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Promoting Scientific Literacy in High School: Insights from Short-Term STEM Collaborative Projects

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ABSTRACT

Fostering scientific literacy is a key societal goal to equip individuals with skills to navigate and make informed decisions in an increasingly complex world. The development of project-based learning (PBL) approaches can effectively promote scientific engagement, but their implementation often presents challenges for teachers. This study presents a framework implemented in a Portuguese high school that encourages collaborative partnerships between schools and research institutions, actively involving students in STEM research projects. This approach consists of the development of year-long scientific projects that rely on a PBL framework, but in which researchers guide ideation and implementation, therefore overcoming challenges for teachers, who take a supporting role. Through a case study in Biology, we illustrate a practical application and share insights from an evaluation survey that assessed students' experience and acquired knowledge, highlighting valuable lessons and areas for improvement. Our findings indicate that these initiatives improve students' comprehension of the scientific process, offering an effective model to enhance their scientific literacy.

Keywords: scientific literacy, project-based learning (PBL), STEM education, school-research partnerships, student engagement

INTRODUCTION

Scientific literacy has long been recognised as a desirable attribute of informed and engaged citizens (McFarlane, 2013; Osborne, 2023; Turiman et al., 2012). In the face of 21st-century challenges, science education and literacy have become essential tools for addressing global problems and developing solutions through a community-based participatory approach (McFarlane, 2013). Traditionally, science education was based on promoting the retention of scientific knowledge and concepts over the development of scientific reasoning (Bao et al., 2009; Linn et al., 2006) or a clear understanding of scientific topics (Clark and Linn, 2003). However, the importance of developing scientific skills, such as critical thinking and scientific reasoning (Osborne, 2013; Santos, 2017; Vieira and Tenreiro-Vieira, 2014), and of understanding the nature and process of science (Kwok, 2018; Lederman et al., 2013), is now widely recognised. The development of these skills promotes students' scientific literacy, enabling them to connect science to their daily lives and supporting informed decision-making and active participation in society (Holbrook and Rannikmae, 2007; McFarlane, 2013).

Project-based learning (PBL) has emerged as a valuable, student-centred teaching approach (Kokotsaki et al., 2016; Thomas, 2000), promoting the development of key scientific skills. As summarised by Kokotsaki et al. (2016), PBL is an approach characterised by "students' autonomy, constructive investigations, goal-setting, collaboration, communication and reflection within real-world problems". Numerous studies highlight that students engaged in PBL approaches achieve higher learning success than those taught using traditional teacher-centred methods (Balemen and Keskin, 2018; Chen and Yang, 2019; Freeman et al., 2014; Holmes and Hwang, 2016), including through informal PBL implementations (Santhosh et al., 2023).

Beyond academic performance, PBL has been shown to foster a higher interest in and understanding of scientific topics or fields (Fernandes et al., 2014; Han et al., 2016; Tseng et al., 2013), while also contributing to the acquisition of interdisciplinary skills (Bell, 2010; Holmes and Hwang, 2016). These include inquiry, collaborative work, technological proficiency, effective communication, and problem-solving skills, considered essential for the 21st century (Bell, 2010). Furthermore, PBL can contribute to a more positive attitude towards future careers, particularly in science, technology, engineering, and mathematics (STEM) fields (Beier et al., 2018; Tseng et al., 2013). Nonetheless, educators face challenges in implementing PBL, including limited support and resources, insufficient understanding of PBL requirements, the need to develop project ideas, and scheduling constraints (Aldabbus, 2018; Haatainen and Aksela, 2021; Viro et al., 2020).

In the Portuguese education context, hands-on learning initiatives have been described, particularly in the context of citizen science projects (Araújo et al., 2022; Boaventura et al., 2021; Silva et al., 2016) and inquiry-based activities (Boaventura et al., 2020; Guilherme et al., 2016), engaging students across different education levels. These studies have explored the impact of these actions on students' conceptual knowledge in the project field (Araújo et al., 2022; Boaventura et al., 2021; Guilherme et al., 2016) and development of investigation skills (Boaventura et al., 2020), but also students' self-assessed perception of the value of science (Guilherme et al., 2016), understanding of the work of a researcher (Silva et al., 2016), and their satisfaction and difficulties with the activities (Boaventura et al., 2020; Guilherme et al., 2016). Despite this, literature explicitly exploring project-based learning in the Portuguese education system is limited, with only a few examples, such as the work of Lima et al. (2017), focused on PBL implementation in higher education. This suggests that PBL is not yet widely adopted in Portuguese compulsory education.

To address this gap, our work explores the application of a PBL framework aimed at fostering students' engagement with science within the context of compulsory schooling. Specifically, we present a framework developed through a formal partnership between a research institution and a high school in the Porto district, Portugal. This framework has been applied in recent years to develop short-term scientific projects with high school students, aiming to promote scientific literacy and engagement. In Portugal, high school covers mostly students aged 15 to 18 years and comprises a three-year cycle (10th to 12th grade) of upper secondary education, which is compulsory up to the age of 18 (Eurydice, 2025). The most common upper secondary education route comprises science-humanities courses (SHC) (DGEEC and DSEE, 2024). In these courses, the core curriculum consists of subjects that are common across SHC (e.g., Portuguese and Philosophy) and subjects specific to each SHC, such as STEM disciplines, including Biology, Chemistry, or Mathematics, which are part of the *Science and Technology* SHC. In the final year (12th grade), up to two SHC-specific subjects are elective (Eurydice, 2025).

The projects developed under this partnership are usually aligned with ongoing funded research projects focused on STEM fields, allowing students to experience the research process and gain insights into scientific methodologies and key concepts. This approach incorporates key pillars of PBL, including active student involvement, autonomy and responsibility in project development, and a central driving question addressing real-world problems (Thomas, 2000). Moreover, these projects are designed to promote the development of critical thinking and technical and interpersonal skills (Bell, 2010). We first describe our framework, which can serve as a roadmap for developing similar partnerships and projects. Then, we present a case study in Biology that illustrates the practical application of this model over a school year. Finally, using insights from an evaluation survey, we analyse the impact of the case study on participants' learning experiences and extract lessons for future iterations.

To support the dissemination and implementation of similar initiatives with Portuguese-speaking students, a Portuguese version of this article is available at: https://doi.org/10.5281/zenodo.13373749.

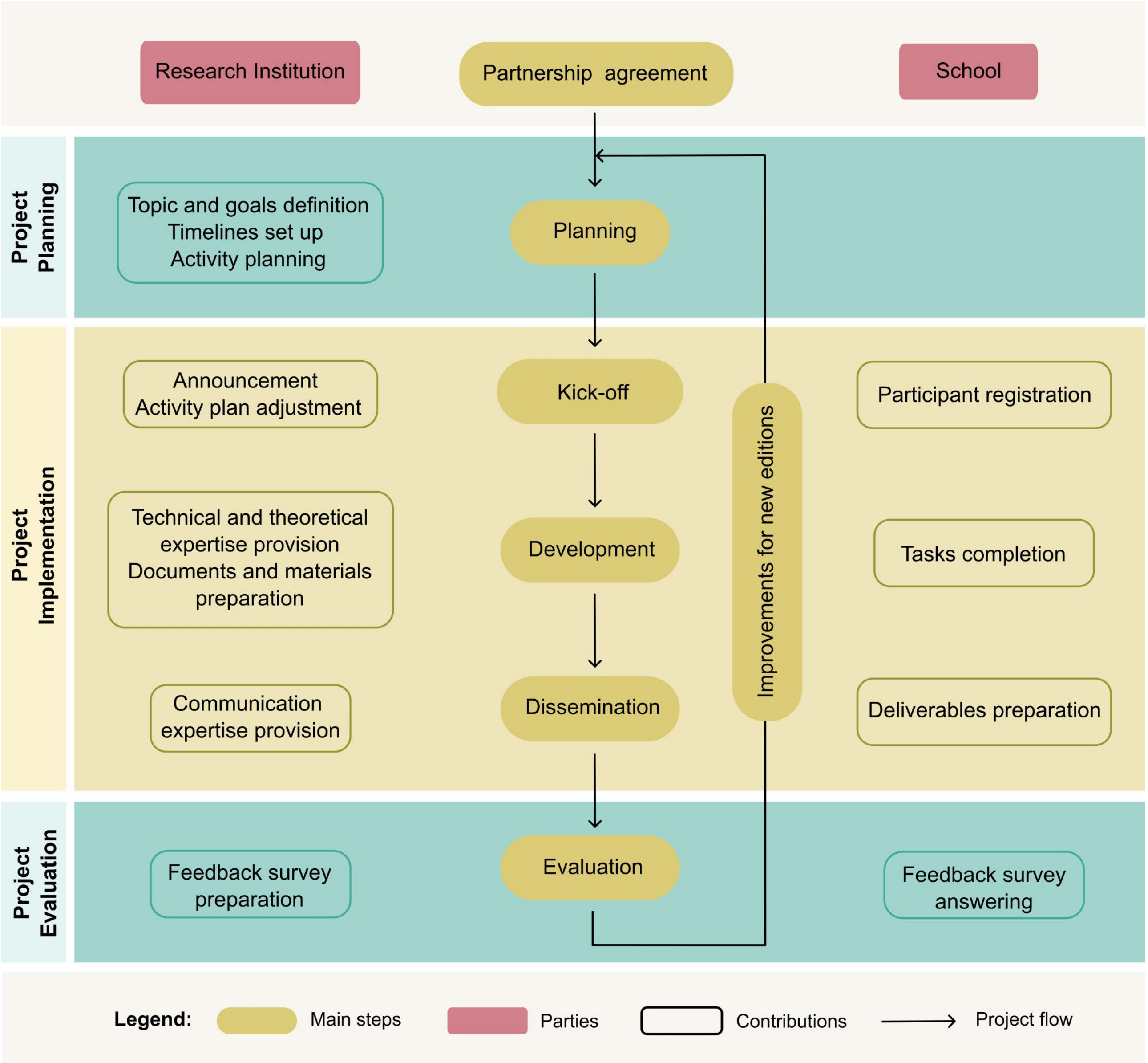

Figure 1. Framework developed for implementing a formal partnership between a research institution and a school to develop scientific projects with local students (depending on the context, schools collaborate in the definition of the topic and goals and in the planning of the activity)

METHODS

A Roadmap to Implement Collaborative Scientific Projects

The approach we developed to implement short-term scientific projects through a formal institutional partnership is outlined in **Figure 1** and consists of four distinct stages, each essential to the success of these projects. This framework was designed to be adaptable to various STEM fields and contexts, making it suitable for diverse educational settings, which might target students of any age range. We therefore chose to keep the description as general as possible, detailing the specificities of our collaborative partnership only in the case study presented below, in order to avoid constraining the design of similar future initiatives.

Partnership agreement

Collaborative projects often begin with informal collaborations between researchers and non-academic institutions, such as schools or science centres. While informal understandings can sometimes suffice, a formal partnership protocol at the institutional level ensures a more robust and enduring collaboration. To start the collaboration, both parties sign a protocol, establishing obligations, benefits, shared responsibilities, and the partnership duration. This protocol promotes clarity, alignment, efficient resource utilisation, and ethical practices in these collaborative projects (a generic protocol template is available in **Appendix A**).

Project planning

Each year, a new scientific project is planned, with the definition of the topic, scientific questions, core goals, and methodologies. Depending on the context in which the project will be implemented, this planning can be done in collaboration with students and/or teachers. In addition, a project calendar is developed, detailing the necessary steps, deadlines for tasks, deliverables, and outputs. Projects follow state-of-the-art scientific approaches and are designed to be attractive both in terms of their topics and the skills that participants can develop.

Project implementation

The implementation phase of each project is structured into three main steps, each with a specific objective:

- Kick-off: After planning, the project is announced to prospective students, usually through an introductory project session or activity led by researchers with teachers' assistance. The strategies used for project promotion can vary but should focus on explaining the project's theme and the scope of the work to students. Participation is voluntary, and students from different school years are invited to attend this activity. The range of school years to target should be that deemed adequate for the project theme and objectives. After, a registration period is opened for those interested in participating in the project.
- Development: During the pre-established timeline, project activities are conducted with mentorship from researchers, who provide the necessary documentation and materials. Researchers provide participants with training in project-specific topics, concepts, and skills needed to achieve the project goals, such as laboratory and field techniques or software for data analysis. Students autonomously develop the project, consulting with researchers whenever needed. All the work is accompanied by the teachers involved in the project. The project might take place within or outside class hours, depending on the context, but the schedule must be compatible with students' curricula.
- Dissemination: At the end of the project, students, with researchers' input, showcase and debate their results with the school community through planned deliverables and/or activities. This step emphasises the importance of sharing findings and engaging the broader community.

Project evaluation

Upon completion of the project activities, researchers collect feedback from participants about the strengths and weaknesses of the project and their personal experiences. This feedback, collected anonymously, is used to improve and plan follow-up editions.

Our structured approach incorporates several key features that enhance the overall effectiveness and impact of these projects: first, establishing a formal written protocol ensures a lasting and positive cooperation between institutions; second, leveraging ongoing funded research projects enables students to engage as scientists in addressing timely and relevant societal challenges; and third, promoting direct contact and active collaboration fosters a strong partnership between researchers, teachers, and students. Additionally, conducting thorough final assessments ensures a more comprehensive and enriching experience for everyone involved. Together, these elements foster a deeper engagement and understanding of the scientific process among participants.

Case Study Project in Biology

Partnership agreement

This case study was developed within the context of a partnership agreement between a research centre and a high school that has been ongoing since 2019 but was initially impacted by the COVID-19 lockdown. It thus represents the first project in which we were able to fully implement the roadmap detailed in **Figure 1** in an in-person setting, serving as a pilot to test the feasibility of the framework within the classroom. For our partnership, the projects are developed in the scope of Biology, given the expertise of the research centre involved in this collaboration. In Portugal, at the upper secondary education level and in SHC, students only attend Biology class if enrolled in the *Science and Technology* course, and Biology is fully elective in the 12th grade (Eurydice, 2025). At the high school involved in the partnership, students enrolled in Biology are encouraged to choose and develop a scientific project as part of their curriculum, among a set of possible project topics.

Project planning

During the 2022-2023 school year, we implemented a scientific project focused on seasonal colour change, an adaptive trait shared by several mammals and birds inhabiting regions with winter snow cover. This trait consists of seasonal changes of coat or plumage colour, from brown in summer to white in winter, ensuring year-round

Table 1. Detailed description of each step of the case study *Project implementation* phase

Step	Description
Kick-off	Main goal: introduce the project through a practical activity with two main challenges. • Challenge 1: add onto a georeferenced map hypothetical observations of a species with two hypothetical phenotypes (brown or white coat), based on provided locations for observations, to understand the geographic distribution of each phenotype. • Challenge 2: compare phenotype distribution with environmental conditions, using maps showcasing variations in several environmental and climatic variables (provided), to identify those that vary similarly to phenotype distributions.
Development	Main goal: Work in pairs or individually to complete project tasks (developing scientific and technical (informatic) skills). • Task 1: Collect data on observations and sightings of species that seasonally change colour from public databases (*data collection*). Analyse records to check for information on individual phenotypes, date and location of observations (*data pre-treatment*). • Task 2: Produce a map of the geographic distribution of observations retained for further analysis (*figure production*; uses specialised software [SS]). • Task 3: Gather environmental and climatic variables from public databases (*data collection*) and prepare variables for usage (*data pre-treatment*; SS). • Task 4: Remove variables with redundant information (*data analysis*). • Task 5: Estimate the present distribution of alternative winter phenotypes, using retained observations and variables, and modelling approaches (*data analysis*; SS). Produce a map with the estimated distribution (*figure production*; SS). • Task 6: Predict future phenotype distributions under distinct climatic scenarios through modelling (*data analysis*; SS) and produce maps with predicted distributions (*figure production*; SS). • Task 7: Infer how climate change scenarios may affect the occurrence of alternative winter phenotypes (*result interpretation*).
Dissemination	Main goal: Share project results and conclusions with the school community (consolidate knowledge and develop communication skills). • Mandatory deliverables: production of a scientific poster about the project (*scientific poster preparation*) and development of an exhibition for the school science fair, including activities for visitors (*outreach activities preparation*). • Optional deliverable: oral presentation for the school science meeting (not compulsory, thus not evaluated on the project's feedback survey).

camouflage in seasonally changing environments (Zimova et al., 2018). However, global warming is challenging this adaptation due to reductions in the duration and extent of snow cover (e.g., Kunkel et al., 2016), potentially disrupting winter camouflage (Mills et al., 2013). Variation in winter colour (i.e., alternative winter colour morphs) exists across the distribution range of several species that harbour this adaptation, with some populations maintaining a brown colour year-round, in regions with less or non-existent snowfall (Mills et al., 2018). The occurrence of alternative winter colours can be key to allowing rapid adaptation to changing environments (Ferreira et al., 2023). Understanding the main environmental and climatic factors that explain the presence of alternative morphs across geographic regions with distinct conditions (see, e.g., Mills et al., 2018) can help predict how phenotype distributions may shift under future climatic scenarios (Ferreira et al., 2023). This, in turn, can help predict the scope of phenotypic change needed to ensure adaptation under new conditions. The goal of the project was to understand how the present occurrence of alternative winter colours (white or brown) across the range of different species is influenced by distinct environmental variables and how that occurrence may evolve under future climate scenarios.

This project topic enabled students to deepen their understanding of various discipline-specific topics, including intraspecific diversity, evolution by natural selection, habitat and ecosystem dynamics, species-environment interactions, the impacts of global warming on species and ecosystems, as well as practical skills in data analysis software, statistics, mathematical modelling, and trend prediction using real-world data sets. The project was initially presented and discussed with schoolteachers to evaluate its suitability for different high school years, considering the concepts to address in the project and their alignment with the Biology curriculum of each year. Given that, and the complexity of the methodological approaches that would be needed, the project targeted students aged 16 to 18 years old, i.e., those enrolled in the last two years of high school.

Project implementation

The list of available scientific projects was announced to the target student community at the beginning of the school year, including our "seasonal colour change" project, along with others on topics such as fish protein evolution or soil contamination assessments. For our project, we promoted an announcement activity (**Figure 1**, *Project kick-off*) through an open practical session. This session took place in school, outside of class hours, was open to all students from the target school years, and participation was optional. Students were engaged in an activity mimicking the project's tasks without *a priori* context and during which they were asked to complete two main challenges (see **Table 1**; Miranda et al., 2024). This approach encouraged hypothesis construction based on their previous knowledge and on clues that they could infer from the proposed challenges. Participants successfully deduced the project topic and could pinpoint several key concepts relevant to the next steps.

After the kick-off phase, the possibility to register for *Project development* was open for all projects. Students could choose, from the variety of projects presented to them, the one they wanted to develop. Eleven high school students, aged 16 to 18 and enrolled in 11th (one student, male) or 12th grade (10 students, four males and six females), registered in the "seasonal colour change" project and participated in all its stages.

During *Project development* (**Figure 1**), the eleven students undertook tasks involving data collection, pre-treatment, and analysis, figure production, and result interpretation (detailed in **Table 1**); each task was designed to represent specific steps of the scientific research process. The scientific goals of these tasks included: (a) collecting data on observations of species with distinct winter colour phenotypes and map their distribution, (b) collecting and processing environmental and climatic data that might explain the distribution of winter phenotypes, (c) model the current probability of distribution of alternative winter phenotypes, and (d) predict the future probability of distribution of alternative winter phenotypes under climate change scenarios (**Table 1**; Miranda et al., 2024). Guidelines on how to complete each step were provided, but students were responsible for autonomously completing the proposed tasks. The resources developed in this project and a more detailed description of its tasks, including software used, have been published elsewhere (Miranda et al., 2024). Weekly out-of-class sessions were scheduled to support project activities, in a total of 15 sessions spread throughout the school year, with one or two sessions dedicated to each project task (**Table 1**). The sessions took place at school, and researchers were present in all sessions to accompany task progress and provide guidance as needed. Teachers were present in the sessions and assisted with classroom management and any logistical needs that might arise.

To present the results to the school community (*Project dissemination*, **Figure 1**), students completed two mandatory deliverables: a scientific poster and activities for the school science fair. The poster relied on strict rules that followed the conventions of scientific work, while the science fair activities allowed creative freedom in the presentation format and content. Both tasks prompted the students to critically reflect and evaluate their role in the development of the project and the different learning outcomes they each obtained from the experience.

Project evaluation

At the end of the project, participants were invited to complete an online survey to evaluate the impact of the initiative on their scientific knowledge, engagement, and skills and to inform future improvements (**Figure 1**, *Project evaluation*).

The survey assessed three main aspects: (i) students' personal experience, (ii) knowledge construction regarding the scientific process, and (iii) understanding of the project theme (seasonal colour change evolution under climate change). Questions included multiple-choice and five-point scale answers, together with a final open-ended feedback question. Concerning the sphere of personal experience, questions were sectioned into two parts with two distinct goals. The first part assessed the impact of the project on bridging the gap between students and science. Participants ranked their agreement with five statements using a five-point scale ranging between "totally disagree" and "totally agree". The second part was based on participants' self-assessment of their enjoyment and challenges when completing different project tasks, using multiple-choice questions where exactly two answers were required, for a total N = 22 responses per question. The assessment of consolidated knowledge about the scientific research process and the project-specific topic of seasonal colour change was done using two sets of single-answer multiple-choice questions (N = 5 and N = 6 questions, respectively) in which a single correct answer was considered. The complete questions can be found in **Appendix B**. The eleven students that participated in the project completed the questionnaire. Given the small sample size, no statistical analysis was conducted, and the results of the survey were quantitatively summarised.

Ethical considerations

Prior to the start of the project, formal authorisation was obtained from the Directive Board of the high school to ensure that all activities aligned with institutional guidelines and ethical standards, as well as the established partnership protocol. While participation in a scientific project was encouraged, the choice of which project to pursue was exclusively from the students. Participation in the project evaluation survey was anonymous and voluntary, and participants could withdraw from the survey at any time without consequence. Written informed consent to participate in the survey and this study was obtained from students (if aged 18) or their parents or legal guardians (if underage).

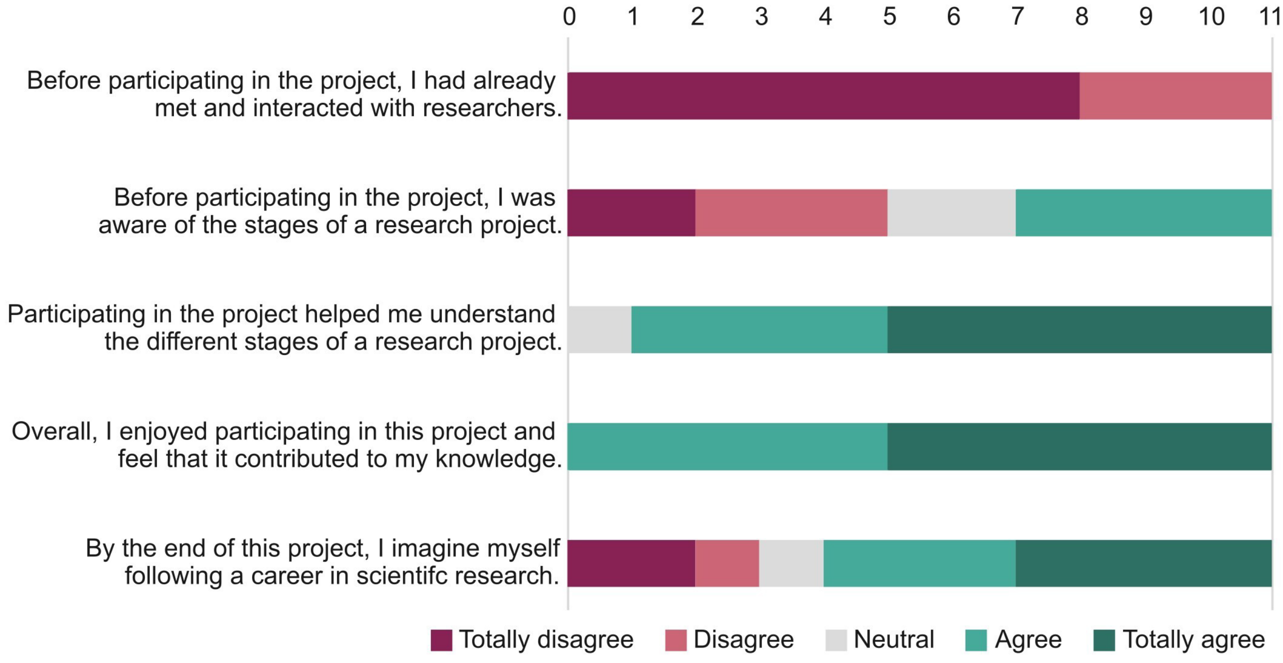

Figure 2. Students' perception of the project's contribution to their knowledge and understanding of the scientific process and scientific career (the axis on the top of the plot shows the number of responses per scale point)

RESULTS

Concerning students' personal experience in the project, the results of the survey showed that none of them had interacted with researchers before their participation (**Figure 2**). Despite this, four participants (36%) stated they were aware of the stages of scientific research before the project, whereas five (45%) were not. Ten students (91%) further said that this project helped them better understand the different steps of research, and all students agreed that they enjoyed the project and gained knowledge through their participation. Finally, seven students (64%) could envision a scientific research career, while three did not, and one was neutral.

Students' self-assessed experience during project development showed that data collection was identified as the easiest and/or most accessible task (six responses, 27%), followed by figure production, result interpretation, and preparation of outreach activities (18% each; **Figure 3A**). Figure production was also among the top three most difficult and/or challenging tasks (five responses, 23%), together with data pre-treatment (six responses, 27%) and the preparation of a scientific poster (four responses, 18%; **Figure 3B**). The initial project stages – data collection, pre-treatment, and analysis – were perceived as the most uninteresting and/or demotivating (68% of total responses; **Figure 3D**), while latter project tasks, namely result interpretation (six responses, 27%) and outreach activities (five responses, 23%), were seen as the most interesting and/or motivating (**Figure 3C**).

In general, tasks identified as the most challenging required students to use advanced analysis software (e.g., data pre-treatment) or apply new concepts (e.g., scientific poster). Similarly, tasks deemed uninteresting or demotivating involved advanced software or analytical tools (e.g., data pre-treatment and analysis) or repetitive processes (e.g., data collection). In contrast, tasks identified as the most accessible include those: (i) in which students were not required to learn complex analysis (i.e., data collection); (ii) which allowed them to link their results with biological concepts (i.e., data interpretation); and (iii) that relied on their creativity and communication skills (e.g., preparing outreach activities for the science fair). There was some overlap of these with the most engaging and interesting tasks, where students favoured activities that allowed them to derive biological meaning from their data (result interpretation, scientific poster preparation) and showcase their results, fostering their communication capacities (poster and outreach activities production).

Regarding the knowledge acquired by students, on average, 87% of answers about the research process were correct, whereas 62% correctness was obtained for the project-specific topic (**Appendix C**). Higher variation in the number of correct responses was also observed in project-specific questions (6.8 ± 2.5; mean ± standard deviation) compared with questions on the research process (9.6 ± 1.36).

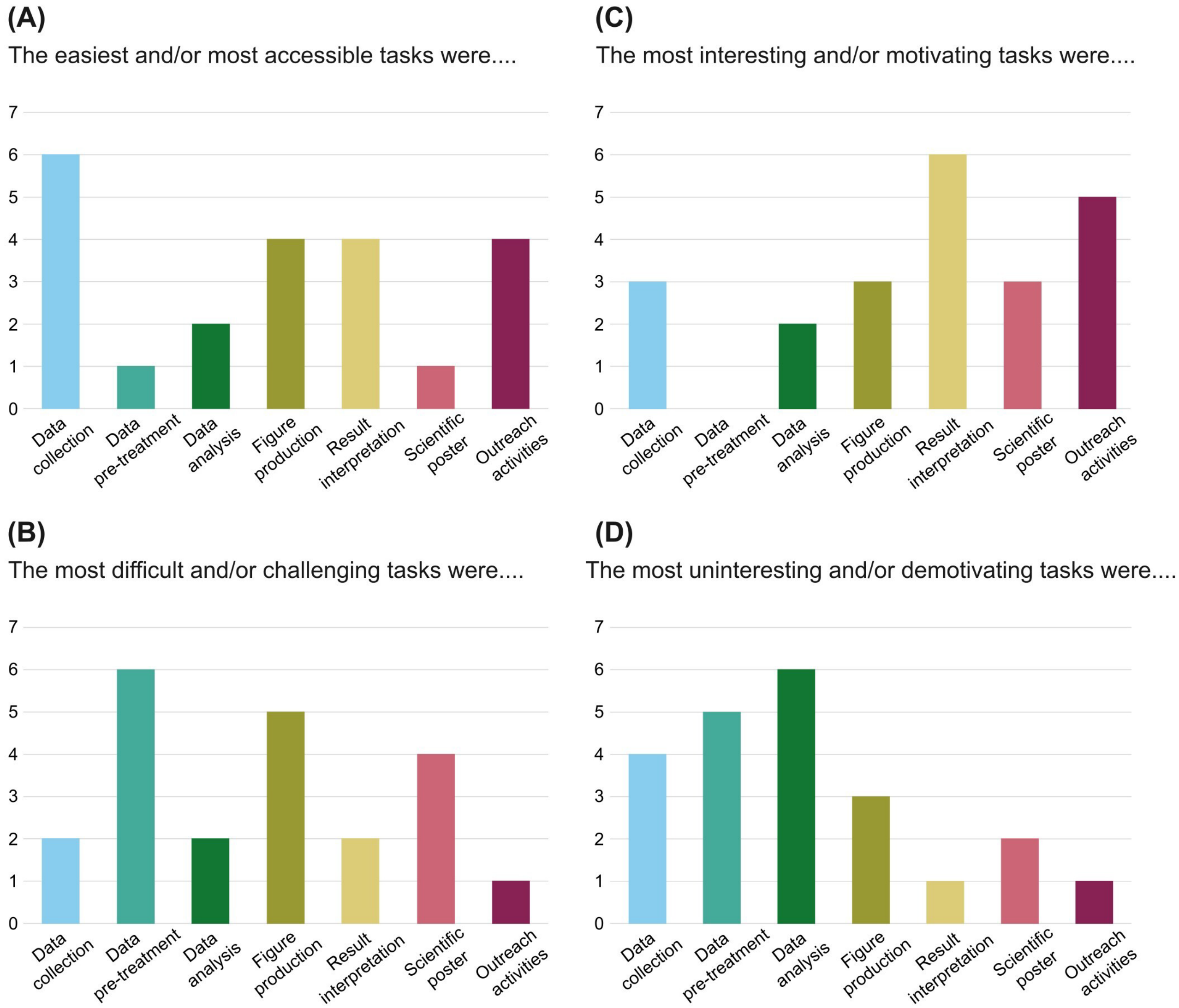

Figure 3. Students' self-assessed enjoyment and challenges during the development of the project, translated into the tasks that were considered as the (A) easiest and/or more accessible; (B) most difficult and/or challenging; (C) most interesting and/or motivating; and (D) most uninteresting and/or demotivating (each respondent was asked to select two tasks for each question and numbers indicate response counts)

In the open-ended feedback question, two students gave further comments on their project experience that highlight other skills acquired during their participation in this activity:

> "I just wanted to say that this experience allowed me to develop diverse skills, not only at the scientific level but also social and work skills."

> "This was an interesting project that helped me develop knowledge in areas such as scientific research and programming, skills that I hope to continue using in my future learning."

DISCUSSION

The value of science education and awareness in developing informed, engaged societies is well-documented in the literature (McFarlane, 2013). However, while project-based learning (PBL) approaches are recognised for improving scientific literacy, practical barriers often impede their effective implementation in school settings (e.g., Aksela and Haatainen, 2019; Aldabbus, 2018; Viro et al., 2020). To address these issues, this initiative engages students in year-long STEM projects, emphasising hands-on learning and fostering close collaboration between schools and research institutions. This model leverages external research expertise to enrich the learning experience while easing logistical challenges for educators.

Case Study Lessons

The survey results suggested that students were happy with their experience in the research project (**Figure 2**). Active involvement in each project stage was essential to students' positive evaluations of their participation, supporting previous work that highlights the importance of hands-on activities in student learning (Sadi and Çakıroğlu, 2011; Satterthwait, 2010). Our data showed that practical engagement enhances students' comprehension of scientific methodologies and processes, including their understanding of each research step and how they inform each other. This was reflected by the high rate of correct answers to the survey questions about the scientific process (**Appendix C**), a result that agrees with students' self-assessment of their scientific understanding (**Figure 2**). Additionally, analysing students' perceptions of different scientific tasks, including their most and least preferred project activities, allowed us to identify aspects that might contribute to a detachment from science and those that are rewarding, fostering a positive research experience (**Figure 3**). While task satisfaction is dependent on the specifics of the project, these results can inform future project planning by identifying approaches or project steps that may require adjusted approaches to maintain engagement. On the other hand, we obtained a lower rate of correct answers to the questions about the project-specific topic (**Appendix C**), suggesting a higher level of difficulty that could have resulted from little time dedicated to exploring the project theme in more detail. This underscores the need to reiterate key specific concepts throughout the project.

The project also allowed participants to develop new technical skills (e.g., in informatics), which can be useful in other academic or professional contexts, as well as important interpersonal and work skills, an outcome pointed out by two students in their survey responses. This feedback showed that participants valued their learning beyond the specificities of the case study, further highlighting the relevance of this type of initiative to the development of key transversal skills (Bell, 2010; Stehle and Peters-Burton, 2019).

Long-term feedback from students would be important for understanding whether an increased understanding of the scientific process and the nature of science fosters active participation in informed decision-making and civic discourse (Howell and Brossard, 2021; McFarlane, 2013). Furthermore, such feedback could help to clarify the impact of the project on participants' academic or professional paths. For example, Beier et al. (2018) suggest that PBL can positively impact the STEM career perspectives of college students. Preliminary data on this matter was gathered from our survey (**Figure 2**, last question), suggesting that this initiative helped students assess the fit of scientific work for their future career goals. Although no long-term follow-up is currently planned, future iterations of this initiative could integrate tools to evaluate its enduring influence on students' education and career paths.

Given the well-documented importance of early experiences in shaping STEM aspirations (Archer et al., 2013; DeWitt et al., 2011; Shin et al., 2019; Vinni-Laakso et al., 2019), it is also worth considering the translatability of this approach to younger-aged groups. While our current partnership is limited to a high school setting where Biology is an elective subject, expanding to different age groups would be a valuable direction for future research. Testing the implementation of similar partnerships in schools with younger students could help evaluate whether early engagement leads to stronger or more lasting interest in science while contributing to the prevention of misconceptions about science from an early age.

It is important to note that our implementation relied on students' freedom to choose projects, likely attracting those with a prior interest in the topic or methodologies to explore, thereby increasing the probability of positive experiences. Additionally, in Portugal, Biology is not compulsory at this level, and students in this study had actively chosen to pursue this subject. Therefore, our cohort may have been predisposed to show higher engagement. Designing partnerships that specifically target less engaged or more sceptical students could broaden the impact of PBL approaches and foster greater inclusion in STEM fields. Research by Bedessem et al. (2023) suggests that science participation can increase trust in different scientific dimensions, and Tseng et al. (2013) showed that PBL can positively shift perceptions of the importance of STEM in society.

The Value of School-Research Partnerships

More broadly, our results provide further evidence of how PBL can foster science literacy and education. Two critical features of our framework arose as particularly important for a successful initiative. First, establishing a formal partnership protocol between a research institution and a high school enabled open communication and mutual support between the school community and researchers. Informal feedback from students, teachers' comments, or researchers' observations throughout the project allowed for in-time adjustments, for example, providing more time for challenging tasks or adapting project topics and activities based on students' prior knowledge. A similar collaboration has been described by Fernández et al. (2024) for an engineering project, showing that these partnerships are feasible across STEM disciplines. Second, our framework addressed some commonly cited obstacles in PBL implementation, namely project ideation and lack of teachers' skills and/or clear guidelines for project implementation (Aksela and Haatainen, 2019; Viro et al., 2020), by involving researchers directly in these tasks. Additionally, this project promoted first-time contact with researchers for all student participants (**Figure 2**), stressing how STEM projects can create opportunities for dialogue and shared experiences between the research and school communities that might not be otherwise accessible to high-school students. This approach aligns closely with the OECD Learning Compass 2030 (OECD, 2019) by fostering students' critical thinking, creativity, and sense of community while promoting deep learning, collaboration, and effective communication.

Limitations and Future Prospects

Despite the encouraging outcomes, our study had some limitations that should be acknowledged. First, the small sample size may limit the generalisability of the findings. Future projects involving multiple schools or broader student cohorts would provide stronger insights into the effectiveness of this approach across contexts, such as by targeting students from different school levels or different social contexts. Second, as previously noted, the possibility to choose what project to pursue and the elective status of Biology in the curriculum suggest a self-selected, potentially more motivated group of students engaged in the activities. Exploring how similar partnerships could engage less science-inclined students would be a valuable extension of this work, for example, by expanding the same initiative to students in other high school courses in which Biology is not part of the curriculum. Lastly, project evaluation was conducted at a single time point, which limited the scope of our insights. The collection of structured and longitudinal data could allow a better assessment of the impact of these partnerships. On one hand, additional data collection before project initiation, for example, with a pre-test and post-test design, would provide clearer insights into the project's impact on student knowledge improvement. On the other hand, data collection on student outcomes after project conclusion, for instance, through alumni surveys or short interviews, could provide valuable insights into students' subsequent academic and career trajectories, strengthening assessments of long-term STEM engagement impact. In addition, structured feedback from teachers (e.g., via a focus group) on their own participation and on students' performance in the classroom during and after their participation in the project could give important indications of the impact of this participation on students' educational progress and support more widespread use of this approach by teachers.

CONCLUSION

Overall, our approach shows that engaging students in collaborative STEM projects can contribute to the understanding of the nature of science and research topics explored in these initiatives. Fostering closer interactions between scientists and students through institutional partnerships can facilitate mutual learning, enriching the experiences of everyone involved and fostering a culture of scientific awareness and engagement among students. Within the limits of the data, our results encourage further exploration of these partnerships and how they might contribute to STEM engagement and scientific literacy in the context of compulsory schooling.

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APPENDIX A: PROTOCOL EXAMPLE

Partnership Protocol Between *[Name of Education Institution]* and *[Name of Research Institution/Organisation]*

[Name of Education Institution]*,** a public entity, with registered office at ***[Institution Address], represented herein by ***[Representative's Name]***, in the capacity of ***[Position].***

and

[Name of Research Institution/Organisation]*,** with registered office at ***[Institution Address], registered under ***[Registration Number]***, here represented by ***[Representative's Name]***, in the capacity of ***[Position]***, with the necessary authority to act in this matter.

Hereinafter collectively referred to as "the Parties."

Considering that:

1. The ***[Education Institution]*** is responsible for the educational activities conducted at ***[School Name].***
2. The ***[Research Institution]*** is dedicated to developing scientific projects, research, and innovation in the fields of ***[Research Institution fields of expertise]***. It also promotes scientific culture and supports public policy dissemination in the context of ***[STEM field].***
3. The ***[Research Institution]*** actively participates in various science education activities and, since ***[Starting Year]***, has collaborated with ***[School Name]*** to deliver scientific outreach and education sessions.
4. Recognising the importance of this collaboration and aiming for its continuity, the Parties enter into this Agreement, which is governed by the following clauses:

Clause 1 – Purpose

This Agreement aims to establish the framework for educational activities to be conducted by ***[Research Institution]*** at ***[Education Institution].***

Clause 2 - Obligations of the parties

[some examples]

1. ***[Research Institution]*** commits to providing educational sessions on dates to be agreed upon by the Parties. It shall ensure the availability of volunteer researchers to lead these sessions and inform the school in advance of the session's content and the identities of the researchers involved.
2. ***[Education Institution]*** commits to facilitating access for designated researchers to the classroom or other suitable locations within its premises. The group may comprise approximately 10 individuals or more, depending on session content. A minimum of one member must be present throughout each session.
3. ***[Education Institution]*** agrees to provide the necessary materials for the sessions.
4. ***[Education Institution]*** authorises ***[Research Institution]*** to mention these educational sessions as part of its outreach activities related to externally funded projects, in which volunteer researchers are team members. Photographs from these sessions may be included, subject to prior agreement with the school.
5. ***[Research Institution]*** agrees to facilitate student visits to its premises on a date to be determined, for specialised sessions as mutually agreed.
6. ***[Education Institution]*** ensures that all students visiting the premises of ***[Research Institution]*** as part of an educational session are covered by personal accident insurance.

Clause 3 - Financial conditions

The educational sessions provided by ***[Research Institution]*** shall be conducted free of charge. However, ***[Education Institution]*** is responsible for supplying any necessary supporting materials.

Clause 4 - Monitoring

The implementation of this Protocol shall be jointly overseen by designated representatives:

- For ***[Research Institution]*: *[Name and Position].***
- For ***[Education Institution]*: *[Name and Position].***

The designated representatives shall maintain regular communication to coordinate the educational sessions.

Clause 5 - Duration and termination

1. This Agreement enters into force on ***[Start Date]*** and remains valid for a period of two (2) years. It shall be automatically renewed for successive periods of equal duration unless either Party notifies the other of

its intention to terminate the Agreement, with at least sixty (60) days' notice before the end of the current term.

2. Notwithstanding the above, either Party may terminate this Agreement at any time by providing written notice via registered letter to the other Party, with a minimum notice period of sixty (60) days.

Clause 6 - Other provisions

1. This Agreement constitutes the entire understanding between the Parties. Any amendments or additions shall only be made in writing and signed by both Parties.
2. Signed in ***[Location]***, on ***[Date]***, in two original copies, both considered as one and the same document, with each Party retaining one copy.

For ***[Education Institution]*** For ***[Research Institution]***

[Representative's name] *[Representative's name]*
[Position] *[Position]*

APPENDIX B: PROJECT FINAL SURVEY

PART I - Personal Experience During the Research Project

For each of the following statements, select the option that best classifies your personal experience during the research project, according to the scale below:

Scale:
1 – Totally disagree
2 – Disagree
3 – Neutral
4 – Agree
5 – Totally agree

Statements:
1 – Before participating in the project, I had already met and interacted with researchers.
2 – Before participating in the project, I was aware of the stages of a research project.
3 – Participating in the project helped me understand the different stages of a research project.
4 – Overall, I enjoyed participating in this project and feel that it contributed to my knowledge.
5 – By the end of this project, I imagine myself following a career in scientific research.

PART II - Personal Experience During the Research Project

For each of the following statements, select the two (2) options that best complete the sentences, according to your personal experience during the project:

Options:
- Data collection
- Data pre-treatment
- Data analysis
- Figure production (with main results)
- Result interpretation
- Scientific poster preparation
- Outreach activities preparation

Statements:
1 – The most difficult and/or challenging tasks of the research project were…
2 – The easiest and/or most accessible tasks of the research project were…
3 – The most uninteresting and/or demotivating tasks of the research project were…
4 – The most interesting and/or motivating tasks of the research project were…

PART III - Knowledge Acquired During the Research Project

For each of the following questions relating to the process of developing a research project, select the <u>correct option</u>. Select only one (1) option per item.

1 – Which of the following stages takes place first in a research project?
a) Data analysis.
b) Data collection.
c) Publication of results.
d) Data treatment.

2 – The results of a research project may be shared:
a) In research papers.
b) In specialised scientific conferences.
c) In public science outreach events.
d) All the above.

3 – What is the importance of the Methods of a research project?
a) Describing the results of the analyses.
b) Explaining the context of the project.
c) Detailing the collection, treatment, and analysis of the data.
d) Interpreting the obtained results.

4 – In a scientific communication (poster, research paper, etc.), the section that explains the relevance of the project is/are the:
a) Introduction.
b) Results.

c) Discussion.
d) Conclusion.

5 – The interpretation of results obtained in a research project allows:
a) Understanding how it fits with previous works.
b) Defining the goals of the research project.
c) Making new inferences based on the collected data.
d) Summarising the main points of the research project.

PART IV - Knowledge Acquired During the Research Project

For each of the following questions on the topic of seasonal colour change, choose the option that best answers the question. Select only one (1) option per item.

1 – The following sentences refer to seasonal colour change. Select the incorrect option.
a) It is an adaptive trait that results in seasonal changes in the colour of individuals.
b) It is a trait shared by birds and mammals.
c) It is a trait that allows maintaining adaptation to environments with seasonally changing conditions.
d) It is a trait with polymorphism of the winter colour, in response to variations in photoperiod.

2 – In Spring, seasonal coat colour change is initiated due to: (select the correct option)
a) Increasing environmental temperature.
b) Decreasing snow cover.
c) Decreasing photoperiod.
d) Increasing photoperiod.

3 – What is a biological polymorphism? (select the correct option)
a) Hereditary disease that affects the morphology of an individual.
b) Phenotypic variation among individuals of the same species or population.
c) Capacity of an individual to change its phenotype in response to variation in environmental conditions.
d) Genetic resistance in the face of mild to strong environmental changes.

4 – The occurrence of populations with distinct winter colours, in species that undergo seasonal coat colour change: (select the correct option)
a) Is linked to mutations in genes involved in pigment production.
b) Allows adaptation to environments with higher temperature variation.
c) Is controlled by photoperiod.
d) Is due to increased snow cover in mountain areas.

5 – When camouflage mismatch occurs, in the face of unfavourable environmental conditions, individuals: (selection the correct option):
a) Change their colour to adapt to the new environmental conditions.
b) Have higher probability of being seen by their prey.
c) Have lower probability of being seen by their predators.
d) Hide so that they are not seen by other animals.

6 – In a context of climate change, which of the following statements is correct?
a) Environmental conditions will be more favourable to the expansion of winter-brown populations.
b) Reductions in snow cover will lead to an increase in the areas of winter-white populations.
c) Winter-white populations will stop changing colour, to maintain camouflage.
d) Brown populations will expand northwards in the species distribution, becoming extinct in the south.

PART V - Final Comment

If you have any additional comments or feedback about your participation in this research project, please write it in the box below.

APPENDIX C: SURVEY RESULTS

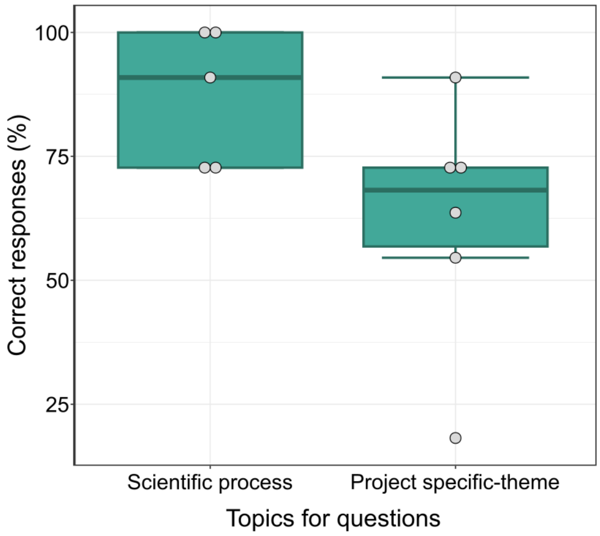

Figure C1. Boxplots of the percentage of correct responses (total N = 11) obtained in each question of the project survey aimed at assessing the acquired knowledge about the steps of the scientific process (N = 5) and the project-specific theme of seasonal coat colour change (N = 6) (each grey dot represents the value of a single question)