production [149], and critical perspectives on science, education, and human rights. The discussions also introduced me to authors such as Frantz Fanon, Achille Mbembe, and Nego Bispo, whose reflections on coloniality, identity, territory, and knowledge contributed to broadening my understanding of epistemological plurality beyond the predominantly Western references.

Discussions on Cultural History of Science were particularly interesting because they offered a perspective on the history of science that differed from the approaches more commonly encountered in the research context of this PhD. Particularly relevant was the way the historical development of scientific knowledge was discussed in close connection with social transformations, material conditions, and the long-term consequences of colonial processes.

This made more evident how scientific and technological developments are never separate from history, but are often linked to environmental exploitation, unequal power relations, and changing social needs. In this sense, it further reinforced the reflection on sustainability education by showing how scientific development is shaped by broader historical and social dynamics.

The visit to the Museum of Astronomy and Related Sciences (MAST) was also important. Beyond its historical dimension, particular attention was given to the inclusion of Afro-Indigenous and culturally situated perspectives on astronomy and cosmology. This made explicit how even strongly disciplinary scientific fields can be presented in ways that acknowledge the plurality of cultural perspectives through which the natural world has been interpreted.

The postgraduate course *Language and Science Teaching* was another particularly significant

part of the experience. Scientific concepts were addressed through their historical development, philosophical reflection, and the role of language in the construction of meaning. A central feature of the course was its dialogic approach: students read texts in advance, developed their own interpretations, and then discussed them collectively in class.

This made explicit that disagreement, multiple viewpoints, and interpretation were not treated as obstacles to learning, but as part of the learning process itself. In relation to teacher education, this offered a useful perspective on how dialogue can support a deeper engagement with complex and contested issues, especially when dealing with sustainability.

Another meaningful part of the experience was the opportunity to take part in activities within a local school. A particularly relevant aspect was the strongly practical and inquiry-based way in which science was approached, through hands-on activities, group work, and short collective presentations, even with very young students.

Although active learning is not absent from the educational contexts more familiar to this PhD, observing these practices within formal school settings made more visible how inquiry, collaboration, and oral discussion can be introduced from the early years of schooling.

One of the most meaningful aspects of this experience was the possibility of engaging with perspectives that are usually less visible in mainstream science education, particularly those connected to knowledge developed by Indigenous and Afro-descendant communities in the Brazilian context.

While the content dimension of these forms of knowledge was certainly important, an even more interesting aspect concerned the questions they raised about knowledge itself. How is this knowledge constructed? Through which practices, experiences, and collective processes is it transmitted? And what happens when it is placed in dialogue with scientific knowledge?

These questions were central to the reflection developed during the mobility. They opened a broader reflection on different ways of knowing, on what counts as knowledge, who has the authority to define it, and whose ways of knowing remain excluded when imagining sustainable futures.

This led to a more specific reflection on the role of science education in addressing sustainability issues. Scientific knowledge remains essential, especially for understanding physical processes such as climate change. However, it is clearer that scientific understanding alone is not enough to address the complexity of sustainability challenges, especially when these are inseparable from questions of justice, participation, and unequal recognition.

An important part of this reflection concerns the relationship between science, identity, and epistemic legitimacy. This also raises questions about how historically dominant, often Eurocentric forms of science have contributed to shaping not only what is recognised as valid knowledge, but also whose voices are more easily recognised as legitimate within educational contexts [43, 45, 143]. This also highlights that not all students, teachers, or communities may recognise their own experiences and ways of knowing in the forms of science mobilised in sustainability education, while other perspectives remain at the margins.

This has important implications in terms of representation, sense of belonging, and the possibility of building scientific identities that feel meaningful within diverse educational contexts.

In this sense, engaging with knowledge developed by Indigenous and Afro-descendant communities did not primarily move the focus toward the content of these knowledges, but toward their epistemological status and the conditions under which they are recognised as legitimate within educational contexts [146].

5.1 Theoretical results

Building on these reflections, the experience also contributed to the development of a more explicit theoretical perspective centred on the idea of a transcultural shift in scientific literacy. Taking inspiration from Graeber and Wengrow's (2022) call to envision alternative and desirable futures, this perspective points to the need to rethink science education beyond the simple inclusion of cultural elements [149]. In this view, knowledge developed by Indigenous communities is not considered as something to be added onto Western science, but rather as part of a plurality of knowledge systems whose epistemological foundations and specificities deserve to be taken seriously [146].

This approach can make an important contribution to sustainability education, especially in areas such as cultural astronomy and intercultural environmental education [150]. Engaging in dialogue with cultures where knowledge is built collectively can help foster a sense of shared belonging, rooted in common histories and in respect for Indigenous cultures that are increasingly under threat [150, 151]. The destruction of forests and the invasion of Indigenous territories do not only affect the environment, but also lead to the loss of these living forms of knowledge and historical memory [151]. From this perspective, respect for indigenous knowledge is not only an educational issue, but is also closely connected to human rights and to the recognition of forms of knowledge that have been historically marginalised. Integrating these perspectives into science education means questioning the idea that Western scientific rationality alone is sufficient to understand and address complex problems such as the global environmental crisis.

This reflection is part of a broader critique of traditional approaches to Western science teaching, which are often still organised around a hegemonic, empirical-inductive view that tends to privilege certain forms of knowledge at the expense of others. Such an approach represents one of the expressions of the coloniality of scientific knowledge, which extends beyond the boundaries of Western scientific institutions [152].

In searching for possible cross-cultural shifts in teaching, this work values the concept of epistemological diversity [153], attributing to it a role comparable to that already recognised for biodiversity in the survival of life on Earth.

Rather than identifying fixed correspondences, the aim becomes that of exploring possible connections and points of resonance between different knowledge systems. Some of these can be found in the ways in which knowledge is understood as relational, situated and collectively constructed. In particular, several contributions highlight that different epistemologies deal with complexity, interdependence, and human–non-human relationships, and understand knowledge as something shaped by social processes and specific contexts, rather than as fixed and universal.

Some of these can be found in the ways in which both scientific and Indigenous or Afrodescendant knowledge approaches engage with complexity, interdependence and the relationship between human beings and the natural world. In both cases, knowledge can be understood as a process that is collectively constructed, open to uncertainty and shaped by specific contexts, rather than as a set of fixed and universal truths. From this perspective, these elements do not imply a convergence between epistemologies, but can offer starting points for dialogue without reducing their differences.

These reflections do not provide definitive answers, but they have helped to shed light on certain issues, particularly those concerning the role of science and the assumptions underlying it.

5.2 Conclusions

Overall, this experience can be understood as the beginning of an ongoing theoretical reflection aimed at more clearly identifying the epistemological values that characterise the knowledge systems of indigenous and afro-descendant cultures, as well as those typically associated with Western science. The goal is not to establish hierarchies or to propose simplified comparisons, but rather to develop conceptual tools that allow for a more rigorous and informed dialogue between different ways of knowing, recognising their specificities, limitations, and potential points of resonance. From this perspective, the Brazilian experience contributed to shifting the focus from the mere inclusion of cultural perspectives towards a deeper reflection on the epistemological conditions that make meaningful comparison between knowledge systems possible.

This approach opens up research perspectives that extend beyond the specific context of the mobility experience and align with the broader trajectory of this PhD project. The experience can be seen as a continuation of the broader trajectory developed throughout this thesis. While the earlier chapters focused on students' understanding of climate-related phenomena and on educational approaches to sustainability, the Brazilian context brought additional questions concerning culture, knowledge, and the ways sustainability itself is interpreted and taught in different contexts. In this sense, it contributed to the progressive broadening of perspective that characterises the thesis as a whole, moving from the understanding of physical phenomena towards a greater consideration of the social, cultural, political, and epistemological dimensions of sustainability education.

However, this chapter should not be interpreted as the establishment of a fully developed dialogue between Global North and Global South perspectives. It represents a first encounter with different epistemological traditions. For this reason, the aim is not to reinterpret the findings presented in the previous chapters through a decolonial lens. Such a task would require a deeper engagement with perspectives that remain relatively new within my own research trajectory. One of the most important insights emerging from this experience was the recognition that not only theoretical frameworks, but also methodologies and analytical approaches, are themselves rooted in particular epistemological traditions. Understanding how these assumptions shape research practices remains an open question that deserves further exploration.

These reflections open research perspectives that extend beyond the specific context of the mobility experience. In particular, they create opportunities to develop Teaching–Learning Sequences and sustainability education initiatives that take into account the cultural and epistemological plurality of educational contexts, avoiding universalistic assumptions while maintaining scientific rigour. The questions that emerged during this experience suggest the need for further reflection on the relationships between sustainability education, cultural diversity, and epistemological plurality. While these issues lie beyond the scope of the present thesis, they represent an important area for future research and may contribute to developing educational approaches that are both scientifically grounded and sensitive to different social and cultural contexts.

Chapter 6

Science theatre for physics education

While the previous chapters focused primarily on conceptual understanding, teacher education, and the role of cultural and contextual dimensions in sustainability education, this chapter explores another dimension that emerged progressively throughout the thesis: the importance of emotional engagement and personal meaning-making. Sustainability-related challenges are not addressed through scientific knowledge alone, but also through the ways people emotionally connect with these issues and position themselves in relation to them.

In fact this chapter focuses on a different aspect of my PhD work, namely the use of science theatre as a form of scientific communication developed alongside the research activities described in the previous chapters. In the previous chapters, the thesis mainly focused on formal educational contexts and research-based approaches. In this chapter, however, the focus shifts to informal contexts, where physics is communicated through storytelling, performance, and emotional engagement.

The aim of this chapter is not to provide a systematic evaluation of theatre-based interventions, but rather to reflect on what these experiences reveal about communicating science to diverse audiences. In particular, the chapter explores science theatre as a form of non-formal scientific communication, characterised by a transversal approach that can be adapted to different scientific contents. Science theatre can create spaces in which scientific concepts and personal narratives, offering alternative ways to engage with physics and with broader issues related to sustainability and scientific citizenship.

The visual materials presented in this chapter are sourced from the official website and social media platforms of the theatre company *Arditodesìo*.

6.1 Science theatre as a form of scientific communication and education

Part of the skepticism that some people feel toward science and scientists may be linked to the way science is communicated. Scientific communication often uses formal, one-way methods, rather than leaving space for dialogue and personal involvement [154]. In fact, the relationship with science is not built solely on accurate information, but also on emotions, curiosity, and imagination. Emotions can help people engage with scientific knowledge, stimulating interest, a desire to understand, and respect for the work of researchers [155].

In this context, science theatre can be described as a form of expression that combines theatrical language with the communication of scientific content. Through performances designed to actively engage audiences, this practice aims to make complex scientific concepts more accessible by using non-traditional and audience-friendly communication strategies.

In recent years, there has been an increase in initiatives using theater as a means of communicating science. There are various practices in this field, but they are united by the attempt to create a dialogue between science and society [156, 157]. Museums and science festivals are using theater to engage diverse audiences and promote new forms of interaction with science [157, 158]. These experiences can also have a positive impact in the field of climate education: for example, viewers felt more informed about climate change after attending a theater performance on the subject [159].

However, the use of theater in science communication does not automatically have a positive and, above all, inclusive aspect. Language, style, and cultural references profoundly influence who feels included and who remains excluded. If not carefully designed, some initiatives risk appealing only to an audience that is already interested or reinforcing existing social and cultural and clichés [160]. For this reason, artistic choices become a starting point for reflecting on how science communication can reach diverse audiences and engage with the issues of inclusivity that characterize sustainability education [161].

From an educational point of view, science theater can be seen as an informal learning space that offers interesting opportunities to work on competences related to sustainability education. In fact, theater allows sustainability issues to be addressed through stories, characters, and situations that also engage on an emotional level, such as care for the environment, social responsibility, and the ethical implications of scientific choices. In this way, sustainability can be presented as a set of open questions to reflect on and discuss, helping the public understand that environmental and social challenges cannot be addressed with simple or isolated solutions.

Science theater offers a potential space in which to imagine possible futures and reflect on the consequences of individual and collective choices, taking into account the cultural and social contexts in which these choices are made. Even without indicating specific actions, these experiences can foster a sense of responsibility, participation, and comparison between different points of view.

In this sense, science theatre can broaden the discussion on sustainability education by creating spaces for dialogue where science, values, and context meet, supporting the development of a more aware and critical scientific citizenship [161].

During the PhD program, various types of performances related to science theater were explored, characterized by different formats and narrative structures. These experiences were not designed with the specific aim of explicitly addressing sustainability issues, but provided contexts for experimenting with different languages of scientific communication and for reflecting on the role

of science with the public in informal contexts.

6.2 Science theatre activities

The science theatre activities developed during the PhD programme were carried out in collaboration with the theatre company *Arditodesìo*, founded in Trento in 2002 by playwright, actor and physicist Andrea Brunello.

From its beginnings, the company has been characterised by a strong commitment to civic and narrative theatre, with a focus on contemporary issues and an active dialogue with society. Over time, this orientation evolved into a distinctive approach that brings together theatre and science, understood as two central dimensions of contemporary culture and as complementary sources of human and creative inspiration. This context provided a coherent framework for the development of science theatre activities combining scientific content with storytelling and performance in informal communication settings.

Within the science-theatre activities developed by *Arditodesìo*, I was involved in several communication formats characterised by different levels of interaction and narrative structure. One of these formats is the 'Open Mike', a series of open-stage events organised in collaboration with *Arditodesìo* and the University of Trento.

In this context, researchers from the University of Trento take the stage as storytellers, sharing short personal narratives that reveal the human dimension of their scientific work and research paths. These events are part of a broader approach to emotional science communication, in which scientific content is conveyed through personal stories, live music, and direct engagement with the audience.

As part of this format, I personally took part in the event held in Trento on 12 May 2023, presenting a short narrative performance entitled *Errare è umano* ('To err is human').

The performance was centred on the role of error in learning processes and on how mistakes are often perceived as failures rather than as integral steps in the construction of knowledge. Drawing on a personal experience, the narrative explored how playful approaches and non-judgemental teaching practices contributed to rebuilding my relationship with physics during a period in which my motivation towards the discipline was progressively diminishing.

This experience was later revisited and expanded in an interview for the podcast *Riflessi di Scienza*. The interview made it possible to return to the themes addressed during the live performance and to explore them in a more reflective and conversational way, with particular attention to learning, error, and scientific identity.

Figure 6.1: Promotional material for the 'Open Mike' science communication event held on 12 May 2023 at Teatro Portland (Trento) and the podcast 'Riflessi di Scienza'.

Another key format is the *Augmented Lecture* (AL), an innovative form of science communication in which a scientist and an artist collaboratively design and perform a live event. Augmented Lectures combine scientific discourse with theatrical language, music, and visual elements, adding an emotional and narrative dimension to scientific content.

The AL format was developed as a tool for outreach and public engagement, designed to open communication channels that are both intellectual and emotional [154]. Scientific concepts are presented in a rigorous manner, while at the same time moving away from highly formal or academic communication styles. In this sense, the format seeks to make complex or challenging scientific topics more accessible, without oversimplifying their content [154].

Emotions play an important role in helping the audience feel attentive and involved, supporting a more meaningful engagement with scientific content [162, 163]. For this reason, the AL treats emotions as a central resource for communication.

I had the opportunity to directly experiment with this format through a performance developed in collaboration with theatre director Maura Pettorruso, with lighting and sound design curated by Giacomo Gottardi. Working within this format allowed me to engage with scientific content not only as a communicator, but also as a performer, exploring how narrative structure, staging, and technical elements can support the communication of physics-related themes. Within the Augmented Lecture format, I developed the performance *La mia storia di cadute e rinascite. Quando sbucciarsi le ginocchia insegna più di un 30 e lode* ('My story of falls and rebirths. When scraped knees teach more than top grades'), created in collaboration with theatre director Maura Pettorruso.

The performance is structured as a narrative monologue that reflects on the meaning of teaching and learning, questioning the idea of a single, universal educational method and exploring what lies behind the act of teaching. It is based on my personal educational and academic trajectory, following a path marked by failures, doubts, discoveries, and moments of renewal. Through autobiographical storytelling, the narrative traces the search for meaning within science, portraying an initially distant and challenging discipline that gradually becomes a space for personal and professional recognition through the encounter with physics education.

While grounded in an individual story, the performance opens up to more universal questions related to learning, vulnerability, expectations, and identity within academic contexts. The performance concludes with a participatory moment involving the audience in simple physics experiments,

explicitly highlighting the role of active engagement and participation in teaching and learning processes.

Figure 6.2: Images from the Augmented Lecture *La mia storia di cadute e rinascite. Quando sbucciarsi le ginocchia insegna più di un 30 e lode.*

The performance was first presented on 16 November 2023 at the *Teatro della Meraviglia*, an annual science theatre festival organised in collaboration between Arditodesio and the University of Trento. The show was later performed again in Trento on 28 February 2024. A further presentation took place on 20 May 2024 in Trento as part of the *10th Anniversary of TIFPA* (The Trento Institute for Fundamental Physics and Applications), a national research centre focused on fundamental physics and advanced technological development. The performance was also presented in Trieste (Italy) within the programme of *Scienza e Virgola 2024*, an annual cultural festival organised by the Interdisciplinary Laboratory of SISSA, aimed at engaging the general public with scientific topics through talks, workshops, performances, and public dialogues centred each year on a specific theme.

In addition to these formats, the activities also include performances related to science busking, a street-based approach to science communication that uses live demonstrations, theatrical techniques, and interactive experiments in informal public spaces.

In this case, scientific concepts are introduced through engaging and sometimes unconventional experiments, designed to capture attention and encourage spontaneous interaction with passers-by. Within this framework, I was involved in the development and performance of *Non me la sento*, a science busking show focused on basic concepts of acoustics. The performance was structured in two parts of approximately 30 minutes each and was presented in Trento in November 2024 within the programme of the *Teatro della Meraviglia*. Through a narrative scenario centred on a group of university students preparing for an acoustics exam under time pressure, the show addressed fundamental topics related to sound, hearing, and wave propagation. Scientific concepts such as the nature of sound waves, sound propagation in different media, and the functioning of the human ear were introduced through live demonstrations, short experiments, and interactive moments with the audience. The informal and performative setting allowed scientific content to be presented in a playful and accessible way, encouraging curiosity and spontaneous engagement while maintaining a clear connection with physics-related ideas.

6.3 Final considerations

Overall, the science theatre activities presented in this chapter represent an important part of the research work carried out during the PhD programme. These experiences have allowed us to experiment with different ways of communicating physics through performative and narrative formats developed in informal contexts, highlighting the human and emotional aspects of learning physics. These experiences have allowed me to observe how scientific content can be shared outside traditional academic contexts, reaching diverse audiences. In this sense, science theatre is a significant space for experimentation, capable of enriching reflection on scientific communication and scientific citizenship.

From the perspective developed throughout this thesis, science theatre can be understood as a complementary educational space within sustainability education. While the previous chapters highlighted the importance of scientific understanding, teacher education, and the influence of cultural and social contexts, the experiences described in this chapter draw attention to another dimension: the role of emotions, personal narratives, and public engagement.

Rather than replacing formal educational settings, science theatre may offer opportunities to connect scientific knowledge with personal experiences and collective reflection. In this sense, it contributes to a broader understanding of sustainability education, in which learning involves not only understanding complex phenomena but also developing meaningful relationships with the issues at stake.

Future research could also explore connections between science theatre and participatory educational traditions that emphasise dialogue, critical reflection, and collective action, examining their potential contribution to sustainability education.

Conclusions

This thesis shows how science education, and physics education in particular, can offer a meaningful contribution to sustainability education when scientific understanding is connected with interpretation, responsibility, and action. More specifically, this thesis explored how physics education can contribute to sustainability education not only by supporting the understanding of climate-related physical phenomena, but also by fostering broader educational approaches capable of engaging social, cultural, emotional, and epistemological dimensions of sustainability. Across the different studies presented, the findings highlight a progressive expansion from the analysis of students' conceptualisations of the greenhouse effect to broader educational pathways that engage teachers, contexts, and multiple ways of knowing.

The study of students' mental models of the greenhouse effect represented a first entry point into this complexity. The results show that many students, even at advanced levels, develop representations that are coherent from their perspective but do not align with scientific explanations. This highlights the need for teaching approaches that make the underlying physical mechanisms more explicit, especially those related to energy balance and the interaction between radiation and matter. At the same time, these findings suggest that understanding climate change cannot be reduced to the acquisition of isolated concepts, but requires supporting students in building more structured and meaningful interpretations of complex phenomena. In this sense, the findings reinforce the idea that conceptual scientific understanding is necessary, but insufficient on its own, for addressing the complexity of sustainability-related issues.

Building on these insights, the research was extended to the design and analysis of a multidisciplinary teacher training course on sustainability. The results show that such programmes can support teachers in integrating environmental, social, and economic dimensions into their teaching practices, moving beyond a purely disciplinary approach. Teachers demonstrated the ability to reinterpret scientific content and translate it into meaningful educational activities, often connecting climate-related topics with everyday life and societal issues. The use of frameworks such as GreenComp also helped to structure this process, highlighting the role of competences such as systems thinking, futures literacy, and collective action in sustainability education. Within this perspective, physics education emerged not as an isolated disciplinary domain, but as a possible starting point for developing more multidimensional and transformative approaches to sustainability education.

Taken together, these findings suggest that both students and teachers need learning experiences that help them connect scientific concepts with real situations, future consequences, and possible ways of acting. As discussed throughout the thesis, climate change is a complex issue that involves values, decisions, and actions across multiple domains, and therefore calls for educational approaches

that connect knowledge with reflection and action. From this perspective, teachers emerge as key actors in creating learning environments where students can engage with complexity, uncertainty, and multiple perspectives.

The international dimension of the research further expanded this perspective. The experiences in Portugal and Brazil highlighted how sustainability education is deeply shaped by cultural, institutional, and epistemological contexts. In the Portuguese context, this became evident through the design of interdisciplinary learning activities with pre-service teachers, where scientific knowledge about climate change was translated into discussions around policy decisions, trade-offs across sustainability dimensions, and the design of concrete teaching proposals, showing how sustainability education gains meaning when it is carefully reinterpreted within specific local and institutional contexts. Alongside this, the research also began to extend the use of drawing-based methods to younger students in a different educational setting. Overall, these experiences showed how sustainability education gains meaning when it is carefully reinterpreted within specific local and institutional contexts.

Engaging with different knowledge systems in the Brazilian context led to a reflection on the need to critically examine the role of science in education, and on how different epistemologies can contribute to a more inclusive and plural understanding of sustainability. The idea is not to homogenise perspectives, but this work highlights the importance of creating spaces for dialogue, where different ways of knowing can coexist and interact without being reduced to a single framework. From this perspective, sustainability education becomes not only a matter of transmitting scientific knowledge, but also of reflecting critically on whose knowledge is legitimised, how it is produced, and how different perspectives may contribute to imagining more sustainable futures.

Taken together, these international experiences reinforced the idea that sustainability education cannot be reduced either to the transmission of scientific concepts, nor to the rigid use of predefined competence frameworks. Instead, it requires educational pathways that remain sensitive to context, open to plurality, and able to connect scientific rigour with dialogue, reflection, and action.

Overall, this thesis shows that addressing sustainability in physics education means working on different but connected dimensions. This includes strengthening the understanding of fundamental scientific concepts, supporting teachers in designing multidisciplinary and practice-oriented activities, exploring non-formal and affective ways of engaging through science theatre and narrative-based communication, and paying attention to the wider cultural and epistemological dimensions of knowledge. These aspects do not stand alone, but continuously shape and reinforce one another. Across the thesis, there is therefore a progressive movement from a primarily conceptual focus on climate-related physical phenomena towards broader and more transformative perspectives on sustainability education.

From students' drawings to teacher training, from international contexts to science theatre, this work provides a basis for suggesting that engaging with sustainability involves learning to connect scientific knowledge with lived experience, cultural perspectives, and future-oriented action. In this sense, physics education may contribute not only to explaining the world, but also to expanding the ways in which it can be critically interpreted and responsibly transformed.

Rather than proposing a single model of sustainability education, this thesis highlights the importance of developing educational approaches that remain scientifically grounded while also being sensitive to context, plurality, and the diverse cultural and social dimensions through which

sustainability is experienced and interpreted.

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Appendix 1 – Teachers' Lesson plans – First Cycle

LESSON PLAN 1

THEMATIC:

Greenhouse effect and climate change

PSYCOLOGICAL OBJECTIVES:

- Trust in institutions
- Theory of Change
- Implementation intentions

PROCEDURE:

- Theoretical explanation of concepts related to pollution and climate change: identification of protagonists
- Presentation of scenarios in progress
- Presentation of possible consequences of these scenarios
- Activation of virtuous behaviour through scenario change with mitigation of negative consequences

PRACTICAL ACTIVITIES:

- Collection of scientific data at Museo Civico di Rovereto on climatic factors recorded by the weather station at the Convent of San Rocco
- Graph construction
- Identification of correlations between parameter trends and possible causes
- Elaboration of a questionnaire to be given to family members in which the relationship between the respondent and the causes is highlighted
- Presentation to local politicians (Municipality of Rovereto) of the work carried out

LESSON PLAN 2

THEMATIC:

Energy and decarbonization

PSYCOLOGICAL OBJECTIVES:

- Trust in institutions
- Efficacy
- Imagination

PROCEDURE:

- Explanation on Ecological Footprint and Earth Overshoot Day
- Demonstration of global consumption differences
- Demonstration of local consumption situation (in Italy/Trentino area)
- Presentation of virtuous examples of effective policies

PRACTICAL ACTIVITIES:

- Ecological Footprint Calculation
- Game: meeting a set CO2 budget by choosing between various activities
- Discussion on the effectiveness of CO2 reduction behaviours
- Final quiz

LESSON PLAN 3

THEMATIC:

Energy and decarbonization

PSYCOLOGICAL OBJECTIVES:

- Social Norm
- Efficacy
- Imagination

PROCEDURE:

- Explanation of primary energy sources
- Explanation of energy use divided by sectors
- Conversion of energy use divided by energy source into diesel equivalent litres
- Study of plant capacity factor for studying production redundancy (non-flat generation and consumption)

PRACTICAL ACTIVITIES:

- Calculation of energy consumption with 'jerry can' with blackboard calculations involving students: each individual student calculates his or her own jerry can and then the class average is taken (psychological factor 1 and 2)
- Calculation of ecological footprint on the website: students are divided into groups of 3, each student impersonates a minister (economics, ecology, social) and they have to calculate their ecological footprint as if they were the 'typical citizen' of the community they represent. The aim is to try to reduce the ecological footprint in a realistic way (psychological factor 2 and 3).

LESSON PLAN 4

THEMATIC:

Energy and decarbonization

PSYCOLOGICAL OBJECTIVES:

- Social Norm
- Theory of change

PROCEDURE:

Construction of graph of:

- time series of energy demand to be compared with CO2 increase
- origin of energy
- energy use

PRACTICAL ACTIVITIES:

- Calculating one's ecological footprint
- Group discussion on practical actions that can reduce consumption and possible problems that may arise from those actions
- Completion of a logbook for a defined time in groups
- Production of a publicity campaign in the school in groups
- Calculation of your final energy footprint

LESSON PLAN 5

THEMATIC:

Energy and decarbonization.

PSYCOLOGICAL OBJECTIVES:

- Personal identity.

PROCEDURE:

Presentation of the degradation times of certain materials:

- plastic (bag, lighter, bottle),
- aluminium cans,
- glass.

Discussion on which environmentally sustainable materials could be used.

PRACTICAL ACTIVITIES:

Implementation of a practical outdoor activity.

LESSON PLAN 6

THEMATIC:

Energy and decarbonization.

PSYCOLOGICAL OBJECTIVES:

- Personal identity.
- Imagination.
- Efficacy.

PROCEDURE:

Presentation by:

- breakdown of consumption into types and areas,
- global needs and sources of production,
- types of energy savings (building, industry, transport, lifestyle),
- types of decarbonisation with pros and cons of the various solutions (effectiveness, availability, ability to meet demand).

PRACTICAL ACTIVITIES:

Class research and discussion of:

- production of intermittent sources (wind, photovoltaic, hydroelectric) on a daily and seasonal basis,
- pollution produced by the sources (emissions, land consumption, census of areas polluted by extraction),
- tracing the future in the two hypotheses (BAU, limit of development)
- legislation (citizen's rights and duties),
- method on how to interface with institutions (contacts with politicians, referendums).

LESSON PLAN 7

THEMATIC:

Energy and decarbonization.

PSYCOLOGICAL OBJECTIVES:

- Implementation intentions.
- Emotional Engagement.
- Theory of change.

PROCEDURE:

- Explanation on climate change (role of CO_2, greenhouse effect, 1.5 °C net zero, why to act).
- Explanation of Overshoot Day and Carbon Footprint with the addition of new concepts by reading articles and understanding the text.
- Discussion on how to act.

PRACTICAL ACTIVITIES:

First lesson:

- Implementation of an initial survey.
- Application of Jigsaw with five Ted Talks with map
- Completion of a final questionnaire to check understanding.

Second lesson:

- Construction of word cloud to recap the previous lesson.
- Read-out of graphs on Overshoot Day and CO_2 emissions in the world.
- Calculation of ecological footprint.

Lesson three:

- Creation of final product to raise awareness.

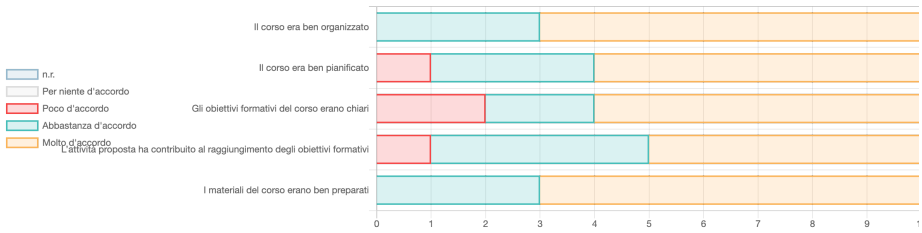
Appendix 2 – Teachers' Questionnaire Statistics – First Cycle

Educare alla complessità della sostenibilità: un approccio scientifico multidisciplinare e transdisciplinare

v.31 Questionario di Gradimento IPRASE — Corrente — 14/03/2022 — 10

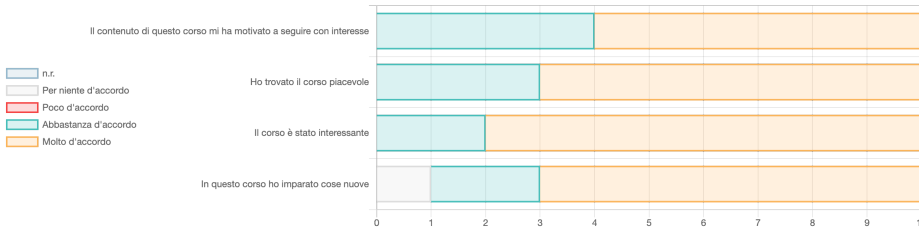
id:482 Organizzazione dell'attività formativa

Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il corso era ben organizzato	0	0	0	3	7
Il corso era ben pianificato	0	0	1	3	6
Gli obiettivi formativi del corso erano chiari	0	0	2	2	6
L'attività proposta ha contribuito al raggiungimento degli obiettivi formativi	0	0	1	4	5
I materiali del corso erano ben preparati	0	0	0	3	7



id:483 Soddisfazione per i contenuti

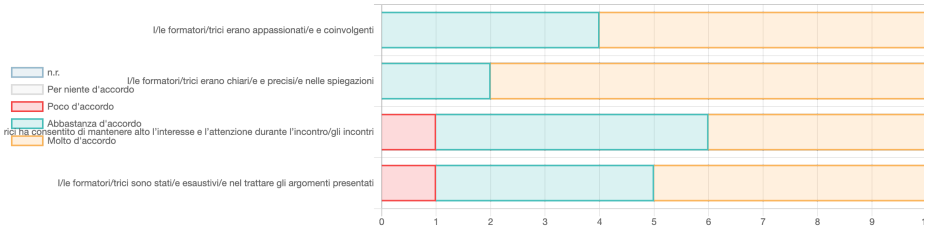
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il contenuto di questo corso mi ha motivato a seguire con interesse	0	0	0	4	6
Ho trovato il corso piacevole	0	0	0	3	7
Il corso è stato interessante	0	0	0	2	8
In questo corso ho imparato cose nuove	0	1	0	2	7



id.484

Formatori/trici

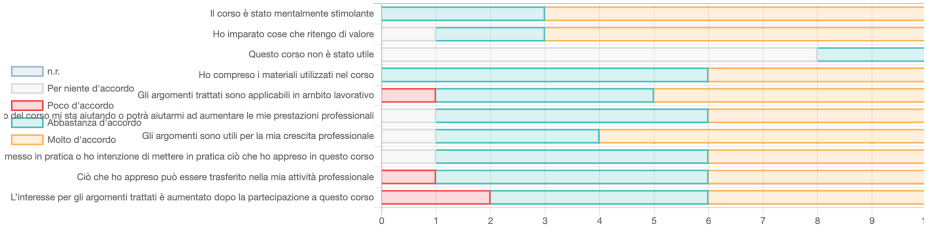
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
I/le formatori/trici erano appassionati/e e coinvolgenti	0	0	0	4	6
I/le formatori/trici erano chiari/e e precisi/e nelle spiegazioni	0	0	0	2	8
Lo stile di presentazione dei/delle formatori/trici ha consentito di mantenere alto l'interesse e l'attenzione durante l'incontro/gli incontri	0	0	1	5	4
I/le formatori/trici sono stati/e esaustivi/e nel trattare gli argomenti presentati	0	0	1	4	5



id.485

Utilità e ricadute dell'attività formativa

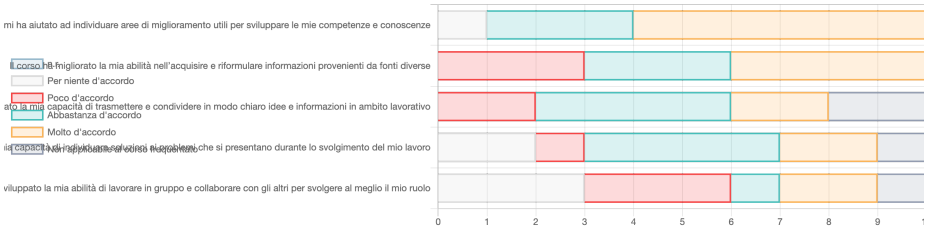
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il corso è stato mentalmente stimolante	0	0	0	3	7
Ho imparato cose che ritengo di valore	0	1	0	2	7
Questo corso non è stato utile	0	8	0	2	0
Ho compreso i materiali utilizzati nel corso	0	0	0	6	4
Gli argomenti trattati sono applicabili in ambito lavorativo	0	0	1	4	5
Il contenuto del corso mi sta aiutando o potrà aiutarmi ad aumentare le mie prestazioni professionali	0	1	0	5	4
Gli argomenti sono utili per la mia crescita professionale	0	1	0	3	6
Ho già messo in pratica o ho intenzione di mettere in pratica ciò che ho appreso in questo corso	0	1	0	5	4
Ciò che ho appreso può essere trasferito nella mia attività professionale	0	0	1	5	4
L'interesse per gli argomenti trattati è aumentato dopo la partecipazione a questo corso	0	0	2	4	4



id:486

Competenze generali acquisite

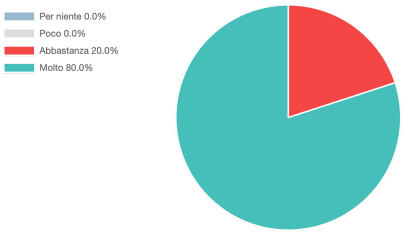
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo	Non applicabile al corso frequentato
Il corso mi ha aiutato ad individuare aree di miglioramento utili per sviluppare le mie competenze e conoscenze	0	1	0	3	6	0
Il corso ha migliorato la mia abilità nell'acquisire e riformulare informazioni provenienti da fonti diverse	0	0	3	3	4	0
Il corso ha migliorato la mia capacità di trasmettere e condividere in modo chiaro idee e informazioni in ambito lavorativo	0	0	2	4	2	2
Il corso ha migliorato la mia capacità di individuare soluzioni ai problemi che si presentano durante lo svolgimento del mio lavoro	0	2	1	4	2	1
Il corso ha sviluppato la mia abilità di lavorare in gruppo e collaborare con gli altri per svolgere al meglio il mio ruolo	0	3	3	1	2	1



id.487

In quale misura riterrebbe utile un percorso di approfondimento sulle tematiche affrontate?

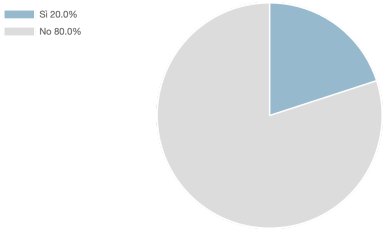
#	Testo opzione	Freq.	
1	Per niente	0	0.0%
2	Poco	0	0.0%
3	Abbastanza	2	20.0%
4	Molto	8	80.0%
	Totale	**10**	



id.488

Ci sono stati argomenti che non sono stati trattati e avresti voluto affrontare?

#	Testo opzione	Freq.	
1	Sì	2	20.0%
2	No	8	80.0%
	Totale	**10**	



id.489

Specificare brevemente gli argomenti che avresti voluto affrontare

Nessuna risposta : 1
Risposte inviate : 2

Risposte

- applicazione pratica dei contenuti.
- Stabilità delle reti elettriche completamente decarbonizzate. Ad esempio la Francia ha emissioni basse ma non arriva a zero poiché mantiene alcune centrali a gas pur producendo molta più energia elettrica di quanto consumi. Esistono tecnologie che permettono a un paese industrializzato di rinunciare completamente alle centrali a gas?

id.490

Spazio per commenti e osservazioni

Nessuna risposta : 1
Risposte inviate : 3

Risposte

- Il percorso andrebbe pensato in maniera differente. E' vero che la partecipazione era obbligatoria solo al modulo iniziale e finale ma così si sono perse per strada un sacco di persone. Consiglierei dei moduli indipendenti più piccoli con un focus maggiore all'applicazione scolastica. Va bene la chiave della complessità ma se questa complessità non trova una chiave di lettura comune è solo complessa.
- Molto bello l'aspetto laboratoriale del corso. Decisamente importante essere in presenza, ma la sede di Rovereto è per me molto scomoda e non proponibile con assiduità. Più comodo Trento per chi viene da fuori. Grazie per il corso, davvero interessante; mi sarebbe piaciuto frequentare anche gli altri moduli.
- Non ho potuto seguire tutti i moduli perché alcuni si sovrapponevano ad impegni scolastici non differibili. Sarebbe stato utile avere la registrazione degli interventi, in modo da poterli seguire in un secondo momento. Sarebbe interessante poter avere un seguito, con ulteriori interventi (oppure la ripetizione di alcuni, per dare più ampia diffusione), sugli stessi temi o su temi legati (ad esempio il nucleare; l'impatto energetico del turismo invernale; vantaggi e svantaggi dell'idroelettrico)

Appendix 3 – Teachers' Lesson plans – Second Cycle

Lesson Plan

School level Secondary I/II	Subject Citizenship Education	Group 1

GreenComp Area 4 "Acting forsustainability"	Competence 4.2 Collective action

Learning objectives
Students become aware of the amount of food wasted every day and learn to value sustainability.

Trialogic artefact Documentary film containing interviews and presentation of data collected for city institutions	Expert 1)Consultancy from an agronomist economist 2)Point of contact for local authorities in the field of waste disposal

Draft project based on the six principles:
Initial brainstorming on the concept of food waste
Meeting with one or more experts to learn about the key locations in the area where the survey will be conducted
Creation of working groups: each group chooses an area to investigate (markets, restaurants, canteens, private individuals, etc.)
Creation of working materials: questionnaires and interview questions
Field trips to collect data and video documentation
Sharing and selection of material
Data processing and production of the documentary film Final event to present the results in the area

Technologies
Video recording and editing with programmes such as Capcut
For data collection: Excel + animated data presentation tools
Canva/Genially

Lesson Plan

School level Secondary I/II	Subject Citizenship Education	Group 1

GreenComp Area 4 "Acting forsustainability"	Competence 4.2 Collective action

Learning objectives
Students become aware of the amount of food wasted every day and learn to value sustainability.

Trialogic artefact Documentary film containing interviews and presentation of data collected for city institutions	Expert 1)Consultancy from an agronomist economist 2)Point of contact for local authorities in the field of waste disposal

Draft project based on the six principles:
Initial brainstorming on the concept of food waste
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Creation of working materials: questionnaires and interview questions
Field trips to collect data and video documentation
Sharing and selection of material
Data processing and production of the documentary film Final event to present the results in the area

Technologies
Video recording and editing with programmes such as Capcut
For data collection: Excel + animated data presentation tools
Canva/Genially

Lesson Plan

School level Secondary I	Subject Citizenship Education	Group 2

1 Embodying the values of sustainability.	1.1 Valuing sustainability

Learning objectives

1. Knowledge of the production chain.
2. Calculation of the ecological footprint.

Creation of a 'traffic light' system to consult before making a new purchase.	ATOTUS + environmental expert

Brainstorming with a Google form among group members to gather information about their wardrobes (how many items, how often they wear each item, why they rarely wear a certain item, etc.). Statistical representation of the data collected. Visit to the ATOTUS factory to learn about the textile supply chain, identification of critical points for environmental and social impact, knowledge of the materials used to avoid allergies, supporting knowledge over time; photographing the wardrobe in autumn and planning new purchases if necessary. Creating outfits with your own garments, getting to know your entire wardrobe and thinking about possible combinations. Before making a purchase, assess whether that garment is really necessary; if not, make a note of how much you have saved and use the resources in the future.

Tecnologie

Appendix 4 – Teachers' Questionnaire Statistics – Second Cycle

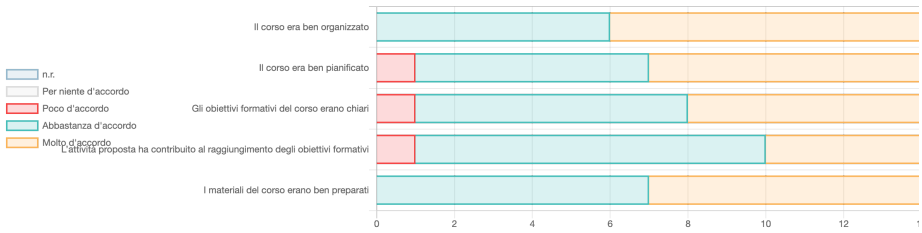
IPRASE ISTITUTO PROVINCIALE PER LA RICERCA E LA SPERIMENTAZIONE EDUCATIVA

Educare alla sostenibilità con GreenComp

v.31 Questionario di Gradimento IPRASE — Corrente — 14/03/2022 — 14

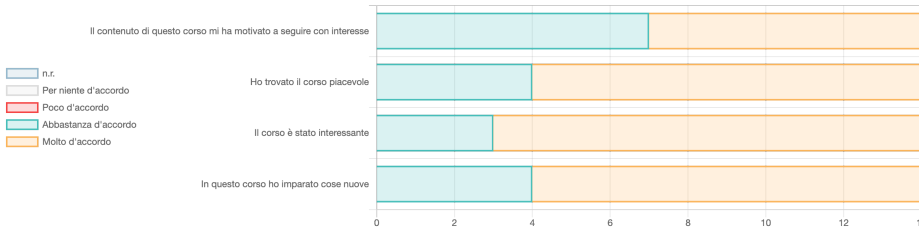
id:482 — Organizzazione dell'attività formativa

Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il corso era ben organizzato	0	0	0	6	8
Il corso era ben pianificato	0	0	1	6	7
Gli obiettivi formativi del corso erano chiari	0	0	1	7	6
L'attività proposta ha contribuito al raggiungimento degli obiettivi formativi	0	0	1	9	4
I materiali del corso erano ben preparati	0	0	0	7	7



id:483 — Soddisfazione per i contenuti

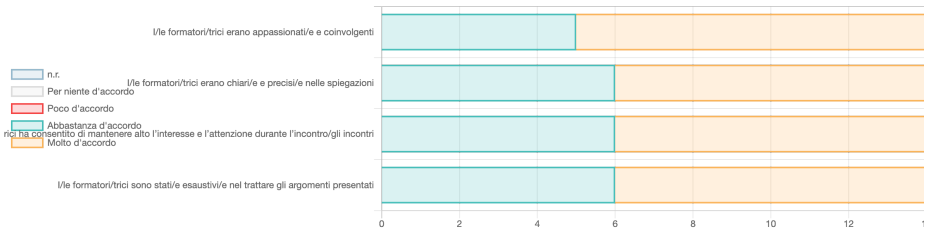
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il contenuto di questo corso mi ha motivato a seguire con interesse	0	0	0	7	7
Ho trovato il corso piacevole	0	0	0	4	10
Il corso è stato interessante	0	0	0	3	11
In questo corso ho imparato cose nuove	0	0	0	4	10



id.484

Formatori/trici

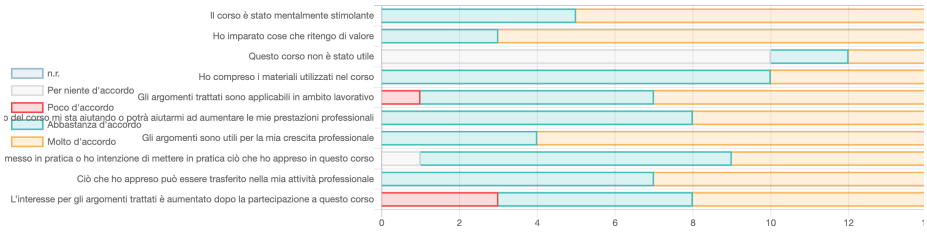
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
I/le formatori/trici erano appassionati/e e coinvolgenti	0	0	0	5	9
I/le formatori/trici erano chiari/e e precisi/e nelle spiegazioni	0	0	0	6	8
Lo stile di presentazione dei/delle formatori/trici ha consentito di mantenere alto l'interesse e l'attenzione durante l'incontro/gli incontri	0	0	0	6	8
I/le formatori/trici sono stati/e esaustivi/e nel trattare gli argomenti presentati	0	0	0	6	8



id.485

Utilità e ricadute dell'attività formativa

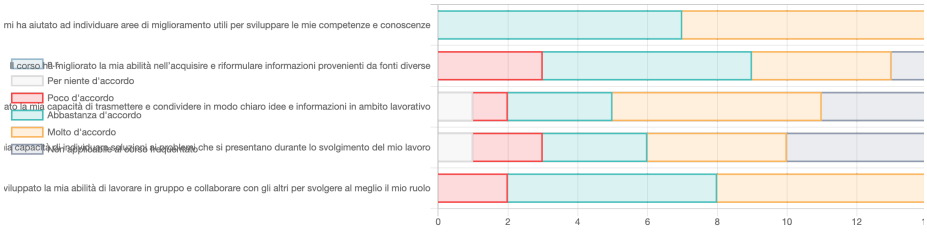
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo
Il corso è stato mentalmente stimolante	0	0	0	5	9
Ho imparato cose che ritengo di valore	0	0	0	3	11
Questo corso non è stato utile	0	10	0	2	2
Ho compreso i materiali utilizzati nel corso	0	0	0	10	4
Gli argomenti trattati sono applicabili in ambito lavorativo	0	0	1	6	7
Il contenuto del corso mi sta aiutando o potrà aiutarmi ad aumentare le mie prestazioni professionali	0	0	0	8	6
Gli argomenti sono utili per la mia crescita professionale	0	0	0	4	10
Ho già messo in pratica o ho intenzione di mettere in pratica ciò che ho appreso in questo corso	0	1	0	8	5
Ciò che ho appreso può essere trasferito nella mia attività professionale	0	0	0	7	7
L'interesse per gli argomenti trattati è aumentato dopo la partecipazione a questo corso	0	0	3	5	6



id:486

Competenze generali acquisite

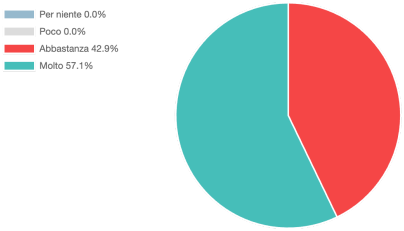
Testo opzione	n.r.	Per niente d'accordo	Poco d'accordo	Abbastanza d'accordo	Molto d'accordo	Non applicabile al corso frequentato
Il corso mi ha aiutato ad individuare aree di miglioramento utili per sviluppare le mie competenze e conoscenze	0	0	0	7	7	0
Il corso ha migliorato la mia abilità nell'acquisire e riformulare informazioni provenienti da fonti diverse	0	0	3	6	4	1
Il corso ha migliorato la mia capacità di trasmettere e condividere in modo chiaro idee e informazioni in ambito lavorativo	0	1	1	3	6	3
Il corso ha migliorato la mia capacità di individuare soluzioni ai problemi che si presentano durante lo svolgimento del mio lavoro	0	1	2	3	4	4
Il corso ha sviluppato la mia abilità di lavorare in gruppo e collaborare con gli altri per svolgere al meglio il mio ruolo	0	0	2	6	6	0



id.487

In quale misura riterrebbe utile un percorso di approfondimento sulle tematiche affrontate?

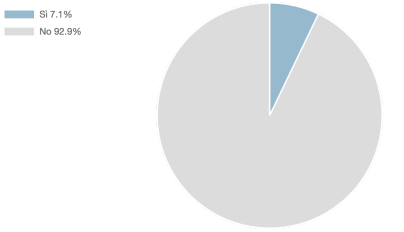
#	Testo opzione	Freq.	
1	Per niente	0	0.0%
2	Poco	0	0.0%
3	Abbastanza	6	42.9%
4	Molto	8	57.1%
	Totale	**14**	



id.488

Ci sono stati argomenti che non sono stati trattati e avresti voluto affrontare?

#	Testo opzione	Freq.	
1	Sì	1	7.1%
2	No	13	92.9%
	Totale	**14**	



id.489

Specificare brevemente gli argomenti che avresti voluto affrontare

Nessuna risposta : 1
Risposte inviate : 1

Risposte

- Ricaduta didattica dell' argomento

id.490

Spazio per commenti e osservazioni

Nessuna risposta : 1
Risposte inviate : 8

Risposte

- Forse si potrebbe approfondire ulteriormente l'aspetto della verifica delle fonti che i docenti utilizzano per documentarsi o per preparare materiali autentici da utilizzare nelle loro lezioni. Può accadere di utilizzare (anche in buona fede) materiali che non sono precisi o addirittura scientificamente non corretti, frutto di interpretazioni soggettive. Occorrerebbe che i materiali fossero vagliati da un organismo supervisore autorevole, indipendente, composto da più esperti, che ne garantisse la qualità...
- Ho apprezzato in particolare le formatrici
- Il corso è stato molto interessante .
- Il corso ha affrontato molti argomenti di interesse su una vasta gamma di discipline. Come possibile approfondimento, nel mio caso e per le materie di mio interesse, l'intervento di uno storico potrebbe dare un taglio ancora più ampio. Grazie, è stato molto interessante!
- Interessante la conferenza
- La prima parte del corso è stata troppo 'frontale' e accademica. La seconda giornata è stata molto coinvolgente e più spendibile.
- mi sarebbe piaciuto avere più tempo nella II giornata per poter avere più tempo nella fase della progettazione
- Sarebbe stato utile avere più tempo (un paio d'ore in più) per sviluppare il lavoro svolto sabato mattina.

Acknowledgements

Al termine di questo percorso, non è semplice racchiudere in poche parole la profonda gratitudine che sento verso tutte le persone che, in modi diversi, mi hanno accompagnata e hanno reso possibile questo traguardo.

Il primo ringraziamento va di cuore al mio supervisore, Stefano Oss, con cui è stato davvero un piacere lavorare in questi anni. Lo ringrazio per avermi dato la possibilità di esplorare diverse sfumature della ricerca in didattica della fisica, permettendomi di seguire curiosità e direzioni nuove con fiducia e autonomia. Per tutto questo percorso, è stato una guida costante e presente, capace di lasciarmi libertà di esplorazione senza far mai mancare orientamento e confronto.

Un sentito ringraziamento va al mio co-supervisore, Pasquale Onorato, che, nonostante il mio carattere testardo, è sempre stato disponibile e capace di spronarmi a dare sempre di più. Il suo incoraggiamento costante ha contribuito in modo significativo alla costruzione di un percorso di ricerca ricco e stimolante.

Ringrazio anche tutto il gruppo di ricerca dell'Università di Trento, presente e passato, Marco Di Mauro, Stefano Toffaletti, Luigi Gratton, Eugenio Tufino, Marica Perini, Tommaso Rosi, Alessandro Salmoiraghi, Caterina Giovanzana, Andrea Zambon, che hanno reso questo percorso non solo scientificamente ricco, ma anche umanamente significativo. Non è scontato trovare un gruppo che ti faccia sentire accolta, stimolata e accompagnata nella crescita, e per questo sono loro profondamente grata.

Un sentito ringraziamento va a IPRASE, e in particolare a Roberto Strangis e Tatiana Arrigoni, con cui ho avuto il piacere di interfacciarmi durante questo percorso. Grazie per aver creduto nel valore di questa collaborazione e per aver reso possibile un dialogo così ricco tra ricerca e pratica educativa. Grazie per la fiducia e il confronto costante, e per aver contribuito a rendere questa esperienza ancora più significativa.

Um agradecimento especial vai para as pessoas que me acolheram durante as experiências internacionais. Dentre essas, obrigada à Betina Lopes e à Valentina Piacentini da Universidade de Aveiro, obrigada à Clara Vasconcelos e à Marta Paz da Universidade do Porto, obrigada à Gloria Queiroz e à Giselle Faur da Universidade do Rio de Janeiro.

Um agradecimento sincero vai também para todas as pessoas extraordinárias que encontrei durante as minhas caminhadas nos países onde eu passei, que direto o indiretamente contribuiram nesse meu percurso.

Em cada cidade que visitei senti-me acolhida. As pessoas que encontrei souberam abrir-me não só as portas das suas universidades, mas também as das suas vidas, fazendo com que me sentisse

cada vez menos sozinha e colorindo esta experiência com momentos humanamente belíssimos.

Para além do lado humano, estas experiências foram profundamente enriquecedoras também no plano profissional, permitindo-me contactar com diferentes formas de fazer investigação, de pensar a didática e de olhar para o mundo.

Espero que, mesmo à distância, possa chegar a todas estas pessoas a minha mais profunda gratidão, juntamente com um grande e sincero abraço.

Vorrei ringraziare tutta la comunità di ricerca della *science education*, perché proprio durante conferenze e momenti di incontro ho avuto la possibilità di scoprire una comunità bellissima, fatta di persone animate dal desiderio di dialogare e di dottorandi e dottorande che cercano sempre più di costruire reti e connessioni.

In un contesto in cui individualità e competitività sono spesso incoraggiate, ho trovato invece una comunità capace di andare in direzione opposta: persone che, in modo spontaneo e generoso, mi hanno aiutata nel mio lavoro, collaborando attivamente con me oppure attraverso suggerimenti, confronti e condivisione di materiali.

Questo lavoro non sarebbe stato possibile senza il dialogo e la riflessione condivisa con ricercatrici e ricercatori, professoresse e professori, dottorandi e dottorande appartenenti ad altri gruppi di ricerca italiani, da Napoli a Bologna, da Padova a Palermo, da Torino a Bolzano.

Grazie a tutta la comunità della *science education* e, in particolare, a quella di FIS/08, per aver reso i momenti di incontro e le conferenze non solo preziose occasioni di crescita scientifica, ma anche spazi di leggerezza e divertimento.

Un ringraziamento speciale va anche alle realtà del territorio trentino che mi hanno dato l'opportunità di mettermi ulteriormente alla prova sul fronte della comunicazione della scienza: la compagnia Arditodesìo, Level Up e Glow. Grazie per avermi permesso di esplorare linguaggi, contesti e modalità diverse di fare divulgazione, arricchendo profondamente questo percorso.

È bello e profondamente significativo vedere come esistano persone e realtà che si impegnano ogni giorno per portare la scienza al maggior numero possibile di persone, valorizzandone anche la dimensione emotiva, narrativa e umana.

Un ringraziamento speciale va ad Andrea Brunello, Maura Pettoruso e Giacomo Gottardi, che hanno scelto di darmi l'opportunità di mettermi in gioco anche attraverso la recitazione, aprendomi uno spazio nuovo di espressione, crescita e scoperta.

Grazie anche a tutte le persone con cui ho condiviso questa passione, dai momenti di *Open Mike* fino allo spettacolo *Non me la sento*, per aver reso questa esperienza una parte così viva e significativa del mio percorso.

Un ulteriore ringraziamento va a Micaela Paoli, presenza costante e prezioso punto di riferimento in tutto ciò che riguarda la vita amministrativa del dottorato. Grazie per avermi tranquillizzato in ogni passaggio burocratico.

Vorrei ringraziare anche tutte le persone che ho incontrato in questi anni a Trento, diventate per me una seconda famiglia. Con loro ho condiviso il tempo libero, le pause caffè, i pranzi della domenica, i compleanni, gli allenamenti di capoeira, le risate e anche i momenti di difficoltà, trovando sempre presenza e sostegno.

Grazie per essere stati la mia rete in una città nuova, per la vostra presenza costante e per tutti i momenti condivisi che hanno reso questi anni ancora più belli.

Un ringraziamento profondissimo va, come sempre, alla mia famiglia: a mia mamma, a mio

papà e a mia sorella.

Ringrazio i miei genitori per avermi lasciata libera di andare, senza mai farmi pesare le loro preoccupazioni o il desiderio di avermi accanto. Mi hanno sostenuta nel crescere, nel costruirmi a modo mio e nel seguire la mia strada, restandomi sempre vicini e non facendomi mai mancare nulla.

Ringrazio mia sorella per esserci sempre stata, soprattutto nei momenti di bisogno, con il suo modo pratico e concreto di affrontare ogni situazione.

Alla mia famiglia devo moltissimo, molto più di quanto un semplice grazie possa esprimere.

L'ultimo ringraziamento va al mio compagno Daniel, che mi permette di vedere il mondo in maniera diversa attraverso i suoi occhi da filosofo, che mi ha permesso di esplorare una realtà culturalmente diversa dalla mia e di iniziare a comprendere le discriminazioni sistemiche che le persone nere vivono all'interno della nostra società (e non solo della nostra), e quanto sia importante prendere coscienza della nostra responsabilità storica e agire collettivamente per modificare la realtà che ci circonda, a partire anche dalla nostra quotidianità.

Grazie per aver avuto, e continuare ad avere, la pazienza di costruire con me, passo dopo passo, la nostra realtà e grazie per il supporto quotidiano.

Insomma, questo percorso di dottorato è frutto del mio lavoro, ma soprattutto dell'incontro con altre persone. In questi ringraziamenti ho sottolineato molte volte il valore umano di tutti i miei incontri; ancora una volta, e per l'ultima, ci tengo a riaffermare questo aspetto importantissimo, che mi ha permesso di apprezzare questa esperienza nella sua totalità, con i momenti di difficoltà e quelli di gioia, di fatica e di entusiasmo, di decostruzione e ricostruzione, e, più in generale, come un percorso di profonda crescita. È stato un percorso veramente bello, che mi ha dato tanto, e di questo sono immensamente grata. Grazie a tutte le persone che ne hanno fatto parte e *até à próxima*!

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Piano Nazionale di Ripresa e Resilienza (PNRR)