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"Our School's Biodiversity": Design and Evaluation of a Teaching–Learning Sequence for Prospective Primary Teacher Education

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Abstract

Species literacy and awareness is in decline among both primary students and their teachers. This is of particular concern in the context of the current unprecedented collapse in global biodiversity that threatens our wellbeing and our ability to cope with other global challenges. In this article we present a Teaching–Learning Sequence (TLS) about biodiversity implemented with Prospective Primary Teachers (PPT) designed to address this problem. The development of the TLS, centred on-campus organic learning gardens, deployed an iterative process of design, implementation, evaluation and refinement. This application of Design-Based Research methodology ultimately produced a didactic unit. We evaluated the TLS against both quantitative and qualitative criteria, including student's learning outcomes. The results show that the inquiry-centred TLS contributed to conceptual and procedural learning gains, particularly regarding invertebrate identification. Additionally, the participating PPTs reported a closer connection to and awareness of nature and biodiversity. However, specific knowledge, especially around plant taxonomy, remained low. The paper concludes by identifying a number of limitations that are being taken into account for future refinement. Specifically, activities aimed at imparting a deeper understanding of habitats, and improving knowledge on the identification and classification of living beings will be included in future iterations.

Keywords: biodiversity; design-based research; species literacy; science education; prospective primary teachers; organic learning garden; connection with nature

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1. Introduction

A substantial body of science education research demonstrates the importance of facilitating students' direct experiences in the environment. Studying animals and plants present in daily life offers a means to build towards more abstract generalisations (Ayotte-Beaudet et al., 2025). On the one hand, this strengthens student's interest in and connection with nature, as well as their understanding of specific content. On the other, it helps them build a dynamic vision of reality and internalise the complexity of environmental problems. Barrutia et al. (2022) observe that the persistent disconnection of people—including teachers and school children—from nature leads to decreased knowledge of local biodiversity. Both direct experience with nature and abstract knowledge are essential for understanding environmental

issues and adopting a sustainable lifestyle (Skarstein & Skarstein, 2020). Disconnection with nature is also an obstacle to comprehending the magnitude of current biodiversity loss (Lindemann-Matthies, 2005), one of the major socio-environmental challenges of our time.

In this context, school gardens represent an excellent opportunity for students to directly engage with the natural environment. Gardens foster well-being and provide health benefits to the entire school community (Chiumento et al., 2018). In addition, they deserve to be considered learning environments—comparable to classrooms or laboratories—in their own right (Eugenio-Gozalbo et al., 2019; Williams & Dixon, 2013). They have also been recognised as valuable educational contexts for initial teacher training (Eugenio-Gozalbo et al., 2019). Place-based educational interventions on school grounds are attracting considerable interest, as they have clear potential as fruitful, competence-based learning contexts, while simultaneously acting as tools for building ecosocial resilience in schools and communities (Aragón & Erdozain, 2025). However, a need for further evaluation remains (Rammou et al., 2024).

Given this, educators can benefit from familiarising themselves with these educational settings in order to be able to use them effectively. Teachers can act as social multipliers (King et al., 2022) and their own learning in meaningful contexts can counteract the non-experiential, classroom-based learning approach that still prevails in many schools (Ingram et al., 2024; Sherry, 2022). Incorporating university gardens into the curriculum for Primary Education degree programmes, as already demonstrated in our context (Rico et al., 2025), offers an early opportunity to experience this type of teaching and learning. The research presented in the paper, carried out with students enrolled in Primary Education at the University of the Basque Country (EHU) shows that a science education module using on-campus organic learning gardens produced improvement in participants' sustainability awareness and connection with nature.

Prospective Primary Teachers' (PPT) knowledge about ecosystems, species literacy, and their importance is often limited and disconnected from other issues such as biodiversity and ecosystem loss (Lindemann-Matthies et al., 2017; Navarro-Perez & Tidball, 2012; Skarstein & Skarstein, 2020). To address this problem, species literacy is key. Knowledge in this area is related to better conceptualisation of biodiversity and its value (Randler, 2008) and to increased support for biodiversity conservation initiatives (Barrutia et al., 2022, 2023; Bermudez & Lindemann-Matthies, 2020; Chozas et al., 2023). Moreover, several authors argue that education in topics such as biodiversity loss needs to include transformative practices, such as nature- or place-based learning, so that students can apply and transform their knowledge and skills into positive action, particularly in PPT education (Børresen et al., 2023; Genovart et al., 2013; Lindemann-Matthies et al., 2017; Randler, 2008). Following socio-constructivist principles, place-based learning in authentic contexts enables students to actively construct knowledge through direct experience and social interaction with their environment (Ayotte-Beaudet et al., 2025). Consequently, it is essential for PPT to develop their pedagogical content knowledge (PCK) concerning biodiversity through teaching approaches that integrate both the scientific content for learning/teaching and the practices they will later implement in their own classrooms (Grossman, 2018). Despite this recognised need, rigorous evaluation of TLS designs that effectively integrate content knowledge with PCK development in teachers' biodiversity education remains limited. Our research addressed this gap by applying a Design-Based Research (DBR) framework to iteratively design, implement, and evaluate a TLS titled "Our School's Biodiversity." This TLS for PPTs focused on biodiversity in the context of habitats within two on-campus organic gardens. It was grounded in constructivist and inquiry-based learning theories and integrated two fundamental aspects of PPT education that are interrelated: (a) learning scientific content through guided inquiry, that is, reaching an understanding of the concept

of biodiversity, starting from species literacy through to ecological systemic thinking; and (b) learning content-specific teaching core practices, such as the use of guided-inquiry (Rivero et al., 2011).

2. Design-Based Research for Developing a TLS About Biodiversity

We opted for DBR as a methodology to empirically refine a TLS and develop classroom intervention theories that account for contextual characteristics (Guisasola et al., 2023). DBR is a flexible methodology that draws on diverse educational theories to generate useful products and intervention theories through iterative cycles of design, implementation, assessment, and redesign (Guisasola et al., 2023).

Over the past three decades, DBR has become an established framework in science education for developing TLSs—medium-scale curriculum products that enhance student learning of specific scientific topics through sequenced teaching activities (Psillos & Kariotoglou, 2016). In DBR methodology, TLSs serve a dual purpose: they are both interventional research activities and curriculum packages containing well-researched teaching–learning activities adapted to student reasoning (Psillos & Kariotoglou, 2016). This reflects the complex, back-and-forth relationship between developing learning tools/environments and developing theory. General educational principles are applied to specific topics in specific contexts, with each phase providing opportunities to test and refine conjectures about student learning, while redesigning the TLS (Guisasola et al., 2017). The DBR methodology for TLSs consists of three general phases: (i) design, (ii) implementation and (iii) evaluation and redesign, all considering local context characteristics to create feasible TLSs (Guisasola et al., 2023) (see Figure 1).

The design phase considers the educational context and specific content while drawing on socio-constructivist cognitive psychology, the epistemology of science, and science education research findings (Guisasola et al., 2017). It involves three steps: first, defining Learning Goals (LG) through epistemological analysis and identifying learning demands—the gap between these objectives and students' existing conceptions; second, reviewing known learning difficulties within the target group; and third, applying specific design tools that systematically articulate the TLS rationale and address the identified learning demands. The end result is a comprehensive design solution that includes teaching materials, assessment guidelines, and teaching practice guidelines. The implementation phase involves classroom teaching experiments that investigate whether the design leads to better student learning. Adjustments made during implementation are considered part of the data. The evaluation and redesign phase involves retrospective analysis to assess the design solution against the stated objectives using both qualitative and quantitative tools, such as a teacher's journals, student's workbooks, external evaluator's reports, questionnaires or student interviews. This material is used to evaluate two areas: first, clarity of the sequence (whether activities were understood, time required, logistical problems), and second, students' learning outcomes (LO) (understanding of concepts, models, theories, and development of scientific skills) (Ruiz-González et al., 2025). DBR emphasises the importance of retrospective analysis to refine a TLS; that is, instead of focusing only on LO derived from an educational intervention, the framework facilitates the interrogation of explicit and implicit assumptions that affect the design and development of a TLS (Kariotoglou et al., 2003). The results from this bi-dimensional analysis prompt modifications to class material including text, analogies, representations, and the general TLS focus. This can lead to redesign and subsequent re-assessment (Psillos et al., 2016; Ruiz-González et al., 2025). TLS can be considered a product of applied scientific practice, which can evolve and adapt thanks to the adaptability of teaching and learning activities (Psillos et al., 2016).

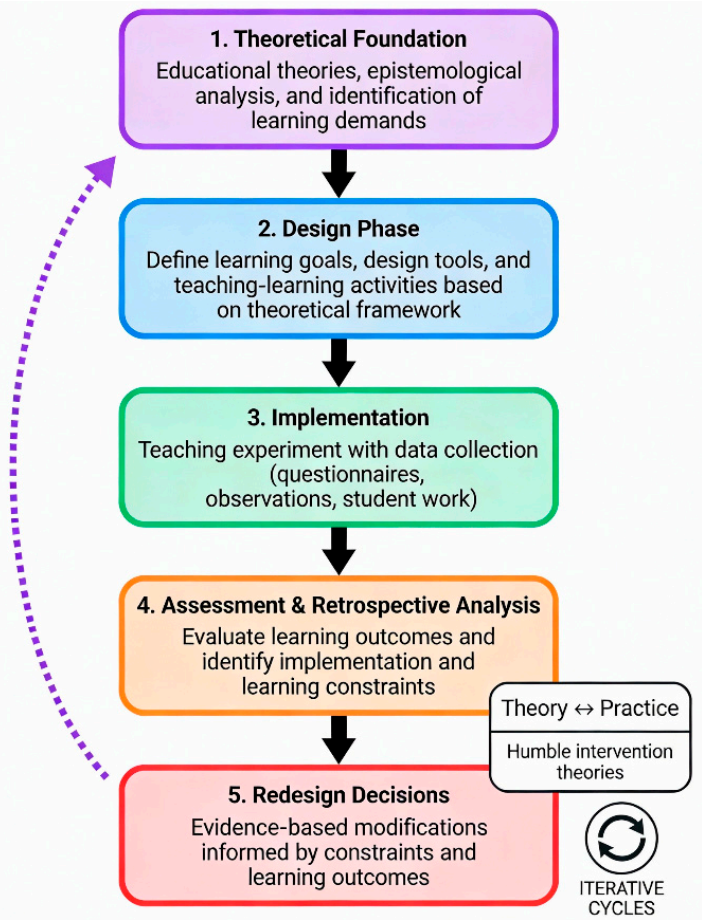


Figure 1. The iterative Design-Based Research framework applied in this study. The process begins with a review of the theoretical foundations and proceeds through design, implementation, and assessment phases. Retrospective analysis identifies constraints that inform redesign decisions, creating an iterative cycle that progressively refines the Teaching–Learning Sequence while generating contextually grounded intervention theories (Psillos & Kariotoglou, 2016; Guisasola et al., 2017).

The long-term objective of our research programme is to iteratively design, implement, and evaluate the TLS "Our School's Biodiversity" for PPTs. In this paper, we present the first iteration. In the following paragraphs, we present the design tools employed, including an epistemological analysis of the content and the identification of student difficulties and learning demands. Second, we present results from the first teaching experiment. This provides empirical data on the effectiveness of the TLS in its first iteration. Finally, we conduct a retrospective analysis of the TLS which identifies factors and assumptions that affected its development and evaluation. These reflections will inform improvements for future iterations.

2.1. Epistemological Insights

The concept of biodiversity is not generally well understood by the general public, such that the term 'biodiversity awareness disparity' has been coined to describe this phenomenon (Barrutia et al., 2022; Navarro-Perez & Tidball, 2012). According to the Convention on Biological Diversity (United Nations, 1992), biodiversity or biological diversity is "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". That is, biodiversity comprises the variety of all forms of life and is organised at several levels: genetic, species and ecosystem diversity (Campbell et al., 2020). In addition to the number

(richness) of genes, species, or ecosystems present, the biodiversity of a place is influenced by their relative abundance. For example, places with the same number of species can display varying degrees of diversity depending on whether there are dominant species (lower biodiversity) or whether there is a balance among the different species present (higher biodiversity). The different species that make up ecosystems include producers, primary, secondary and tertiary consumers, and decomposers. Each performs different functions. This functional diversity is a key consideration, as the greater the biodiversity within a functional group, the more resilient an ecosystem will be. Biodiversity is also essential for human well-being, as properly functioning ecosystems provide crucial benefits known as ecosystem services. These include water and food, climate regulation, the hydrological cycle, pollination, and recreational and aesthetic opportunities (Millennium Ecosystem Assessment, 2005).

The conservation of biodiversity is important, not only for its intrinsic value, but because the removal of a species can lead to the transformation or even collapse of the ecosystems it inhabits. Each species is unique and contributes to ecosystem functioning; however, this contribution occurs through the combined action of many species, making it difficult to isolate the impact of a single species or to predict how much biodiversity loss an ecosystem can withstand before collapsing. Despite current conservation efforts, biodiversity is in decline due to human activity. This includes processes such as habitat fragmentation and destruction, overexploitation of resources, increased pollution, intensification of agriculture and livestock farming—particularly through monospecific systems—and global warming. Together, these drivers have substantially accelerated species extinction rates, leading many authors to describe the current period as a sixth mass extinction (Cowie et al., 2022). Climate change, one of the biggest challenges of our time, is intimately bound to the biodiversity crisis (IPBES, 2022). Biodiversity loss endangers not only the conservation of ecosystems, but also the human quality of life (Millennium Ecosystem Assessment, 2005). As Pascual et al. (2023) have pointed out, a system-wide transformative change is needed to address the current global biodiversity crisis and climate emergency simultaneously. This would mean basing decisions on a global understanding of human interdependence with nature, and the complex interrelationships between different dynamics including socio-environmental problems, pollution, pandemics and environmental injustice. Values impact decision-making around biodiversity conservation. These values range from ecocentric (understanding that genetic flexibility aids survival in changing conditions), to utilitarian or anthropocentric (food, medicines, aesthetic, enjoyment) (Pascual et al., 2023).

In the development of the PPT, four key ideas shaped our approach the concept of biodiversity:

E1. Species literacy. There are millions of different living beings on Earth; some are very similar to each other, while others are very different. Living beings can be classified into different groups based on their shared characteristics and features.

E2. Habitats and ecosystems. Populations of a given species live in a specific place, which is called a habitat. The survival and reproduction of a species depends on the physical conditions and resources of this habitat. A healthy ecosystem is one in which a diversity of species are each able to meet their needs in a relatively stable web of life. Newly introduced species or other changes can damage the balance of an ecosystem.

E3. Eco-dependent beings. Our own well-being depends on the well-being of other living beings and the environment. Ecological processes interacting with the atmosphere, geosphere, and hydrosphere shape the environment on which organisms, including people, depend. Direct benefits such as food crops, clean water, clean air, and aesthetic pleasures all depend on biodiversity, as does the persistence, stability, and productivity of natural systems.

E4. Human impacts on biodiversity. Human activities have negative consequences on biodiversity due to (i) growing human population; (ii) overexploitation of natural resources; (iii) habitat destruction; (iv) pollution; (v) the introduction of invasive species and (vi) global warming. Humans can also play a positive role in sustaining biodiversity through sustainable policies and actions.

In the following sections we focus exclusively on key ideas E1 and E2 and their corresponding LGs (Table 1). These ideas were selected as representative examples to illustrate the main outcomes and insights derived from the educational intervention.

Table 1. Learning Goals for the TLS "Our School's Biodiversity" in Prospective Primary Teacher Education.

Elements from the Epistemology of Biology	Learning Goals
E1. Species literacy. There are millions of different living beings on Earth, some are very similar to each other, while others are very different. Living beings can be classified into different groups based on their shared characteristics and features.	LG.1. To understand that there are many kinds of living beings.
	LG.2. To learn to classify living beings into different groups according to their characteristics.
E2. Habitats and ecosystems. Populations of a given species live in a specific place, which is called a habitat.	LG.3. To understand the connection between living beings and specific habitats in the surrounding environment.
E3. Eco-dependent beings. Our own well-being depends on the well-being of other living beings and the environment.	LG.4. To learn about the contributions of biodiversity and ecosystems to human wellbeing and understand human's dependence on nature.
E4. Human impacts on biodiversity.	LG.5. To recognise the impacts of human beings on biodiversity and ecosystems, and understand our capacity to act on them, both positively and negatively.

2.2. Students' Difficulties and Learning Demands

The second step in the design phase of our TLS was the analysis of gaps in students' existing knowledge. These were identified through an analysis of the ontological and epistemic differences between students' ideas and the scientific concept to be taught. These differences would later guide the development of our TLS. The identification of learning demands, and related anticipation of potential difficulties, plays an important role in the design of activities, because the anticipated learning demand partially determines the number of activities (Guisasola et al., 2023; Ruiz-González et al., 2025). In this section, we describe the learning difficulties and demands for LGs 1, 2 and 3 (see Table 2). The associated activities and evaluation are further discussed in the following sections (see Table 3).

Regarding learning difficulties, the literature suggests that species literacy is often impacted by misconceptions that are shared by secondary students, undergraduate students and prospective teachers alike. For example, students tend to define biodiversity as the diversity of living beings, understood as the number of species or living beings and, therefore, confuse species richness with biodiversity (Bermudez & Lindemann-Matthies, 2020). Furthermore, they tend to ignore genetic diversity as an integral part of biodiversity, and even educators do not tend to acknowledge the multi-scalar dimension of biodiversity (Fiebelkorn & Menzel, 2013). When investigating young students' knowledge about the diversity of living beings, Barrutia et al. (2022) observed that their knowledge was limited,

identifying mammals first when listing living beings and showing native species and plant awareness disparity (Barrutia et al., 2022; Pedrera et al., 2021). The authors suggest that this so-called "extinction of experience" (Lindemann-Matthies et al., 2017; Miller, 2005) could be responsible for the reduction in their knowledge of local organisms and lead to disaffection with and apathy towards nature. Tergenbayeva et al. (2023) have suggested that a lack of holistic environmental education and incomplete or inaccurate species literacy education contribute to the general prevalence of insufficient knowledge and awareness of biodiversity among prospective primary and secondary teachers. We found that the species literacy and identification skills of the PPTs who participated in our research were akin to those of their future students (Burgoon & Duran, 2012; Lindemann-Matthies et al., 2017).

Table 2. Alignment of learning difficulties with Learning Goals 1, 2 and 3 and identification of learning demands for a TLS about biodiversity in Prospective Primary Teacher Education.

Learning Difficulties	Learning Goals *	Learning Demand
- Biodiversity as number of species only (Bermudez & Lindemann-Matthies, 2020) - Native species awareness disparity (Barrutia et al., 2022) - Plant awareness disparity (Lindemann-Matthies et al., 2017)	LG.1.	Medium
- Difficulties in biological classification of plants, invertebrates, amphibians and reptiles (Burgoon & Duran, 2012; Lindemann-Matthies et al., 2017)	LG.2.	Low
- Limited knowledge about habitats makes it difficult to relate a specific living being to a habitat (Marulcu, 2014; Savvaidou-Kambouropoulou & Skoumios, 2012)	LG.3.	Medium

* Learning Goals are described in Tables 1 and 3.

Table 3. Driving Question and sequence of activities for the Learning Goals 1, 2 and 3 of the TLS "Our School's Biodiversity" for PPT.

Driving Question	Learning Goals	Strategies to Foster Learning	Activities
DQ1. What kind of living beings can we find in our school garden, and where can we find them?	LG.1. To understand that there are many kinds of living beings LG.2. To learn to classify living beings into different groups according to their characteristics LG.3. To understand the connection between living beings and specific habitats in the surrounding environment	A. Make student's prior knowledge explicit. B. Place-based learning C. Open inquiry: sampling, observation, identification and classification as scientific practices D. Guided inquiry: Observation, under a digital magnifying glass and microscope, of the distinctive characteristics of the specimens found in the school microhabitats	**A0-Questionnaire of initial ideas *** **A1 Let's find living beings in our school garden** 1.1. Identification of habitats 1.2. Sampling and annotation of specimens in each habitat 1.3. Examination of microscopic specimens from microhabitats (moss, soil, pond)

* See Section 4.3.

Furthermore, children's understanding of the biological classification of plants and animals is poor. For example, children classify bats as birds, and sea turtles and crocodiles as amphibians (Yen et al., 2004). These authors have also shown that students' conceptions of invertebrates, amphibians, and reptiles is problematic. Other research has shown that, among secondary students, exotic species are better known than local fauna (Almeida et al., 2020; Genovart et al., 2013). This could explain why the prevailing criteria for conservation among students of all ages are visual attractiveness, size, usefulness to humans and domestication in the case of animals, and sources of food and medicine in the case of

plants (Lindemann-Matthies, 2005). Genovart et al. (2013) have also shown that primary school students associate wildlife and its conservation with exotic species.

Finally, several studies have shown that students' conceptions of habitats are incomplete, vague or inaccurate (Marulcu, 2014; Savvaidou-Kambouropoulou & Skoumios, 2012). Lock (1996) found that, in a freshwater environment, students could identify fewer plants and invertebrates than vertebrates such as fish or amphibians. Savvaidou-Kambouropoulou and Skoumios (2012) have attributed these shortcomings to a lack of time spent outdoors.

Based on the limitations described above, we anticipated the learning demands shown in Table 2.

The relationship between people and nature, linked to key ideas 4 and 5 (Table 1), should also be addressed in discussions about biodiversity. Biodiversity conservation is a relevant concern with respect to environmental, economic, and political issues. As such, it is vital to communicate its inherent value, its importance in ecosystems, and its contribution to human well-being (Millennium Ecosystem Assessment, 2005). Ottogalli and Bermudez (2024) reviewed prospective teachers' PCK on biodiversity and concluded that PPTs in general understand biodiversity from a biological point of view (taxonomic, ecosystemic, genetic) and disregard sociocultural, philosophical, economic, and political considerations. In our context, Rodríguez-Loinaz and Palacios-Agundez (2024) have shown that PPTs are not generally able to identify many of the contributions that nature provides to people.

2.3. Methodological Considerations: Guided Inquiry in the School Garden as a Framework for Teaching and Learning About Biodiversity

The integration of guided inquiry within on-campus gardens provides a powerful pedagogical framework for PPT education in biodiversity. School gardens enable learners to encounter biodiversity as a living, evolving reality, linking abstract ecological concepts to direct, empirical experience (Eugenio-Gozalbo & Ortega-Cubero, 2024). This aligns with constructivist educational theory which emphasises lived experience and allows PPTs to situate new learning within prior conceptual frameworks. This fosters a conceptual shift and the development of ecological literacy grounded in real contexts (Ayotte-Beaudet et al., 2025; Doychinova, 2023).

Within this framework, guided inquiry is structured around oriented research activities that reproduce aspects of scientific practice that students are to become familiar with. The instructor's role shifts from transmitter of knowledge to mediator of learning, facilitating students' engagement in processes that emulate scientific reasoning. This pedagogical approach not only enhances conceptual understanding but also fosters epistemic agency and prepares future educators to guide inquiry-based science learning in primary classrooms (Grossman, 2018; Rivero et al., 2011).

Existing research on experiential learning about biodiversity highlights the importance of direct interaction with living organisms. Learners engaged in hands-on, group-based identification and observation activities demonstrate higher retention and deeper conceptual gains than those who receive teacher-centred or screen-based instruction (Lindemann-Matthies et al., 2017; Scott et al., 2012). Species identification is central to the comprehension of ecological concepts, of nature and of our place in it (Lindemann-Matthies et al., 2017; Randler, 2008). However, research suggests that teachers' generally limited taxonomic knowledge undermines their capacity to facilitate such learning. This signals a need to reinforce knowledge of biodiversity and taxonomy within initial teacher education (Lindemann-Matthies et al., 2017; Tergenbayeva et al., 2023). Integrating inquiry with experiential learning has the potential to strengthen biodiversity and taxonomy literacy and harness PPTs' ecological empathy and a sense of moral responsibility toward nature (Aragón & Erdozain, 2025; Otto & Pensini, 2017).

The "Our School's Biodiversity" TLS takes an experiential approach to the concept of biodiversity through guided inquiry using school gardens as a teaching–learning context. Setting out from students' initial mental models of living beings, participants proceed to investigate local biodiversity by taking samples of living beings from different habitats found within an on-campus organic garden.

The TLS also includes: (i) Driving Questions (DQ) that guide students' process of inquiry and that are linked to the key ideas about biodiversity; (ii) the LG linked to each DQ and related set of activities (Table 3), aimed to help students construct their own understandings of each key idea about biodiversity; and (iii) the scientific procedures carried out by the participants. Participants were organised into groups of four and were asked to record their observations in their students' workbook (for specific details on the activities and scientific practices, see Palacios Agúndez et al., 2023). Table 3 shows the DQs and the sets of activities linked to LGs 1–3.

The initial ideas questionnaire and subsequent open discussion lead students to formulate answers to the first DQ of the TLS. They predicted what species they would find and where before visiting the school garden. Once in the garden, students worked in groups of four to study the habitats and living beings in situ, taking field notes and photographs of the process. They collected and analysed samples of soil, moss, and water, and, subsequently, analysed them in the laboratory using magnifying glasses and microscopes to discover the 'hidden biodiversity'. To stress the importance of biodiversity conservation and encourage respectful attitudes, we remind students that they should observe living beings and collect samples with care and respect.

The identification and classification of living beings found in different habitats allowed students to expand their initial conception of living beings and become familiar with different taxonomic categories of scientific classification. Additionally, students documented each habitat they identified with a photo and description. This helped them deepen their knowledge of biodiversity by learning to associate different living beings with each habitat.

This guided inquiry included observation, exploration, analysis, and identification, complemented by an analysis of biodiversity's importance in our lives. To this end, students explored key concepts such as species uniqueness and ecosystem services. We have described activities carried out for the remaining LG of the TLS in other published research; these included a class discussion about the importance of invertebrates for human well-being (see Palacios Agúndez et al., 2023), an evaluation of human impacts on freshwater ecosystems through macroinvertebrate monitoring, and application and evaluation activities that included publishing a Wikipedia article about a living being or creating a poster of school habitats and their organisms (see Supplementary Table S1; Rico et al., 2026; Rodríguez-Loinaz, 2017).

3. Objectives of the Study

DBR is now established as a robust methodology to empirically refine TLSs in a context-dependent manner. Similarly, a growing body of literature recognises science learning in school gardens as a paradigm for meaningful and authentic learning both for young students and future teachers. However, few rigorous evaluations of the effectiveness of educational interventions that follow the approach described in the previous sections have been carried out. In response to this gap in the literature, the objectives of our research were:

(1) To evaluate the impact of a Teaching–Learning Sequence (TLS) about biodiversity directed at PPTs, contextualised in the habitats of a university organic garden, on participants' connection with nature and their biodiversity literacy (through taxonomy tasks).

(2) To identify any significant implementation and learning constraints through a retrospective analysis and propose a redesign of the TLS based on these findings.

To achieve these objectives, we posed the following research questions:

RQ1: To what extent does a TLS contextualised in school garden habitats improve PPTs' biodiversity literacy (ability to carry out biological identification and classification) and connection with nature from pre- to post-intervention?

RQ2: Which implementation and learning constraints emerge from a retrospective analysis, and how might these inform further refinement and improvement of the TLS?

4. Methodology

4.1. Educational and Curricular Context

The TLS was designed to be carried out with students enrolled in the first year of a Primary Education degree at two different campuses of the University of the Basque Country (EHU). Specifically, the TLS was part of the compulsory 6 ECTS course "Natural Sciences in the Primary Education Classroom I". This course is one of the two compulsory science education subjects included in the Primary Education Degree programme. There are no area-specific prerequisites required to enrol in the degree program, and as a result the level of science education in the student body is diverse but generally low: less than half of the enrolled students had studied biology in their last two years of upper secondary education (ages 16 to 18). The syllabus of the course includes an introduction to the nature of science and PCK about biological sciences for primary teachers. There is an emphasis on constructivist science education and conceptual change. The specific topic of biodiversity incorporates the conceptual model of living beings, ecosystems and the interdependence of humans and nature. The TLS "Our School's Biodiversity" addressed this area and involved experiential learning about biodiversity in different environments, including the on-campus organic learning gardens (Figure 2) and the science laboratory.



(**a**) (**b**)

Figure 2. Organic learning gardens at the University of the Basque Country (EHU)] (**a**) Araba Campus in Vitoria-Gasteiz; (**b**) Bizkaia Campus in Leioa. Further details of garden a can be found at www.hazicampusa.eus. Source: Photograph by the authors.

Our on-campus organic learning gardens are organised into cultivated areas in raised beds. They each include a pond, composting areas, and semi-natural zones. These gardens host a wide range of organisms, including small vertebrates (e.g., mice, slowworm, lizards, and small toads), a high diversity of invertebrates (e.g., earthworms, several species of snails and slugs, spiders, centipedes, odonata, coleopterans, ephemeropterans, mayflies, hymenoptera. . .), as well as a rich cryptic biodiversity in moss, soil, and water (tardigrades, rotifers, nematodes, protozoans, copepods, daphnia, mites, insect larvae). Fungal diversity includes lichens, bracket fungi, and small mushrooms, while the plant community comprises both cultivated species typical of Atlantic horticultural systems and aromatic plants (e.g., tomato, lettuce, chard, peas, spring onions, peppers, lavender, comfrey, marigolds),

and a rich assemblage of spontaneous herbaceous plants (e.g., clovers, orchids, buttercups, daisies, various grasses), as well as trees and bushes (e.g., rose bush, wild olive, apple trees, plum trees, etc.).

4.2. Participants

The intervention was carried out in the Basque Country (Spain), during the 2023/2024 academic year. The initial sample consisted of 298 students enrolled in the Primary Education Degree at Faculty of Education of Bilbao and the Faculty of Education and Sport, located in Vitoria-Gasteiz. The students were distributed across 14 class groups, taught by the fauthors of the study. The language of instruction was Basque except for one group that was taught in English.

4.3. Instruments

The evaluation of the LO followed a quasi-experimental pre–post design. First, a pre-questionnaire was developed to explore students' initial ideas and existing knowledge of biodiversity. This instrument was administered one week before the beginning of the educational intervention. Subsequently, one week after the completion of the intervention, a post-questionnaire was used to assess the LO and the impact of the teaching–learning process.

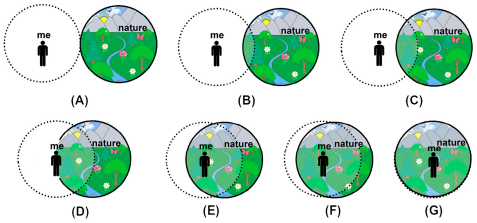
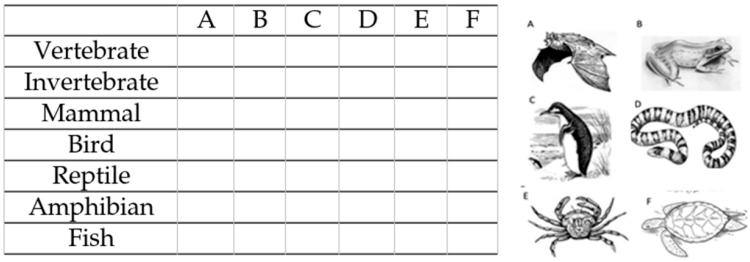
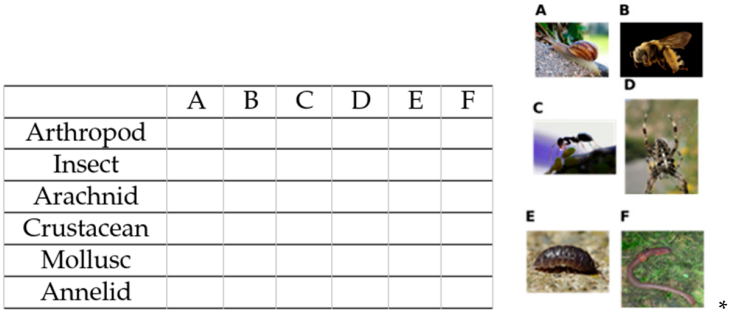
Although the two questionnaires were not identical, they included a set of common questions that enabled a comparative analysis of students' responses before and after the intervention. The present paper focuses on the results derived from the analysis of five of these common questions and a question included only in the post-questionnaire that asked students to self-report their learnings across all the LGs (see Table 4).

The assessment instrument was designed to capture different dimensions of learning, including attitudinal, cognitive, and procedural aspects. Students' attitudinal LO, specifically their connection with nature, were assessed using a pictorial task in which students selected the image that best represented their relationship with nature. This question was based on an instrument developed by Kleespies et al. (2021), grounded in the theoretical framework proposed by Schultz (2002), and has been widely used to assess depth of connection in human–nature relationships. Despite its simplicity, the instrument has been shown to provide valuable insight with diverse audiences, including university students. It has also been correlated with environmental attitudes and pro-environmental behaviours (Kleespies et al., 2021; Pérez-López et al., 2020), a finding that reinforces its validity. Further, results using this indicator show a strong correlation with those produced through other established measures of connection to nature, including the Connectedness to Nature Scale (Kleespies et al., 2021).

LO related to knowledge of biology and classification skills were assessed through a set of tasks requiring students to identify and classify living organisms. Knowledge of local biodiversity was explored by asking students to list living beings from their surroundings, a task commonly used to assess familiarity with biodiversity in educational contexts (e.g., Barrutia et al., 2022). In addition, students' understanding of living being classification was evaluated with three tasks: general classification of animals, specific classification of invertebrate animals, and general classification of plants. Animal classification, specifically the distinction between vertebrates and invertebrates and the classification of vertebrates, was assessed using an instrument developed by Burgoon and Duran (2012) that is based on a classification activity originally developed by Ryman (1974). This implement has been used across multiple educational contexts and age groups, making it a good choice for evaluating conceptual understanding in this domain (Burgoon & Duran, 2012; Ryman, 1974). For the classification of invertebrates and plants in our research, instruments were designed ad hoc, following the structure and classification logic proposed by Burgoon

and Duran (2012). Content validity was established through expert review by two science education researchers who specialised in biodiversity education, and who confirmed that the items adequately represented taxonomic knowledge for the target population. While these instruments have not undergone formal psychometric validation, they were based on established classification task frameworks and aligned with the Learning Goals of the TLS. All three tasks included a visual depiction of different animals or plants. Students were directed to choose the correct taxonomic group for each species represented.

Table 4. Evaluation questions and alignment with the Learning Goals.

Question/Task	Evaluated Topic	References
Q1. Please circle the picture below that best describes your relationship with the natural environment. 	Connection with nature	(Kleespies et al., 2021; Schultz, 2002)
Q2. Please make a list of 10 living beings from your surroundings.	Knowledge of local biodiversity (LG.1)	(Barrutia et al., 2022)
Q3a. Classify these animals using the categories in the table. 	Classification of animals as vertebrates or invertebrates (LG.2) Classification of vertebrates (Class; LG.2)	(Burgoon & Duran, 2012)
Q3b. Classify these animals using the categories in the table. 	Classification of invertebrates (Phylum; LG.2) Classification of arthropods (Class; LG.2)	This study
Q3c. Classify these plants using the categories in the table. 	Classification of plants as vascular or non-vascular (Clade; LG.2) Classification of plants as seed or seedless plant (Clade; LG.2) Classification of seed plants as angiosperm and gymnosperm (Clade; LG.2)	This study
Q4. Could you describe the most important or relevant things that you learned through the project?	Perceived learning (LG.1–5)	This study

	A	B	C	D	E	F
Vertebrate						
Invertebrate						
Mammal						
Bird						
Reptile						
Amphibian						
Fish						

	A	B	C	D	E	F
Arthropod						
Insect						
Arachnid						
Crustacean						
Mollusc						
Annelid						

	A	B	C	D
Vascular				
Non-vascular				
With seeds				
Without seeds				
Angiosperm				
Gymnosperm				

* Source of the images: Wikipedia commons.

Finally, we explored perceived LO across cognitive, attitudinal, and procedural dimensions through an open-ended reflective question, which asked students to describe the most important or relevant things they had learned during the project. This qualitative data complemented the quantitative analysis by providing insight into students' own perceptions of their learning process.

4.4. Data Analysis to Evaluate the Effect of the TLS on Students' Learning Outcomes

The evaluation of LO was conducted using data only from those participants who completed both the pre- and post-questionnaires (N = 196). This criterion ensured the reliability and comparability of the results by including only students with complete paired data sets for the analysis. Quantitative data were analysed using SPSS (version 28.0.1.1.(14)). Statistical significance was set at $\alpha = 0.05$ for all analyses and when necessary, effect sizes are reported to provide information about the magnitude of observed changes beyond statistical significance. Specific analyses are detailed for each task.

4.4.1. Connection with Nature

For the pictorial task, frequencies for each level of the scale were calculated pre- and post-implementation.

4.4.2. Knowledge of Local Biodiversity

The species listed by the students were classified into their corresponding taxonomic groups. All species were first classified by kingdom. Within the Animalia kingdom, organisms were further divided into vertebrates and invertebrates. Invertebrates were classified at the level of phylum, while vertebrates were classified at the level of class. Species belonging to the Plantae kingdom were classified according to their major taxonomic clades, distinguishing bryophytes, pteridophytes and spermatophytes. The organisms that could not be assigned to the pre-defined groups were labelled as Other (e.g., microbes or tardigrades) or, when generic terms such as animal or plant were listed, as undefined. Only species that were listed by at least 2.5% of the students (N = 5) were considered for the analysis. The data was organised hierarchically as a set of nested rectangles using the treemap function of RawGraphs (Mauri et al., 2017), where the number of occurrences of each branch node and its leaf nodes is represented.

4.4.3. Living Beings Classification Tasks

Participants' responses to the classification tasks were coded as either correct or incorrect. For each task, each student could score a maximum of 12 points (Table 5).

Table 5. Structure of classification exercises and scoring criteria.

Task	Classification Criteria	N. Organisms	Maximum Score
1	Vertebrate/Invertebrate Class *	6	12 (6 × 2 criteria)
2	Phylum Class **	6	12 (6 × 2 criteria)
3	Seed/seedless Vascular/non-vascular Taxonomic classification: gymnosperms and angiosperms ***	4	12 (4 × 3 criteria)

* In the case of the crab, the correct response was "no selection". ** In the case of the snails and earthworm, the correct response was "no selection". *** In the case of moss and the fern, the correct response was "no selection".

Prior to the analysis, the scores obtained in each classification task and the total score were converted to a 0–10 scale to facilitate comparison and interpretation. The transformed scores were compared using paired analyses to determine whether there were statistically significant differences between the pre- and post-intervention results. In addition to the significance testing, effect sizes were calculated to assess the magnitude of the observed changes. Given that the data did not meet the assumption of normality, the Wilcoxon signed-rank test was applied, and the corresponding effect size, Rosenthal's r was calculated. Furthermore, to facilitate the interpretation of the effect size and enhance comparability across related research, Cohen's d was also calculated.

4.4.4. Self-Reported Learnings

Self-reported learnings were analysed qualitatively using a phenomenographic approach (Marton & Pang, 2008). To conduct this analysis, the answers provided to the open-ended question Q4-"Could you describe the most important or relevant things that you have learned through the project?" in the post-questionnaire were examined by the four authors of this study, through a process described below.

The analysis began with a familiarisation phase, in which one author analysed the responses from one third of the sample, randomly selected, to become immersed in the data and to identify preliminary patterns in the reported LO. Based on this initial analysis, this author proposed a set of 13 preliminary LO categories, which were subsequently reviewed and discussed with the other three authors. Once agreement was reached on this initial categorisation, three authors independently examined the full set of responses and identified the categories present in each individual answer. Following this stage, these three authors jointly refined the categories. This final set of six categories was then contrasted and discussed with the remaining author. After redefining the six proposed categories, two authors re-analysed all responses, assigning each response to one of the final categories. The classifications produced by these two authors were then compared to assess inter-rater agreement, providing an additional measure of the reliability of the analysis. The inter-rater agreement between these two authors gave a Cohen's Kappa value of 0.77 (substantial agreement). Finally, these researchers met to discuss and resolve the discrepancies until full consensus was reached. This analysis resulted in the identification of six explanatory categories of self-reported learnings, which each had a different level of complexity (see Section 5.1).

4.5. Retrospective Analysis to Evaluate Implementation and Learning Constraints of the TLS

Following DBR methodology (Guisasola et al., 2017; Ruiz-González et al., 2025), we conducted a retrospective analysis immediately following the teaching experiment to identify factors and assumptions that affected TLS development and implementation. Kariotoglou et al. (2003) classify constraints in TLS design as educational, material, or scientific. Building on this framework, our analysis examined two complementary dimensions: (a) implementation constraints, focusing on activity clarity, time allocation, and pedagogical feasibility; and (b) learning constraints, examining students' difficulties in achieving the LG.

In order to assess implementation, we analysed the teacher's journals (which included observations recorded by the authors during each session), students' workbooks (in which we observed completion patterns and difficulties), and notes taken during the post-implementation meeting in which the four authors of this study participated (these captured reflections on practical challenges). These qualitative data were analysed thematically to identify recurring patterns of difficulty, which were then categorised following

Kariotoglou et al.'s (2003) framework and linked to specific LGs. To assess learning, we drew on the LO analysis described in Section 4.4.

Data from both areas were systematically cross-examined to determine whether learning difficulties stemmed from design flaws, implementation issues, or content complexity. For each constraint, we examined which LG were affected, whether it was documented across multiple data sources, and its relationship to student LO. This triangulation process is summarised in Section 5.2, which presents identified constraints alongside corresponding redesign decisions. The analysis was conducted collaboratively by the research team, with findings validated in post-implementation meetings to ensure that redesign decisions addressed both practical feasibility and educational effectiveness.

5. Results

5.1. Evaluation of the Effect of the Sequence on Students' Connection with Nature and Their Biodiversity Literacy

5.1.1. Connection with Nature

Following the implementation of the educational intervention, substantial changes were observed in the sense of connection with nature reported by students (Figure 3). Before the educational experience, 46% of students reported having a close connection with nature (categories E-F-G). After the intervention, this percentage rose to 62%, representing an increase of 16 percentage points. Furthermore, 68% of all participants expressed a stronger connection with the natural environment following the intervention.

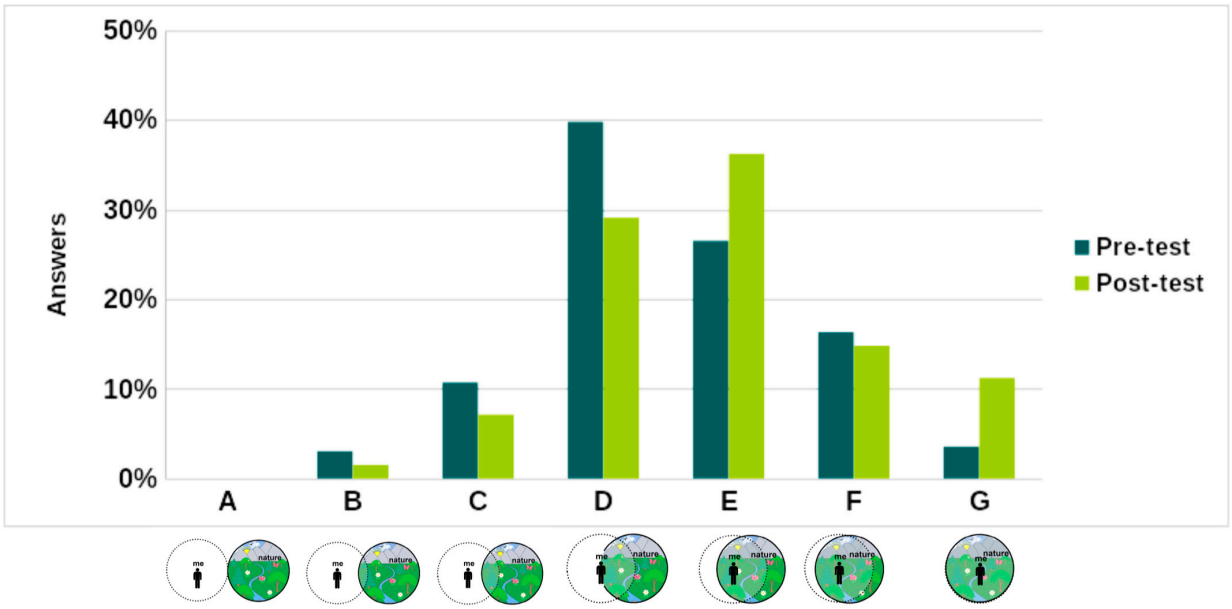


Figure 3. Sense of connection with nature expressed by students before and after the intervention. Each letter corresponds to the diagram below, which shows varying degrees of sense of connection with nature.

A comparative analysis of the categories shown in Figure 3 revealed a reduction in low and medium levels of connection, accompanied by a marked increase in higher levels. Overall, these results indicate that the intervention had a positive impact on students' sense of connection with nature.

5.1.2. Knowledge of Local Biodiversity

Students were asked to list 10 organisms that live around them before and after the educational intervention. Prior to the intervention, 196 students gave 1960 responses.

Following their participation, this number rose to 2004, which shows that the overwhelming majority (95%) were able to complete a list with 10 names. Around 25% (pre-intervention) and 30% (post-intervention) gave more than 10 responses (<16 responses).

By kingdom, animals predominated and constituted more than two thirds of the responses both pre- and post-participation. "Dog", "cat" and "human" were the top three most listed animals before the intervention, while afterwards, "worm" took the third place followed by "human". There was also a surge in the mentions of invertebrates after the intervention, from 160 to 442, which represents an increase of 25% (Figure 4). The representation of invertebrates was also more diverse, with a larger number of arthropods ("bee", "spider", "butterfly"), the addition of "centipedes", and an increase in the mentions of annelids and molluscs. Regarding vertebrates, the complexity increased after the intervention, to the detriment of mammals (a decrease of 22%) in favour of amphibians ("frog", "toad") and reptiles ("snake", "lizard"). This data shows that the intervention had a positive impact as students recognised more invertebrates and a greater diversity within the animal kingdom.

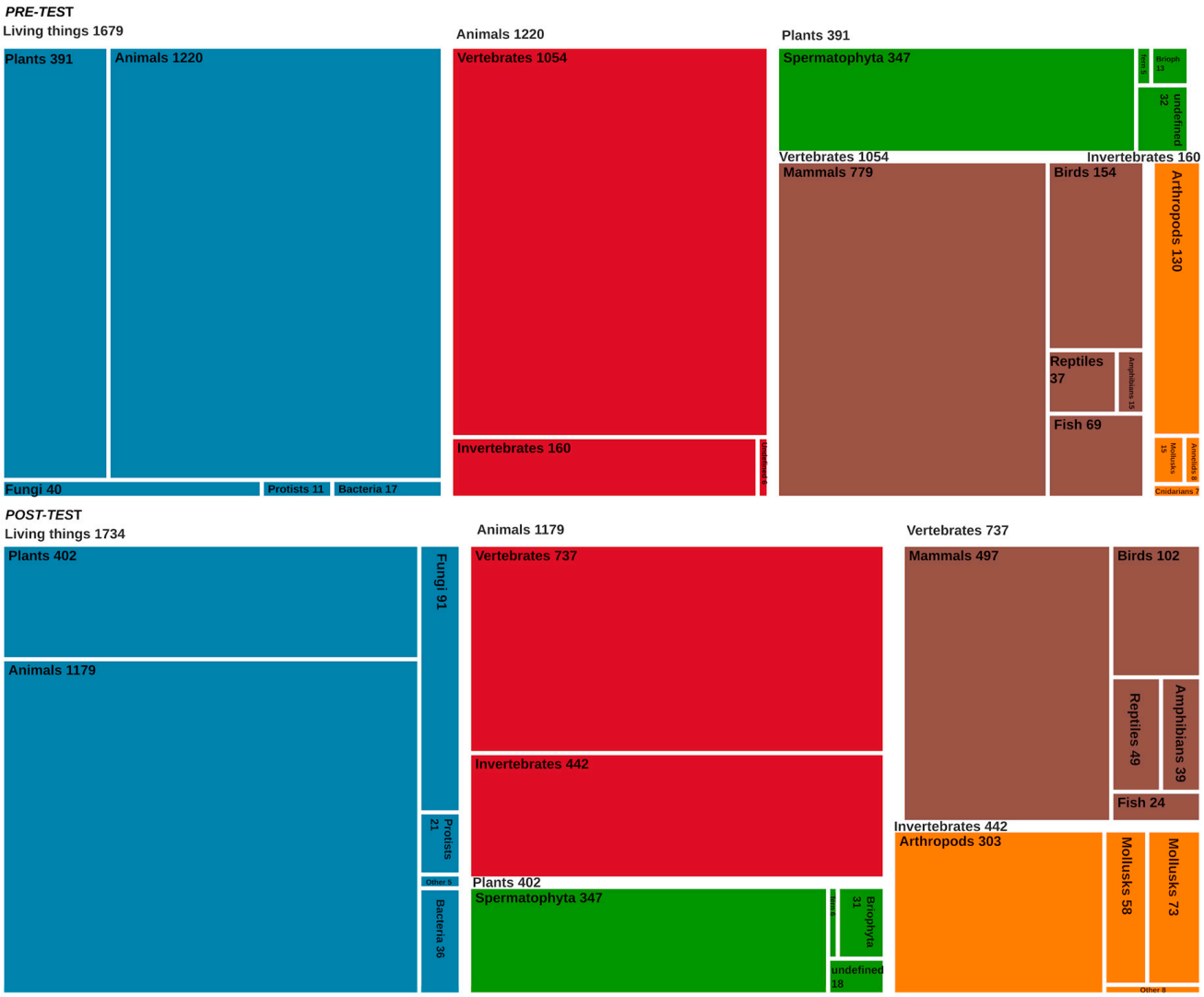


Figure 4. Treemap showing a hierarchical organisation of listed living beings by taxonomic categories before and after the educational intervention. Each category is represented by nested rectangles, and the size of the area represents its numerical value. Blue boxes represent living things of any kingdom, red boxes represent animals, green boxes represent plants, brown boxes represent vertebrate animals and orange boxes represent invertebrate animals.

Plants did not feature prominently in student's listings and represented around 20% of mentions both before and after the intervention. Before the intervention, generic terms such as "tree", "flower", "grass" or "plant" were common (20% of all plants), and two thirds of the mentions belonged to spermatophytes. In fact, trees such as "oak", "beech" and "pine" were the most mentioned species. Plants belonging to Pteridophyta, such as the common fern, or Briophyta, such as moss, were mentioned very infrequently. After the intervention, mentions of "moss" (Briophyta) increased by 4%, and, although there was no change in the most commonly mentioned species, the use of generic terms decreased by 5%.

Regarding other taxa, Fungi, Protists and Bacteria were named more often after the intervention (Figure 4), specifically lichens, yeasts and mushrooms.

5.1.3. Classification Tasks of Living Beings

Before the educational intervention, students already demonstrated a moderate to high level of prior knowledge in several classification tasks, such as the classification of animals as vertebrates or invertebrates, of plants as seed or seedless plants and the classification of arthropods' classes (Table 6). This suggests that these concepts were relatively well established among participants before the intervention. However, notable conceptual difficulties were identified with other taxonomic distinctions, particularly the classification of plants as angiosperms and gymnosperms and the classification of invertebrates by phylum (Table 6). The classification of some vertebrates by class, such as snakes and bats, also proved difficult (Table 7).

Table 6. Students' mean scores (out of 10) ± standard deviation by classification category before and after the intervention. The Cohen's d coefficient and *p*-values and Rosenthal's r coefficient obtained in a paired-Wilcoxon's test are shown.

Evaluated Category	Before	After	*p*-Value	Rosenthal's r	Cohen's d
Classification of animals in vertebrates and invertebrates	7.2 ± 2.7	8.2 ± 2.1	<0.001	−0.35	−0.34
Classification of vertebrates (Class)	6.5 ± 2.4	7.8 ± 2.0	<0.001	−0.46	−0.53
Classification of invertebrates (Phylum)	4.3 ± 2.2	5.2 ± 2.4	<0.001	−0.25	−0.26
Classification of arthropods (Class)	8.0 ± 1.5	8.3 ± 1.5	0.011	−0.17	−0.15
Classification of plants in vascular and non-vascular	5.5 ± 3.9	6.9 ± 3.4	<0.001	−0.26	−0.26
Classification of plants in seed and seedless	7.4 ± 3.1	8.1 ± 2.8	<0.001	−0.19	−0.19
Classification of angiosperms and gymnosperms plants	3.6 ± 1.9	4.6 ± 2.9	<0.001	−0.29	−0.30
Final score	6.2 ± 1.3	7.1 ± 1.2	<0.001	−0.56	−0.65

Table 7. Common errors related to the classification of living beings before and after the intervention.

Organism	Type of Errors	Before (%)	After (%)
Snake	Classified as invertebrate	51	40
Crab	Classified as vertebrate	29	21
Bat	Classified as bird or hybrid (bird–mammal)	40	22
Crab	Classified as fish	36	22
Penguin	Classified as mammal or hybrid (bird–mammal)	23	15
Bee	Not classified as arthropod	79	67
Ant	Not classified as arthropod	74	57
Spider	Not classified as arthropod	75	69
Woodlouse	Not classified as arthropod	62	60
Woodlouse	Misclassified as insect	31	10
Oak	Classified as gymnosperm	47	36
Moss	Classified as gymnosperm or angiosperm	60	68
Fern	Classified as gymnosperm or angiosperm	65	66

Following the educational intervention, the results obtained from all classification tasks show a statistically significant improvement ($p < 0.05$) in students' performance across all categories analysed (Table 6). The average was approximately 10%, indicating an overall improvement in students' understanding and differentiation of major groups of living organisms. The most notable progress was observed in the classification of vertebrates and in the differentiation between vascular and non-vascular plants. In contrast, although the improvement in the classification of arthropods by class and the classification of plants in seed and seedless, was also statistically significant ($p < 0.05$), the associated effect size was small ($r < -0.2$), suggesting more modest learning gains in this area.

Despite the overall improvement, the results indicate that the two main conceptual difficulties detected prior to the intervention persisted among students. After the intervention, students continued to demonstrate limited understanding when categorising plants as angiosperms or gymnosperms, and invertebrates by Phylum (Table 6). Regarding specific classification errors, in the case of invertebrate classification by phylum, the most frequent difficulties were related to the failure to identify bees, ants, spiders, and woodlouse as arthropods (Table 7). In relation to plant classification, the results also revealed the persistence of recurrent mistakes regarding mainly the miss-classification of moss and ferns as angiosperms and gymnosperms. Finally, although the differentiation between vertebrates and invertebrates was generally high before and after the educational intervention, several recurrent errors, such as misidentifying snakes as invertebrates or crabs as vertebrates were also identified.

5.1.4. Students' Self-Reported Learning

The post-questionnaire included an open-ended question that asked students to briefly describe, using concepts (words) or short sentences, what were the most important or relevant things that they learned through the TLS "Our School's Biodiversity". The answers were classified in categories based on their complexity, and whether there were links with the key ideas and LG established in the TLS (Table 8).

Around 40% of the students described concepts and practices related to identification and classification of living beings in specific garden habitats (A categories), but only 9% of this group also reflected on the importance of biodiversity (A1), including ideas such as interdependence between species, as follows "We learned about the critical role biodiversity plays in healthy ecosystems and supporting life on Earth" and "that the acquisition of knowledge about biodiversity is fundamental to understand the functioning of life on the planet and our dependence on ecosystems for survival"; or ideas about bioindicators "it [about biodiversity] gives us a lot of information about the environment that is very useful and this has been something new for me". Many students stated that after the TLS, they realised that "there is more biodiversity than they thought and that it is everywhere" (>30%, categories A1 and B1). Another 25% gave very short answers that suggested specific learnings, such as symbiosis, plant and animal classification or the importance of taking care of nature/biodiversity (category B2). Superficial or out context answers were labelled C and D (8%). All in all, the answers reflect learnings that range from specific concepts to scientific practices. Regarding habitat conceptualisation, some answers suggest that some participants experienced a revelation about where to look, and what can be found, as expressed here by some students: "I have become aware of the importance of biodiversity and the fact that there are many living beings around us, and that there are many different habitats that protect their life cycle", or "I knew there were many living beings, but many of my misconceptions have been broken. When I was used to thinking about a living being, I usually thought about animals. But now I realize that there are more living things, plants, bacteria. . .".

Table 8. Explanatory categories for question Q4 and proportion of students in each category.

Code	Description	%
A1	Students mention and/or discuss biodiversity's importance (including benefits or human impacts) and/or diversity of habitats/ecosystems and ecosystems functioning concepts (like food webs or symbiosis). They recognise that biodiversity is more abundant and widespread than they initially thought. Responses may include examples of organisms or scientific practices like sampling, identification, or classification.	9.4
A2	Students describe learning about living beings (examples, classification, or characteristics) and/or garden habitats as locations for biodiversity and ecosystem concepts (like food webs or symbiosis). They refer to scientific practices such as sampling, classification, or identification, but do not mention or discuss biodiversity's importance, abundance, or widespread presence.	29.8
B1	Students mention that there is more biodiversity than they had thought and/or that it is everywhere without further justification or illustration with examples.	26.2
B2	Students mention only one scientific practice or one concept without giving further explanations (e.g., symbiosis, animal classification, taking care of biodiversity).	25.3
C	Superficial answers, lacking precision or details that help to understand their self-reported learning.	6.3
D	Out of context or no answer.	2.6

5.2. Retrospective Analysis of the TLS and Constraints of the Implementation

In Section 2.1, we presented the LO related to key ideas E1 and E2 (Table 1). There was some success with respect to the LOs, particularly regarding the awareness of invertebrates, which can be easily observed and sampled in a school garden. A stronger connection with nature and a more inclusive view of biodiversity, its ubiquity and the links between habitats, species and their interactions was also detected following implementation. Nevertheless, some other learnings proved to be less successful, as shown by the prevailing plant awareness disparity and persistent problems with specific taxonomic levels (e.g., arthropods and seed plants).

Following the methodology described in Section 4.5, we examined the quality of the TLS using qualitative implementation data from teacher's journals, students' workbooks, and post-implementation meeting notes. Through systematic triangulation of these implementation data with the LO analysis (Section 5.1), we identified several limitations in the TLS, primarily in the material and scientific domains (Kariotoglou et al., 2003). It is important to note that while this analysis identifies which aspects of the TLS require improvement, specific redesign decisions (Table 9) emerged from combining these empirical findings with the authors' PCK and domain-specific research evidence. For example, through systematic triangulation, we noticed that the time devoted to examination and classification of the organisms identified or collected in the garden could have distracted students from knowledge related to taxonomy. One teacher noted that "students want an immediate answer for the collected specimen, either through the use of identification apps or by asking the lecturer directly"; and "we have taken some knowledge for granted and hence, we have not given them enough opportunities to understand which characteristics determine the inclusion of an organism into one group or another before explaining the

taxonomy". During the post-implementation meetings, we confirmed that although the TLS included a lab session to identify microscopic animals and other organisms such as those present in moss, the soil or the pond, other common invertebrates also deserved careful examination after observing them in the garden. Additionally, our retrospective analysis suggested that specific guided work with plant identification and classification was needed, both in the garden and in the lab, to counteract plant awareness disparity. The changes suggested in Table 9 involve reformulating activities to address metacognitive difficulties—ensuring students understand the purpose of activities—and introducing the concept of taxonomic classification based on shared and distinctive characteristics. Another constraint observed during the garden-based inquiry was the need to better scaffold and transpose scientific practices from ecology and citizen science to Primary Education teaching contexts (Eugenio-Gozalbo et al., 2022; Rammou et al., 2024). PPT deserve special attention with respect to developing the confidence to implement these scientific practices in their future classrooms (Rivero et al., 2011).

Table 9. TLS activities for LG.1-3 with a summary of constraints and redesign decisions.

Driving Question	Learning Goals	Activities	Constraints
		A1 Let's find living beings in our school garden	
DQ1. What kind of living beings can we find in our school garden and where can we find them?	LG.1. LG.2 LG.3.	1.1. Identification of habitats 1.2. Sampling and annotation of specimens in each habitat 1.3. Examination of microscopic specimens from microhabitats (moss, soil, pond)	C1: Persistent plant awareness disparity: Students do not recognise plants as species worth registering or as habitats for other organisms. C2: Limited conceptual learning (plant and invertebrate taxonomy)
Redesign decisions			
RD1. Increase the number of visits to the garden: first, to identify the main elements, habitats and design the sampling methodology; secondly, to conduct the sampling and thirdly, to dedicate a specific session to plant sampling and identification. RD2. Use of guided inquiry to introduce ecological sampling for identification, quantification and comparisons, such as methodologies employed in citizen science initiatives. RD3. Add at least one extra session in the lab for dedicated examination of plants, invertebrates and other microscopic organisms using dissecting microscopes and identification guides, including drawing activities to determine distinguishing characteristics and creating ad hoc dichotomic guides.			

6. Discussion

The purpose of this study was to apply the DBR methodology. This enables design decisions to be grounded in epistemology and scientific evidence rather than researcher intuition, and also made it possible for us to systematically refine our TLS about biodiversity through coherent alignment between instructional activities and evaluation tools (Guisasola et al., 2023). The application of DBR principles required justifying design choices, situating learning activities within development zones appropriate for the participating students, and systematically evaluating both students' LOs and the instructional design itself. Critically, the methodology requires confronting the designed TLS with classroom implementation data to assess coherence between intended aims and actual results. The evaluation tools employed in this study—which addressed students' progression in overcoming identified learning difficulties—exemplify how DBR supports evidence-based refinement of instructional sequences.

In the following paragraphs, we discuss the main findings with respect to the two primary objectives and research questions of this paper. Specifically, Section 6.1 addresses the first objective and research question of this paper, which is to evaluate the impact of the designed sequence on PPT's connection with nature and their biodiversity literacy; while Section 6.2 addresses the second objective and research question of the paper, which aims to identify any significant implementation and learning constraints to inform a redesign of the TLS.

6.1. Effect of the TLS on Students' Connection with Nature and Biodiversity Literacy

Overall, our results indicate that the intervention had a positive impact on PPT's sense of connection with nature. This confirms earlier research by our group and others which shows that beyond conceptual gains, relational and emotional values towards nature improve after interventions contextualised in school gardens (Aragón & Erdozain, 2025; Corrochano et al., 2025; Pérez-López et al., 2020; Rico et al., 2025).

Regarding knowledge of local biodiversity, our data suggest that PPT's initial ideas are similar to those of primary and secondary education students, and Primary Education teachers, in the same geographic area. This awareness characteristically demonstrates an over-representation of vertebrate animals—mainly mammals—and only an anecdotal presence of invertebrates, plants, or other taxa (Barrutia et al., 2022). The finding that our prospective teachers initially held misconceptions and difficulties similar to those documented in primary and secondary students is particularly significant, as it highlights both the lack of learning progression throughout compulsory education and the risk that these future teachers may perpetuate such misconceptions in their own classrooms if left unaddressed (Burgoon & Duran, 2012; Rico et al., 2026). This underscores the critical importance of targeted interventions during initial teacher education that develop both content knowledge and PCK related to biodiversity and biological classification.

Data gathered following the intervention showed positive impacts on biodiversity literacy. Students recognised more invertebrates and the diversity of animals they listed was richer. Additionally, some improvements in botanical knowledge emerged: mentions of "moss" (Bryophyta) increased by 4%, and the use of generic terms (e.g., plant) decreased by 5% in favour of specific names. Moreover, other taxa such as fungi, protists, and bacteria were mentioned more frequently after the intervention. However, despite these gains, plants did not have a prominent role in students' listings before or after the intervention. This suggests that plant awareness disparity (Barrutia et al., 2022; Pedrera et al., 2021) remains a persistent challenge among PPT. This finding aligns with widely documented evidence that students and teachers alike show less interest in identifying plants than animals (Lindemann-Matthies et al., 2017; Lindemann-Matthies, 2005; Stagg & Dillon, 2022). As a result, we believe that the TLS redesign should allocate more time to plant identification and classification activities (Randler, 2008).

Overall, students gained a more diverse perspective on species found nearby, which reinforces the idea that inquiry-based and experiential approaches contribute to biodiversity awareness (Niemiller et al., 2021; Palmberg et al., 2019; Stagg et al., 2025). The PPT who participated in our study were able to draw examples from their sampling, observation, and identification activities in the organic learning garden, particularly regarding invertebrates, thus reducing their native species awareness disparity. Therefore, our results underscore the importance of learner-centred education and experiential learning as key approaches to improving species knowledge among PPT (Skarstein & Skarstein, 2020; Tergenbayeva et al., 2023), particularly for students who may have lacked opportunities to experience such approaches in their earlier education (Lindemann-Matthies et al., 2017). Given that students who observe and name more wild plants and animals in their local

environment develop greater appreciation for biodiversity (Lindemann-Matthies, 2005), organic learning gardens offer an excellent opportunity to engage PPT by linking plants with food production, garden aesthetics, and adaptation and resilience to climate change (Aragón & Erdozain, 2025; Stagg & Dillon, 2022), particularly when combined with field and laboratory investigations, identification keys, and discussion-based approaches (Stagg et al., 2025). The use of identification apps such as iNaturalist did not help "per se" in engaging students with classification, likely because they bypassed the cognitive work of observation and classification rather than supporting it. These apps should not substitute the teaching of classification through distinctive characteristics. However, a constructive integration in future TLS implementations, could be the creation of an iNaturalist project where students upload their observations from the university garden, which has been shown to increase biodiversity observations and promote engagement with nature among students (Niemiller et al., 2021; Tiago et al., 2024).

Results from classification tasks of living beings indicate that, before the educational intervention, students held a basic understanding of broad biological categories but faced challenges when dealing with distinctions within plant and invertebrate groups and specific vertebrate classes. Previous studies have also documented the persistence of difficulties in classifying living organisms after completing compulsory education (Lindemann-Matthies et al., 2009; Maskour et al., 2019; Merritt & Bowers, 2020). Importantly, the TLS was effective in reinforcing general classification skills. Although the improvement in some cases (classification of arthropods by class and classification of plants in seed and seedless) was modest, which can be explained by students' prior large knowledge of these groups, notable progress in the classification of vertebrates and in the differentiation between vascular and non-vascular plants were reported. However, the persistence of specific classification misconceptions—particularly regarding the classification of plants into angiosperms/gymnosperms and invertebrate phylum-level classification—suggests that students may be relying on memorisation rather than developing conceptual understandings of hierarchical relationships and diagnostic characteristics within biological classification systems. In other words, major misconceptions regarding taxonomic distinctions persisted among a considerable proportion of students. To overcome this learning demand, more targeted instruction and additional experiential learning may be required. Extra activities could include the design and application of dichotomous keys along with guided observation and drawing of plants and invertebrates. These strategies have been shown to help PPT develop their PCK on biological classification (Eugenio-Gozalbo & Ortega-Cubero, 2024; Stagg et al., 2025).

Finally, students' self-reported LO showed a range of responses from learning specific concepts to grasping scientific practices like sampling, identification, and classification, which can be developed through place-based learning and guided inquiry (Lindemann-Matthies et al., 2009; Stagg et al., 2025). Many excerpts mentioned the importance of biodiversity or the need to protect it, which could be related to students' self-reported improved connection with nature as shown in Figure 3. Regarding habitat conceptualisation, some responses suggest that certain students experienced the revelation that they have learned where to look for biodiversity and what they might find. In future iterations of our TLS, habitat conceptualisation will be addressed before starting the sampling and identification work. It would also be valuable to design an evaluation task that specifically assesses students' understanding of the habitat concept.

6.2. Retrospective Analysis: Constraints to Inform a Redesign of the TLS About Biodiversity

Retrospective analysis in DBR aims to determine both research validity (understanding learning processes) and pragmatic value (implications for teaching practice) (Psillos

& Kariotoglou, 2016). Our analysis revealed that while the TLS successfully promoted awareness of invertebrates and strengthened students' connection with nature, several constraints emerged that limited conceptual gains in specific areas, particularly regarding plant species literacy and taxonomic classification. By following the constraint classification framework proposed by Kariotoglou et al. (2003) and refined by Zoupidis et al. (2016), we identified issues primarily in the material and scientific domains. Material constraints included insufficient time allocated to specific activities, while scientific constraints were related to the depth of engagement with taxonomic concepts. For instance, our teacher's diary revealed that students sought immediate species identification through apps rather than engaging in systematic observation of distinguishing characteristics. Additionally, we identified a metacognitive constraint: students did not fully understand the purpose of certain observation and classification activities. This impeded the development of a systematic approach to biological classification. The persistent plant awareness disparity represents a particularly significant constraint. We did include plants in sampling activities. However, this did not overcome students' deeply rooted tendencies to prioritise animal diversity. This suggests that plant identification requires explicit, dedicated attention with specialised scaffolding. The development of a TLS presupposes the repetition of successive cycles of implementation and formative evaluation of teaching activities (Psillos & Kariotoglou, 2016). Our retrospective analysis has generated specific redesign decisions (Table 9): increasing the number of garden visits to allow focused sampling of different taxa, introducing guided inquiry approaches that model citizen science methodologies, and adding dedicated laboratory sessions for specimen examination and drawing to develop observational skills. These evidence-based decisions based on the analysis of the first iteration represent our synthesis of assessment data, qualitative insights from teachers' journals and students' workbooks, with domain-specific research evidence and PCK, embodying the recursive nature of educational reconstruction that characterises robust DBR methodology.

6.3. Limitations and Future Work

Our research did face several limitations. The first is the instruments used to assess students' LO. Some of these items—particularly those addressing the classification of invertebrates and plants—were designed ad hoc for this study. While these items were based on similar tasks used in other research, they have not undergone formal validation or reliability testing. Consequently, the results derived from these measures should be interpreted with caution. These items may not have fully captured the intended constructs or may have allowed for ambiguous interpretations by students. The format of the activity may have prompted some students to select multiple categories inappropriately, particularly in the plant classification tasks. While we argue that this tendency reflects underlying conceptual difficulties with hierarchical biological classification, the instrument itself may have contributed to or exacerbated the extent to which student error appeared in our results. In response, the second cycle of the TLS will include a reformulation and refinement of these questions, with the aim of reducing ambiguity and improving their alignment with the targeted Learning Goals (see Supplementary File S1 for the redesigned questionnaire and specific recommendations to validate it in different socio-ecological and cultural contexts). This iterative refinement is consistent with the principles of the DBR approach and is expected to enhance the validity and interpretability of the assessment instruments in future implementations. Second, this study employed a single-group pre-post design without a control group. While this limits our ability to definitively attribute the observed improvements solely to the educational intervention, the ethical and practical considerations surrounding control group designs in educational research must also be acknowledged. Withholding potentially beneficial interventions from control groups raises

ethical concerns, particularly in teacher education where students' professional preparation is at stake (Taber, 2019). Moreover, the DBR methodology employed in this study prioritises iterative refinement and validity over experimental control, focusing on understanding how and why interventions work in authentic educational contexts (Psillos & Kariotoglou, 2016). Future research could employ mixed-methods approaches combining quantitative assessments with in-depth interviews. Such interviews would be particularly valuable for distinguishing between genuine conceptual misunderstandings and artefacts of the tasks, thereby providing richer insight into students' reasoning processes and the nature of persistent misconceptions identified in this study.

Third, the sample is relatively small and from a single university, which constrains the generalisability of the findings. The specific characteristics of this institution, its curriculum, and the regional context may limit the extent to which our results can be extrapolated to PPTs in other contexts, even though some of the teaching and learning difficulties encountered are similar to those detected in other international studies. Replication studies across diverse institutional and cultural contexts would be valuable for establishing the broader applicability of these findings and the transferability of the TLS to other settings.

7. Conclusions

The assessment of a TLS for PPT in university organic learning gardens has shown the effectiveness of place-based, inquiry-based learning for enhancing participants' understanding of biodiversity, classification skills, and sense of connection with nature. The significant improvements we observed in students' sense of connection with nature, species awareness—particularly regarding invertebrates—and their improved understanding of taxonomy confirm that experiential learning in organic gardens is able to address multiple dimensions of biodiversity learning simultaneously. However, the results also reveal persistent conceptual challenges that require attention in future iterations of the TLS. Plant awareness disparity persisted despite modest improvements, indicating that more targeted instructional strategies are needed. Similarly, despite improvements in general classification skills, major misconceptions regarding taxonomic distinctions persisted among many participants. This, together with the finding that these prospective teachers held misconceptions and difficulties similar to those documented in primary and secondary students, highlights the critical importance of targeted interventions during initial teacher education to develop both content knowledge and PCK related to biodiversity and biological classification.

Through the application of DBR methodology, this study contributes to what Guisasola et al. (2017) term "humble intervention theories"—contextually grounded insights that acknowledge both the opportunities and limitations of specific educational designs. Rather than claiming universal effectiveness, our findings offer evidence-based principles for biodiversity education in organic garden contexts, while explicitly identifying the limits of our design's success. The iterative cycles of design, implementation, and retrospective analysis characteristics of DBR have enabled us to generate practical knowledge that we hope will inform similar educational interventions while remaining appropriately modest about generalisability (Psillos & Kariotoglou, 2016).

The persistent conceptual difficulties identified in this study provide clear objectives for ongoing iterative refinement of the TLS. We hope that this will ultimately improve the training of future teachers who will effectively foster biodiversity literacy in Primary Education. Our results suggest that future versions of this TLS should incorporate additional strategies such as systematic development and application of dichotomous keys, guided observation and drawing protocols, explicit instruction emphasising hierarchical thinking in classification, and situated examination of specific habitats in the garden. These

inclusions would help students make links between the adaptations and features of living things and their physical environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci16050754/s1, File S1: Questionnaire about biodiversity and living beings (V2); Table S1: Summary and general structure of the TLS "Our school's biodiversity" for PPTs.

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Abbreviations

The following abbreviations are used in this manuscript:

DBR	Design-Based Research
DQ	Driving Question
LG	Learning Goals
LO	Learning Outcomes
TLS	Teaching–Learning Sequence
PCK	Pedagogical Content Knowledge
PPT	Prospective Primary Teachers

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