Collaborative physics teachers: Enhancing the use of the laboratory through action research in a community of learners

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(Received 2 January 2023; accepted 30 October 2023; published 29 November 2023)

This study contributes to the literature on the role of communities of learners in the professional development of physics teachers. It offers insights from the *Collabora—A Community of Learners on Laboratory Work* program, designed to enhance the use of laboratories in secondary school physics teaching. The program's foundation rested upon two pillars: a learning community approach and action research, grounded in the findings of physics education research. Furthermore, the program was structured to encompass the core features of effective professional development as outlined in the literature (content focus, active learning opportunities, coherence with teachers' needs, and sufficient duration). The program spanned 2 years. During the first year, teachers engaged with and discussed different types of experiments, reflected on the assessment of scientific practices, and participated in action research aimed at improving laboratory activities in their classrooms. In the second year, they focused on integrating laboratory work within teaching-learning sequences developed through a backward design process. The research questions of this study were centered on examining the role and relevance of program features, with particular emphasis on the learning community and action research components, and on investigating the changes reported by teachers as a result of participating in the program. The findings emphasize the pivotal role of the teacher community, with reciprocal training identified as the "truly developmental" element. Moreover, they corroborate the relevance of action research in fostering a sense of ownership of research-based innovations. Over the course of the program, teachers reported changes in the personal domain, in the domain of practice, and, particularly in the second year, also in the domain of student outcomes. These changes included the use of different types of experiments, a greater sense of self-efficacy in the laboratory, and an increased focus on the design and assessment of laboratory work. We studied changes through a "growth" lens, both at the group level and within a subset of individual case studies. The latter analysis highlights different possible productive pathways to teachers' growth, supporting a view of teacher professional development as complex and multifaceted. The program structure facilitated the processes of "enactment" and "reflection" that mediated the various changes.

DOI: 10.1103/PhysRevPhysEducRes.19.020162

I. INTRODUCTION

Given the experimental nature of science subjects, laboratory experiences are considered a qualifying elements of science education [1]. However, research indicates that traditional laboratories hardly yield any measurable gains in conceptual understanding [2,3], offer few opportunities for students to engage in "thinking like a physicist" [4], and do not foster the cultivation of expertlike beliefs about experimental physics [5]. For these reasons, numerous international documents over the past two decades have advocated a transition from the traditional "cookbook recipe" to more student-centered approaches focused on the development of scientific practices [6,7]. Yet, the effective implementation of improved laboratory strategies in the classroom remains a challenge [8,9].

To bridge the gap between research and classroom practice, teacher professional development assumes a pivotal role. Research has shown that one-shot, top-down professional development courses are unlikely to have substantial effects [10,11]. For professional development to yield a significant impact, it should engage teachers over an extended period of time [12], be situated in classroom practice [13], and foster authentic collaboration among teachers as well as between teachers and researchers [14–16]. One context in which these conditions can be met is teacher learning communities [17], which provide ongoing opportunities for collaboration and reflection, leverage teachers' knowledge and expertise, and accommodate multiple developmental pathways [18].

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The work presented in this paper originated from a desire to enhance physics laboratory instruction in high schools, aligning it more closely with research findings. In Italy, teachers receive excellent disciplinary training but often lack practical laboratory experience and the opportunity for pedagogical reflection on laboratory work. This is unfortunate, especially considering that, in Italy, high school physics instruction is provided to all students as part of the common core of disciplines from a minimum of 2 (in technical high schools) to 5 years (in high schools with a scientific major). To accomplish this goal, we developed a professional development program grounded in research findings from both physics education research and teacher education research. In particular, the program was structured and cultivated as a community of learners [17]. For this reason, it was named *Collabora—A Community of Learners on Laboratory Work*. The program incorporated the core features of effective teacher professional development as suggested by Desimone [12] and featured action research [19] as a means to engage teachers as reflective practitioners. This study investigates the role and relevance of the different features for program effectiveness and explores the changes in laboratory instruction reported by the teachers as a result of participating in the program.

II. THE LABORATORY IN PHYSICS EDUCATION

Instructional laboratories play a central role in the teaching and learning of physics, making them a major theme within physics education research (PER). This trend has become particularly pronounced in the past decade, with a growing number of publications on this topic [8]. However, the educational value of instructional laboratories has been a matter of debate. Different learning goals are usually claimed, which can be categorized into three main domains: the enhancement of conceptual knowledge, the development of scientific skills, and the nurturing of students' epistemologies and appreciation for science [20]. Recent research has consistently and robustly demonstrated that laboratories focused on concept development do not measurably improve students' conceptual understanding [2,3], nor do they foster students' appreciation for science [20]. Furthermore, these laboratories are often very prescriptive in nature and involve a very narrow subset of the cognitive tasks involved in experimental physics [4,8]. For these reasons, a shift toward more student-centered, open-ended laboratories focused on the development of scientific abilities has been encouraged [5,20,21].

Also in the context of K-12 science education, there has been a call toward these approaches, often referred to as "inquiry-based" approaches. These recommendations have been made explicit by various international documents [6,7]. However, a gap persists between research findings and classroom practice [9]. The reasons range from practical challenges like limited availability of resources, difficulties in classroom management, and the need to meet national standards, to teachers' limited exposure to the lab, unawareness of research findings, and lack of clarity about the practical realization of inquiry-based approaches in the classroom [9,22,23]. In order to make inquiry-based teaching and learning more comprehensible for practitioners, the National Research Council has proposed a reconceptualization of it in terms of "scientific practices," representing a set of actions undertaken by the scientific community during the construction of scientific knowledge. These practices encompass asking questions; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations; engaging in argument from evidence; and obtaining, evaluating, and communicating information [24,25].

Different instructional methodologies have been proposed with the goal of facilitating the incorporation of scientific practices into instructional laboratories. In the present study, we drew inspiration from the ISLE (Investigative Science Learning Environment) approach [21,26] for encouraging and scaffolding a more practice-based approach to laboratory instruction in secondary school.

ISLE was designed specifically for physics education and integrates many of the findings of physics education research. Within the framework of ISLE, each physics unit is structured around a sequence encompassing three types of experiments [27]:

- *Observational experiments*, where students observe new phenomena and formulate explanations or try to identify underlying patterns;
- *Testing experiments*, in which students test explanations and make predictions based on hypotheses;
- *Application experiments*, in which students employ their newly constructed knowledge to tackle new problems or explain new phenomena.

Through these experiments, students develop a variety of "scientific abilities" [28], which are defined as "the most important procedures, processes, and methods that scientists use when constructing knowledge and when solving experimental problems" (*ibid*., p. 1). Scientific abilities share common ground with scientific practices but are more specific and measurable. In fact, in ISLE experiments, the development of scientific abilities is assessed by means of specifically constructed rubrics.

Although it was developed for undergraduate courses, the core principles of ISLE can be adapted to the context of upper secondary education. In particular, we found it particularly suitable for the Italian educational context, where upper secondary school students receive from 2 to 5 years of compulsory physics instruction.

III. THEORETICAL FRAMEWORK FOR PROFESSIONAL DEVELOPMENT

The way we conceptualize teachers' professional development shapes the approach we take to organizing, describing, and evaluating it. Ball and Cohen [29] suggested that professional development should be a matter of "learning," rather than "updating": We embrace this perspective, which implies recognizing that the process is complex and gradual and acknowledging teachers as both individual learners and members of a social and relational system [13,30].

There is a wealth of research on the conditions that foster effective teacher professional development. In a seminal literature review, Desimone [12] concluded that a consensus exists on five "core features": content focus; active learning opportunities; coherence; sufficient duration; and collective participation of teachers from the same school or grade level. In addition to these structural features, numerous studies have emphasized the importance of engaging teachers in inquiry and reflection, situating teachers' professional development in classroom practice, and promoting teacher collaboration [29,31–35].

In the context of physics education, the need for a theoretical model to conceptually organize the many findings and resources associated with effective teacher preparation, making it specific for physics, has recently been advocated [36,37]. In order to outline this theoretical model, Etkina *et al.* argued that teacher preparation programs should encompass three key elements:

- Extensive apprenticeship-based practice, which entails brief teaching tasks followed by reflection opportunities;
- In-depth coursework on the teaching and learning of physics;
- Nurturing from a community of practice.

In line with this view, we posit that the components of effective professional development suggested by the literature are well captured by two pillars: a learning community approach and action research and that for physics teachers, these pillars should be grounded on the findings of physics education research.

A. Teacher communities

The theoretical background for the present study is that of teacher communities as a context for professional development. In a nutshell, a teacher community is a group of teachers who meet regularly over an extended period of time to collectively advance their expertise on a professional topic of common interest. These communities can be initiated either externally or by teachers themselves and can take a variety of forms [17]. Successful teacher communities can foster improvements in teaching practices and student achievements; their effectiveness depends critically on supportive leadership, composition and group dynamics, and trust and respect [17]. The value of teacher communities for enhancing broad or specific aspects of school science, including laboratory work, has been successfully experimented since the 90s [38]. Participation in a teacher community entails "authentic collaboration" with fellow teachers as well as with researchers, an element that has been indicated as "a promising paradigm for physics education reform" [14]. For these reasons, teacher communities are considered an excellent framework for teachers' professional development [15,16,39,40].

As pointed out by recent reviews [17,40], two dominant frameworks are common in the literature to conceptualize teacher communities: communities of practice (CoP) and professional learning communities (PLC). The construct of CoP, originally introduced by Lave and Wenger [41], is rooted in social and situated learning theory. According to Wenger's definition, CoPs are "groups of people who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" [42] (p. 4). A CoP is characterized by three elements: a shared domain of interest, a community (participants and their interactions), and the practice, as CoP members are practitioners who share their experiences and develop a shared repertoire of knowledge, tools, and approaches [42]. CoPs also allow for different levels of participation, from active contributors to passive listeners, and their focus can shift as the community grows and develops new interests [43]. The construct of PLC is more specific to the educational context and draws from learning organization theory [44]. It is typically situated within a specific educational context, such as a school, although there are examples of networked PLCs [18,45]. PLCs operate under the assumption of intentionality and have a specific focus on improving students' learning [40].

The teacher community established in this project was a researcher-facilitated community, with members participating voluntarily from different types of schools covering a relatively broad area (a large region in northeastern Italy). Given its position encompassing elements of both CoPs and PLCs, we opted to conceptualize it under the broader term "community of learners" (CoL), which also aligns with the aforementioned perspective of professional development as a learning process.

The term community of learners was introduced by Brown and Campione [46] to describe a classroom setting where students share the responsibility for learning and engage in reciprocal teaching. They identified five characteristics that qualify a group as a CoL:

1. Individual responsibility coupled with communal sharing

Within a CoL, all members possess "ownership of certain forms of expertise, but no one has it all" [46] (p. 234). In our CoL, researchers contributed with their expertise in PER, while teachers brought insights from their teaching experience. Expertise was also distributed due to differences in age, years of teaching, and teaching contexts. The interactions in the community arise from this diversity and shape its identity.

2. Ritual, familiar participation frameworks

Wenger's concepts of "rhythm" [42], crucial for the success of CoPs, translates into "ritual participation frameworks" within CoLs [46] (p. 235). These "frameworks" shapes the community's interactions, offering a sense of security and facilitating engagement. For this to happen, the learning activities proposed in the CoL must be recognizable, along with the type of interaction expected. In our case, examples of specific types of activities were engaging in and discussing experiment, constructing experiments, microteaching sessions, small group discussions, and peer review.

3. A community of discourse

In a community, "constructive discussion, questioning, and criticism are the mode rather than the exception" (p. 236). This not only contributes to the construction of a safe, nonthreatening environment but also facilitates the development of a shared vocabulary and knowledge base that fosters a sense of belonging in the community.

4. Multiple zones of proximal development

Analogous to CoPs recognizing different levels of participation, CoLs invite the participation of individuals with different levels of expertise [46]. The CoL offers numerous affordances for personal and professional growth, accommodating multiple pathways through which participants can "navigate via different routes and at different rates" ([47], cited in Ref. [46], p. 236).

5. Seeding, migration, and appropriation of ideas

This feature of CoLs extends beyond the mere sharing of materials: ideas are introduced in the community (*seeding*) and can be harvested by other members (*migration*), who then modify and personalize them to make them suitable for their context (*appropriation*). Notably, this process operates in a multidirectional manner, as the "seeder" is not only the facilitator but can be any participant within the community. In the context of teacher CoLs, this is a call for "de-privatization" of teaching, a concept used in adult education and specifically in the context of faculty learning communities [48].

The CoL characteristics outlined above are useful to add nuance and complexity to the teacher learning "community" construct beyond simplistic views of "professionals coming in a group to learn," a recommendation underscored by recent literature [49].

B. Action research

In the context of education, action research is a deliberate process of inquiry undertaken by teachers with the objective of developing more effective teaching practices. Action research can take different forms based on the role of the teacher within the process [50,51]. At one end of the spectrum, the teacher serves "merely" as a facilitator, furnishing context and providing feedback for a researcher-led innovation. At the other end, action research can be entirely teacher-led, with researchers just providing methodological support. Intermediate between these extremes, *participatory* action research entails a close collaboration and mutual negotiation between researchers and teachers. This collaboration encompasses activities aimed at identifying problems, tackling them as they arise, coaching the research process, and jointly analyzing the outcomes. This form of action research has been used in the professional development of science teachers, demonstrating its potential to bridge the gap between research and classroom practice [19,52].

Action research has also been intertwined with teacher learning communities. For example, the Erasmus + project LINPILCARE (LINking Practitioner Inquiry via effective Professional Learning Communities, 2014–2017) [53] involved six European partners with the goal of developing and disseminating know-how about PLCs and inquiry-based practices. The project generated over a hundred protocols intended to assist facilitators in establishing teacher learning communities focused on inquiry-based approaches. LINPILCARE was followed up by the Erasmus + project 3DIPhE (Three Dimensions of Inquiry in Physics Education, 2017–2020) [54].

C. Evaluating the effects of teacher professional development

Once the key elements that are most likely to sustain effective teacher professional development have been identified, a crucial question is how to evaluate its effects. In this study, we employ the lens of *change* and specifically we adopt a perspective of "change as *growth*" as proposed by Clarke and Hollingsworth [55]. In this perspective, teachers are viewed as "active learners who work in a learning community" [56], aligning with our decision to frame the program as a community of learners.

In the literature, three domains are typically considered to describe teachers' professional growth: the domain of personal knowledge and beliefs, the domain of teaching practice, and the domain of student achievement. The interconnections between these domains have been understood through different models. An implicit model, employed in conventional descriptions of teacher professional development, assumes that teacher training programs primarily act by modifying teachers' knowledge and beliefs, with the expectation that these changes will then translate into changes in teaching practice which should, in turn, yield improved student outcomes. Guskey [57] critiqued this model and introduced an alternative one, according to which changes in student learning outcomes are the catalyst for changes in practice and finally in the personal domain.

A third model, which we refer to in this study, was proposed by Clarke and Hollingsworth and is known as the interconnected model of professional growth [56]. This model goes beyond perspectives of causal chains, where changes in one domain are expected to exclusively precede those in others. Instead, change is characterized by the dynamic interplay of four distinct domains:

- The external domain (sources of information, stimulus, or support, including input from facilitators and colleagues);
- The personal domain (teachers' knowledge, beliefs, and attitudes);
- The domain of practice (actions in the classroom);
- The domain of consequence (the domain of outcomes, such as student learning or motivation).

These domains are "interconnected" through the mediating processes of "enactment" and "reflection, which occur within the constraints and affordances of the environment.

A prominent difference between this model and its predecessors is the acknowledgment of multiple entry points and developmental pathways, a perspective supported by recent literature, also for physics teachers specifically [18]. Moreover, by explicitly including the external domain in the description of teacher change, this framework emphasizes the importance of analyzing teacher development along with the conditions that promote it (in our case, the program components).

IV. RESEARCH QUESTIONS

The aim of this study was to identify a teacher professional development strategy able to enhance the use of laboratory work in secondary school physics teaching. Specifically, we hypothesized that structuring the program based on the learning community approach and action research, alongside respecting the core features identified by Desimone [12] and grounding coursework in physics education research, would facilitate changes in laboratory instruction within all three domains of teachers' growth (the personal domain, the domain of practice, and the domain of consequence). While some previous findings in the contexts of primary and middle school support this hypothesis [39,58], the current study extends research into physics instructional laboratories in high school, where the effects of CoLs on teachers' growth have been less extensively studied (exceptions are Refs. [18,59,60]).

To explore our hypothesis, we designed and piloted a professional development program named Collabora—A Community of Learners on Laboratory Work. The name highlights the focus of both professional development (laboratory instruction) and the learning community approach. Moreover, the word "collabora" in Italian sounds like an invitation to collaborate.

In this study, we specifically investigate the following research questions:

RQ1 What was the role and relevance of the program features, particularly the learning community and action research, in facilitating the professional development of teachers in regard to laboratory instruction?

RQ2 What changes in laboratory instruction did the teachers report as a result of participating in the program?

We will first describe the program and our research methods (Sec. V). Then, in Sec. VI, we will present and discuss the results of the study. In Sec. VII, we will address the research questions based on our findings, and in Sec. VIII, we will outline implications and future perspectives.

V. DESIGN

A. The physics topic: Waves

Consistent with literature recommendations to identify a content focus for teacher training programs, we selected a specific physics topic for designing our experiments and related activities. We chose waves as they play a fundamental role in interpreting the natural world and in understanding contemporary technologies. For this reason, they are considered one of the "core ideas" of physics in the *Framework for K-12 Science Education* [24], and they also appear as a key concept throughout the physics curriculum of Italian upper secondary schools [61,62].

Physics education research (PER) has been concerned with defining the conceptual nodes underlying the understanding of wave phenomena while also exploring specific topics in terms of student difficulties and strategies that can promote understanding. Balzano *et al.* [63] identified three pivotal elements for constructing coherent scientific knowledge about waves: understanding *systems* (recognizing the components of interacting systems, such as source, medium, receiver, and the environment); understanding *variables* (differentiating the variables that characterize a wave and understanding how they depend on the medium, source, or source-medium coupling); and recognizing and describing common wave *phenomena*, such as propagation, superposition, and interference.

In designing the program, we started with mechanical waves, specifically with the study of pulses on strings and springs. This approach challenges a common difficulty in wave interpretation, i.e., distinguishing between the propagation of the pulse and the local oscillation of particles within the medium [64,65]. The study of pulses helps reinforce the description of wave phenomena in terms of the source-medium-pulse scheme, identifying the relevant variables, their relationship, and their dependence on the different elements of the system. We emphasized the use of diverse graphical representations, highlighting the distinction between the spatial view ("snapshot graphs," i.e., displacement vs position graphs) and the temporal view ("history graphs," i.e., displacement vs time graphs). The mechanical waves concept survey, proposed to the teachers [66–68], aided us in the discussion of typical student difficulties and strategies to address them [69].

FIG. 1. Visual representation of the Collabora approach.

We then progressed to sound waves, using standing waves on a string as a bridge. Exploring the connection between sound and mechanical oscillations allowed us to interpret sound waves as mechanical waves. Technological tools like Phyphox [70] were used to measure sound properties and introduce new levels of analysis (e.g., frequency analysis).

For light waves, we also began by observing similarities with the phenomenology of mechanical waves. This transition was supported by observing two-dimensional waves in water using a ripple tank, discussing how the behavior of water at distinct points results from wave superposition. Subsequently, we delved into wave optics, exploring interference and diffraction. We emphasized the role of phase differences in explaining the location of maxima and minima, and we generalized this reasoning to understand multiple-slit interference and the functioning of diffraction gratings. This progression is conceptually similar to the one proposed by Wosilait *et al.* [71].

As a last step, we approached modern physics, utilizing diffraction gratings for spectral analysis of various light sources [72] and discussing related teaching and learning challenges [73,74].

Each meeting featured at least one research-based experiment connected to the specific topic covered in the session. Different types of experiments (observation, testing, and application) were incorporated, emphasizing their potential role in the teaching and learning of the concepts and in the development of scientific practices. Some of the experiments were drawn or adapted from the ISLE database, while others were designed for the program according to the ISLE guidelines for the different types of experiment. In addition to the experiments, each topic unit (spanning multiple meetings) included prelab and postlab sessions, topic-specific discussions of PER findings (e.g., students' difficulties, useful representations), and reflections on assessment with rubrics. In one meeting, we arranged a visit to our Museum of the History of Physics, which houses insightful collections of instruments related to optics, sound waves, and more.

B. The Collabora model

In Fig. 1, we present a visual representation the Collabora approach that allows us to visualize its key elements, their relationships, and how the model was constructed. The honeycomb imagery, used for the logo and the representation of program features, was chosen to convey the ideas of collaboration and community.

The orange cells on which the logo rests—the learning community and action research—represent the pillars of the program of our approach to teacher professional development. The gold cells surrounding these two pillars are the core features described by Desimone [12], which provide structure to the program. These features are not unique to programs on physics or laboratory work but, borrowing an expression from [37], they were "furnished" with PER- and laboratory-specific elements, as explained in the following paragraph. As part of our first research question, we wanted to understand how these features "work" in the specific context of in-service physics teachers training for laboratory instruction. One may notice that the "collective participation of teachers from the same school or grade level" (the fifth feature identified by Desimone) is not included, as the participation of teachers from the

TABLE I. Program features and how they were realized.

Feature	Implementation
Content focus	We focused on a specific physics topic (waves) and grounded coursework in physics education research findings.
Active learning	Teachers engaged in direct experimentation, group work, peer instruction, and collaborative tasks.
Coherence	We acknowledged the teachers' backgrounds, contexts, and needs in relation to the laboratory.
Sufficient duration	The course lasted 1 year (then extended to 2) with regular monthly meetings.
Community of learners	The program was built on the principles of shared vision and goals, trust and respect, and shared responsibility for learning.
Action research	Each participant was asked to plan and implement an action research plan in his or her own classroom.

same school, although encouraged, was not mandatory. Nevertheless, Desimone's suggestion of cultivating interaction and professional discourse, which should be promoted through collective participation, is incorporated within the learning community approach. In future projects, it could be interesting to explore how the dynamics changes if this requirement is introduced.

Finally, the yellow cells next to the "content focus feature highlight two elements that we introduced for characterizing the model as specific to physics, and the physics laboratory in particular. First, the program was grounded in the findings of physics education research (PER), in terms of both the physics topic (waves and the specific subtopics) and with regard to laboratory work. Throughout the program, we consistently referred to PER findings and shared selected articles with the teachers to enhance their awareness of PER [75]. The second consideration was an attention to the explicit integration of physics content and scientific practices. This specification was aimed at making scientific practices explicit as a pivotal dimension of physics education and the key goal of instructional laboratories.

Table I offers a summary of the program features and a description of their concrete implementation.

C. Program implementation

The program was initially designed to span 1 year, as outlined in the schedule in Table II. It started with two meetings in May 2018, followed by two additional sessions in September 2018. Subsequently, we met on a regular monthly basis from October 2018 through June 2019, accumulating a total of 45 contact hours. During the sessions, teachers were engaged in a variety of activities, including conducting experiments, discussing disciplinary and methodological issues, and creating laboratory activities along with assessment rubrics.

TABLE II. Schedule and content of the first year of the program.

Date	Activities
May 2018a	Learning community setup. Analysis of an ISLE-based laboratory activity on refraction + discussion.
May 2018b	Laboratory activity (testing experiment + application experiments) on ray optics + discussion.
Sep 2018a	Laboratory activity (observational experiment) on mechanical waves on strings and springs + discussion. Formulation of action research questions.
Sep 2018b	Overview of the educational reconstruction of the topic of waves based on Balzano *et al.* [63]. Development of individual action research plans + peer feedback.
Oct 2018	Discussion of the mechanical waves concept survey (MCWS) and reflection on students' understanding of mechanical waves. Reflection on scientific practices. Laboratory activity on standing waves + discussion.
Nov 2018	Disciplinary review and physics education research on sound waves. Laboratory activity on sound waves produced by different musical instruments (also using Phyphox) + discussion. Peer review of action research plans.
Dec 2018	Visit to the Museum of the History of Physics, highlighting the role of instruments and experiments in the history of physics education. Group work on the different types of experiments and their role in a TLS.
Jan 2019	Collaborative design of a laboratory activity on ray optics. Introduction to the ISLE assessment rubrics and discussion on the assessment of laboratory activities.
Feb 2019	Laboratory activities on wave optics according to the three types of experiments + discussion.
Mar 2019	Individual + group concept map on the topic of light. Laboratory activity on light sources and spectra + discussion.
Apr 2019	Laboratory activity on atomic spectra. Discussion on the value of spectroscopy to introduce modern physics and discussion of relevant literature.
May 2019	Final workshop: Each participant presented the results of his or her project.
June 2019	Final focus group.

TABLE III. Schedule and content of the second year of the program.

Date	Activities
Oct 2019	Setting of common goals for the new year. Introduction to TLS design and to the backward design approach. Division into subgroups and beginning of TLS planning.
Nov 2019	Discussion on the relationship between inquiry, scientific practices, and the ISLE approach. Continuation of TLS planning.
Dec 2019	Presentation of a TLS on measurement previously designed and implemented by one of the participants in her classroom. Experimentation of one of the laboratory activities included in the TLS.
Jan 2020	Presentation, experimentation, and discussion of TLSs on optics designed by the participants.
Feb 2020	Presentation, experimentation, and discussion of TLSs on optics and on kinematics designed by the participants.
Mar 2020	(online) Presentation of TLSs on kinematics and on special relativity designed by the participants.
Apr 2020	(online) Presentation of a TLS on electrostatics designed by one of the participants. Discussion of teaching and learning issues of electrostatics.
May 2020	(online) Presentation of a TLS on the photoelectric effect and a TLS on wave optics designed by the participants.
June 2020	(online) Final focus group.

In the initial meetings, we encouraged teachers to formulate a research question related to laboratory work, relevant to their own teaching context. We scaffolded the formulation of research questions with specific activities and peer feedback. We then assisted the teachers in identifying the data needed to address their questions and in selecting suitable data collection tools. Through guided activities, each teacher drafted an action research plan that was then subject to peer review. Teacher would then implement their plans in the second part of the program and share their results during the final meeting.

At the end of the year, teachers expressed their desire to continue participation in the community. Consequently, we decided to extend the program for another year, scheduling nine monthly meetings from October 2019 to June 2020 (Table III). In March 2020, the COVID-19 pandemic broke out and we transitioned to virtual meetings.

We shaped the second year according to the needs that had emerged at the end of the first one. These were more support for classroom experimentation and enhanced opportunities for collaboration. To address the first need, we decided to refocus the action research element into a more specific task, i.e., the design and implementation a teaching-learning sequence (TLS) incorporating laboratory activities. A TLS is a didactic sequence where the relationship between teaching and learning is made explicit and studied in order to enhance its efficacy. Often, this process involves a recursive approach informed by data [76]. Reflecting at the level of teaching-learning sequences—i.e., not only on the experiments but also on how to embed laboratory activities into a coherent instructional sequence—is crucial for making laboratory work effective [10].

Among the possible strategies for constructing a TLS, we opted for the backward design (BD) approach [77]. In this approach, the conventional logic of activity-oriented planning is reversed: the first step is defining the desired learning outcomes (formulated in terms of "enduring understandings" and related "essential questions"); the second step entails identifying what constitutes evidence of learning; finally, the sequencing of activities is the third step, and should be aligned with the first two. BD has been used in teacher education programs with promising results [78] and it aligns with other approaches proposed in the literature, such as constructive alignment [79]. In our program, the selection of the BD approach was driven by its emphasis on learning goals. Indeed, a lack of clarity regarding learning goals has been recognized as one of the major challenges for the effectiveness of instructional laboratories [10]. To address this concern and align with recent research findings, we prompted the teachers to explicitly consider scientific practices in the definition of their learning outcomes. Since not all participants were teaching wave-related content during the second year of the program, this time we gave them more freedom in the choice of the topic for their TLS. However, we tried to minimize the number of topics in order not to lose the community element and encourage collaboration.

Teachers were supported in the use of backward design through different strategies: (i) the backward approach was explicitly presented and discussed, and all the materials used for the presentation were made available on the course platform; (ii) one of the teachers, who had used the BD approach previously in the design of a lesson cycle, presented her experience and conducted a microteaching session based on it (December 2019); (iii) a handout ("backward design matrix") was given to the teachers, following Wiggins and McTighe's [77] steps and providing structure for each one. Each section of the handout contained summary information on how to compile it (Fig. 2).

Initially, teachers worked through the matrix in groups, according to the topics of experimentation. Specifically, they covered stage 1 of the matrix ("identify desired outcomes") over the course of two meetings at the beginning of the school year (October–November 2019). We decided to focus on this portion of the matrix during

CoLLabora - TLS design matrix

STAGE 1 – Identify desired results

Competences and goals from national and international standards
Include references to competence milestones and learning objectives from the National Guidelines, EU documents and possibly other international references (e.g., *A framework for K-12 science education*, articulating the core ideas and scientific practices included in your TLS).

Area of meanings	
Enduring understanding	
Understandings	**Essential questions**
What do you ultimately want the students to understand? → Not a list of topics or content, but statements that encapsulate key ideas. They can encompass both discipline-specific ideas and broader ideas (cultural, social value of physics).	Questions one aims to answer through the TLS, leading to the enduring understandings. → They provoke thought, discussion, the need for investigation, and lead to the construction of knowledge. They encourage considering alternatives, looking for evidence, questioning one's own ideas, and providing arguments. They are broad enough to remain meaningful in other contexts and open up connections.
Area of aquisitions	
Knowledge and skills	
Knowledge: What will the students know?	**Skills:** What will the students be able to do?

STAGE 2 – Determine acceptable evidence

Authentic performance task	**Other types of evidence**
An open and "complex" task, aligned with the enduring understandings.	Objective evidence (tests, lab reports, quizzes…), nonformal and/or intersubjective evidence (observations, records of conversations, …), students' self-assessment.
Criteria and tools for assessment	Criteria and tools for assessment
E.g., Rubric, with items and descriptors.	Specify the tool(s) and criteria for evaluation.

STAGE 3 – Plan learning experiences

Activities
You can use different models you have experimented in the programme (e.g., ISLE), or other research-based models you are familiar with.

FIG. 2. The backward design matrix provided to the teachers (English version; original in Italian).

in-person sessions for two reasons: to avoid teachers quickly transitioning to the activity phase (thus potentially reverting to the traditional logic) and to support them in articulating learning outcomes using the backward design language, with which they were not familiar. The process of formulating enduring understandings and essential questions led to in-depth discussion about the educational reconstruction of the topics. Teachers engaged in this process through conversations with the researchers, reviews of their notes and materials from the first year of the program (e.g., discussion of experiments), and consultation of research-based textbooks that were available during the meetings. Additional materials, such as research papers on the teaching and learning of specific subtopics, were provided through the Moodle platform or via individual email exchanges upon request or when they came up in the discussions.

Teachers completed the remaining part of the matrix individually at home but were encouraged to engage with their peers and the researchers throughout the process. After drafting a preliminary TLS draft, teachers engaged in microteaching sessions where they presented their TLS and proposed some of the planned activities to colleagues, who gave constructive feedback. These microteaching sessions were scheduled to occupy the rest of the meetings in year 2 (January through May 2020), but due to the pandemic breakout, the structure of (virtual) meetings from March to May 2020 was partially revisited while still entailing the presentation of the designed TLSs.

Several exchanges took place between teachers and researchers during this phase. Typically, teachers would send their draft TLSs to researchers for feedback before their scheduled microteaching session and then again after the session for finalization. This was the case, at least, for teachers ($N = 5$) who had the opportunity to conduct in-person microteaching sessions before the onset of the pandemic. The remaining six teachers, whose microteaching sessions were scheduled later in the program, varied in their completion of the design task. Specifically, two teachers completed the full task framing it for an online teaching setting, one completed it partially (defined some learning outcomes and designed aligned activities), two just outlined some activities, and finally one teacher declared his inability to adapt the task for online teaching, through continuing to participate in the meetings. Although a detailed exploration of the different individual levels of participation is beyond the scope of this paper, these diverse patterns of connections and interactions within the community align with descriptions in both traditional [43] and online [80,81] communities of practice.

An example of a TLS developed through this process, including the compiled BD matrix, details on TLS development and adaptation to the online environment, and data on TLS implementation at school can be found in Ref. [82].

D. Participants

A total of 15 teachers (6 males and 9 females) enrolled in the first year of the Collabora program. Participants came from 11 schools in the Veneto region, one of the 20 Italian regions, located in the north-east of the country. Out of them, 11 participants (6 males and 5 females) from 9 schools continued into the second year.

The majority of the participants' schools (12 participants, 9 schools) were *Licei* (high schools geared toward higher education studies, with various possible "majors" such as science, classical studies, languages, arts, etc.). Students in these schools get a minimum of 3 (for nonscience majors) to 5 years (for science majors) of compulsory physics instruction. Two teachers worked in the same technical school, where students get 2 years of compulsory physics instruction, and one teacher worked in a vocational school, where students get 2 years of compulsory integrated science instruction including physics.

Most of the participants (8) held a degree in mathematics. The remaining participants had a degree in physics (3), engineering (3), or astronomy (1), which aligns with the profile of physics teachers in Italy. Personal experience in the laboratory varied among participants; most of them had low (5) or medium-low (6) experience, while some had greater familiarity with laboratory practices due to their academic background. Although all of the participants' schools were equipped with a laboratory, in an initial survey only 4 teachers indicated that they regularly conducted laboratory activities. The others reported offering these activities occasionally (7) or almost never (4).

The CoL sessions were facilitated by two researchers in physics education (authors of this paper) working at the Department of Physics and Astronomy of the University of Padua, a large university in the same region as the participants' schools.

E. Methods

Our research is a case study conducted over the 2 years during which the Collabora program took place. To gain insights into our research questions, we gathered data from multiple sources (for detailed information, refer to the Supplemental Material [83]):

- Online questionnaires were administered at the end of each year to survey changes in the use of the laboratory, the program's alignment with the desired features, the most beneficial activities for teachers, and the extent to which participants' expectations were met. The questions were structured as either Likert-type items with response options ranging from 1 (not at all) to 4 (very much), multiple-choice questions, or ranking items. In addition, two open-ended questions were included to provide participants with the opportunity to further elaborate on their responses or provide additional comments.
- Focus groups were conducted at the end of each year to discuss the role and relevance of the program features in facilitating professional development on laboratory work and to explore the strengths, weaknesses, and future perspectives of the program.
- Individual interviews were conducted at the end of the program to delve deeper into each teacher's changes in the use of the laboratory.

Both the focus group and interviews were semistructured. The protocol outlined the main themes to be addressed, but the order of the questions was flexible, and some questions were explored in greater or lesser depth based on the respondent's input. During focus groups, where multiple respondents participated simultaneously, the conversation often evolved as teachers' elaborated upon their colleagues' statements.

The interviews, focus groups, and open-ended answers were coded either deductively (for RQ1) or inductively (for RQ2) in order to answer the two research questions. To learn about the role and relevance of program features (RQ1), we coded for each of the features in Table I whenever a participant highlighted it as important in the program. Examples of quotes coded for each feature are provided in Table IV. For the *learning community* component, we introduced subcodes to better explore the facets of the learning community that held greater relevance. We adopted the characteristics of CoLs identified by Brown and Campione [46] as subcodes, as they captured the teachers' comments well. We briefly recall them here: individual responsibility coupled with communal sharing; a community of discourse; ritual and familiar participation structures; multiple zones of proximal development; seeding, migration, and appropriation of ideas.

TABLE IV. Examples of coded quotes for each of the features considered in RQ1.

Category	Example of quote
Content focus	"For example, one of the flaws of my preservice training was that pedagogy courses had nothing to do with the science part. As a result, we sometimes found them a bit distant from our needs. It is far more beneficial to have courses focused on physics education."
Active learning	"Conducting experiments firsthand, while drawing upon diverse expertise and possibly different areas of focus, motivated us and likely gave us a better understanding of how students might perceive a particular activity."
Coherence	"I was really thirsting for it. Ever since I started teaching, one thing I lacked was a little bit of research. So, it gave me a sense of relief to discover that I'm not alone and that there is somebody out there working on this."
Sufficient duration	"It was good that we could experiment during the course, reflect, and try to apply something in the classroom. And if something went wrong, you could catch up the following month."
Community of learners	"It means a lot, that we are together. We all share more or less the same problems and we all try to do our best. Personally, this community is important as it serves as a reference point for me. I feel like I belong here, I feel good here."
Action research	"I was tired of doing things for pretend. This time, I had a classroom where I could experiment, I could try to do it concretely."

The coding scheme for reported changes (RQ2) was defined inductively. Initially, a new category was defined each time a new change was mentioned by a respondent. These categories were subsequently clustered when occurrences were infrequent. As a category emerged, it was categorized within the *personal domain*, the *domain of practice*, or the *domain of consequence*, as defined in the interconnected model of professional growth [56]. This process was initially developed by one of the researchers (M. C.) and later shared and discussed with the other researcher (O. P.) until a consensus was reached. The final categories defined for each domain are detailed in Table V. We notice that, while many of the codes explicitly include terms like "laboratory" or "experiments," some do not. Nevertheless, we retained these codes in order to answer our second research question, as they represent understandings or practices that relate to, though extend beyond, the primary goal of our program.

We also would like to mention that responses to some of the items in the questionnaires, focus groups, and interviews, are not discussed in this paper. While these responses were important for global program evaluation and further project developments, they were not relevant to the research questions addressed here. For those interested, some of these additional findings are provided in the Supplemental Material [83].

VI. RESULTS

A. Relevance and role of the program features

In Fig. 3, we report the number of teachers who mentioned each of the program features as a crucial element for facilitating professional development in laboratory instruction. In the following sections, we will begin by providing a brief discussion on the role and relevance of the structural features from Desimone [12], then we will delve into the significance of the two elements posited as the pillars of the Collabora program: the community of learners and action research. To support our discussion, we have included illustrative quotes throughout the text. Pseudonyms are employed to protect the confidentiality of the participants.

1. Features derived from the literature

Content focus. Participants acknowledged the importance of situating the course within a specific physics topic. They valued the choice of waves for their cross-cutting and

TABLE V. The domains of change and the corresponding subcategories considered for RQ2.

Domain of change	Subcategories
Personal domain	Views and beliefs about the laboratory; understanding of the physics curriculum; knowledge of different types of experiments; knowledge about laboratory assessment; awareness of physics education research; ideas and attitudes about physics teaching; self-efficacy beliefs; knowledge about TLS design.
Domain of practice	Use of more student-centered activities; use of the laboratory for more topics; use of different types of experiments; other new or different activities; use of different laboratory assessment; use of TLS design.
Domain of consequence	Improved students' learning or engagement; improved students' acceptance.

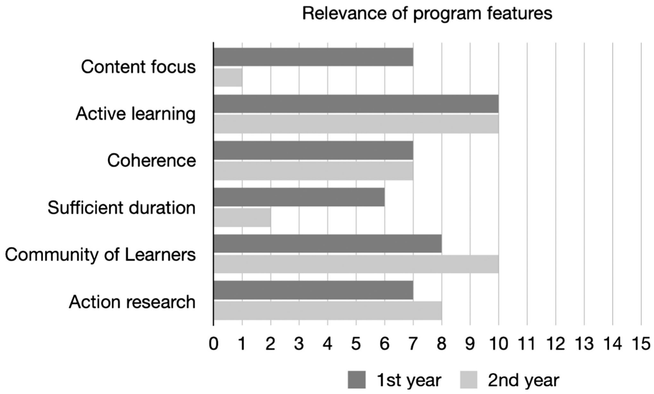

FIG. 3. The count of teachers who mentioned each program feature as pivotal for program effectiveness. The data for the first year are based on a sample of 15 teachers, while the data for the second year represent the 11 teachers who continued their participation in the program.

foundational role in the physics curriculum, with the possibility to design different types of experiments across various subtopics and years, highlighting conceptual and experimental similarities among different areas of physics. In contrast, as the range of topics was expanded in the second year, some teachers encountered greater difficulties in active participation.

Concerning the grounding in PER, one teacher remarked:

> You also pointed us to the literature. The idea that there is someone who has reflected on a topic, that there is a group who has worked on it, was highly valuable for me, to stay in the project. This is an attention you seldom encounter in [professional development] courses, and it is also culturally important. (Gordon)

Active learning opportunities. Nearly unanimous recognition was given to the relevance of active learning opportunities. To understand which activities in particular were most useful, participants were asked to select the three most significant ones from a provided list (Fig. 4). In the first year, the most favored activities were constructing laboratory activities, experimenting with laboratory activities, engaging in group discussions, and personal interactions with researchers. In the second year, alongside experimenting with laboratory activities, designing a teaching-learning sequence (TLS) with a well-defined approach emerged as the most useful activity. One participant commented:

> Experimenting with a more structured design, I found it very useful…trying to rethink something I've always taught the same way and saying, 'Okay, I'm going to pause, I'm going to try and reshape it'. (Lisa)

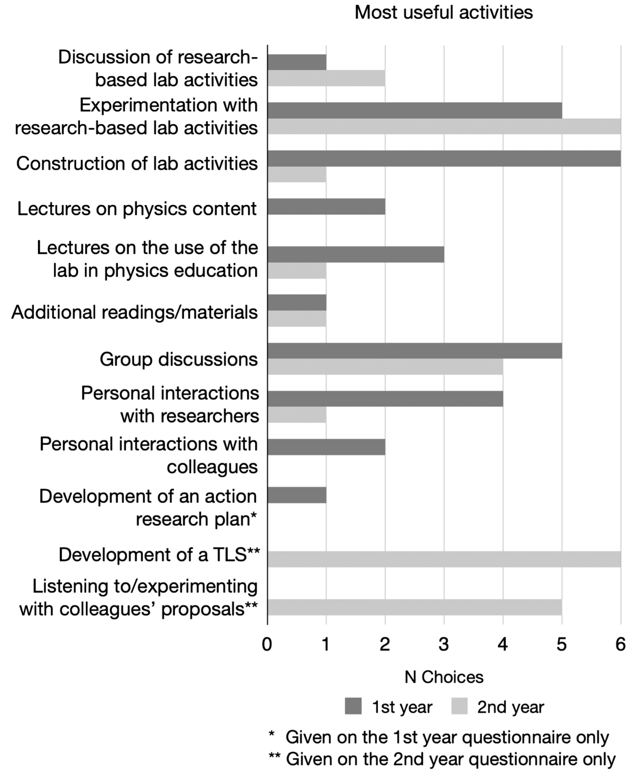

FIG. 4. The count of teachers who ranked each activity among the top 3 most useful ones. The data for the first year are based on a sample of 15 teachers, while the data for the second year represent the 11 teachers who continued their participation in the program.

Another element introduced in the second year that participants found valuable was the microteaching sessions, where colleagues shared some of the activities of their TLSs:

> I greatly appreciated that all of us tried to do something and then shared it. This was really one of the strengths. Whenever a colleague said, 'I tried this,' and shared what they did and how, that was really helpful. (Margot)

Coherence. Participants often referred to program coherence in terms of their need to enhance their understanding of the value of laboratory work. This was especially crucial considering the mathematical background of many teachers. Some of them also reported that the program met their need for a professional development course focused on physics *education*, rather than solely focusing on physics content knowledge or general education.

Sufficient duration. The extended duration of the program allowed for a gradual implementation and appropriation of the proposed innovations. Participants valued the monthly schedule and the establishment of a fixed day (the third Friday of the month), as these elements added structure and rhythm to the program and allowed ample time for reflection:

> This was a strength of the program—the chance to implement small changes step by step. Often, I attend courses that are intensive, valuable, but then I don't apply them right away because they don't align with the timing of the [school] year. Instead, if I have the opportunity to experiment and reflect along the way, I come to program sessions well-prepared and equipped with questions to ask. (Lisa)

2. The community of learners

Participants acknowledged the presence of the learning community and considered it a distinctive element of the program. The appreciation for the CoL approach grew stronger after the second year, and the description of its role in the program became more nuanced. To gain a deeper insight into the most relevant aspects of the CoL approach, we analyzed teachers' comments with respect to the characteristics of CoLs as described by Brown and Campione (Fig. 5).

Nearly all participants referred to the Collabora group as a *community of discourse* for cultivating shared visions about laboratory instruction and developing a common language. The reference to the ISLE model provided this common ground and language (e.g., the categorization of experiments into three types; "scientific abilities" as a framework for articulating and discussing learning outcomes).

> [The community] was important especially when problems and difficulties arise—because they always do—there is an environment in which to report and address them, review them. (Lisa)

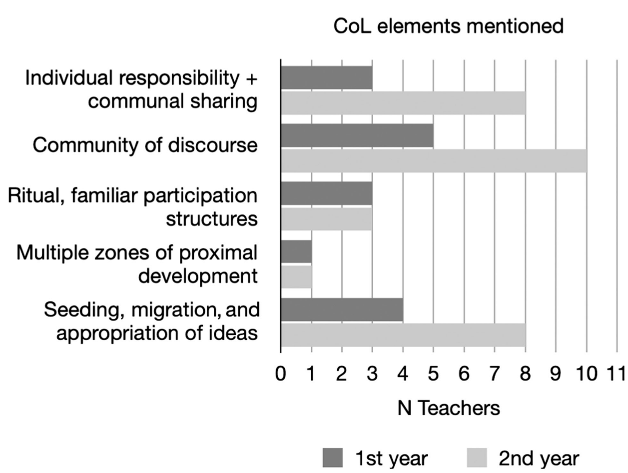

FIG. 5. Aspects of a learning community highlighted by participants. The data for the first year are based on a sample of 15 teachers, while the data for the second year represent the 11 teachers who continued their participation in the program.

The group was depicted it as a safe and nonthreatening place where colleagues with shared interests and visions can be found and where constructive discussions are the norm:

> Being part of this group, listening to the discussions, even as more of a spectator than an actor, gave me an awareness of how one should work, what one could do. It was like an anchor; it gave me companionship, joy, inspiration, and confidence in the future. It reminded me that our work should never lapse into routine, but should rather have continuous inspirations, coming from good trainers, but also from us, the teachers. (Mike)

Teachers particularly underscored the significance of the community during the COVID-19 emergency, citing it as the pivotal factor to maintain their engagement in the program:

> Why I decided to stay? Because it's actually a community. The dimension of community binds you and encourages you to stay. (It's) the fact of recognizing this group as a one in which I recognize myself and I feel at ease. (Fred)
>
> The COVID emergency highlighted the importance of having a community to engage with. This importance should persist beyond the emergency, because physics education is continuously evolving. Thus, having a group of people to engage in discussions with remains essential. (Sophie)

These reports align with recent findings where the community was mentioned as one of the primary sources of support for instructors during emergency remote teaching, facilitating the sharing of ideas and practices, as well as providing moral support [84].

The second most frequently highlighted aspect of the learning community was *individual responsibility coupled with communal sharing*. Specifically, participants emphasized the importance of valuing teachers' expertise and providing opportunities for peer instruction:

> Teachers have a wealth of knowledge and skills that they can do well, but they never share them. Instead, professional development becomes truly 'developmental' when I prepare myself to train others, and in doing so, I also train myself. I try something out, try to teach others, they give me advice, they take something and then try it themselves. This reciprocal training holds immense value, and it works in a community, not when we don't know one another. (Lisa)

Ethan, a teacher with a lot of personal experience in experimental physics (he has a Ph.D. in astronomy), reported learning more than he expected from fellow teachers, including those with less personal academic experience than him in the lab:

> I was impressed by the quality of proposals from my colleagues. At times, [their contributions] hold even more value than those from researchers, because they are conveyed in the language of teachers. While researchers' suggestions may be of superior quality, teachers articulate them in a way that is easier to understand. (Ethan)

Finally, participants acknowledged the advantages of collective learning:

> The most important lesson I've learned is that you cannot teach in isolation. The small things I have been able to accomplish in my classroom were really built upon the contribution of everyone in this community. (Margot)

Participants also recounted instances of *seeding, migration, and appropriation of ideas* as they "harvested" colleagues' ideas and adapted them to their own contexts:

> I accumulated ideas. After each meeting, I would jot down notes, save and organize them. I maintain folders for the different teaching units, and within each one, I would record the good ideas, the notes, so that when I plan for the upcoming year, I can retrieve them and say, well, let's try to do what the colleague did. (Ethan)

To complete the analysis of the role of the CoL in the program, participants were asked to evaluate its utility concerning four broader goals of teacher professional development, mentioned in recent discussions at the national level (facilitating learning, supporting classroom experimentation, fostering collaboration among colleagues, and enhancing the relationship between school and university). Positive feedback was received for all four aspects, as illustrated in Fig. 6.

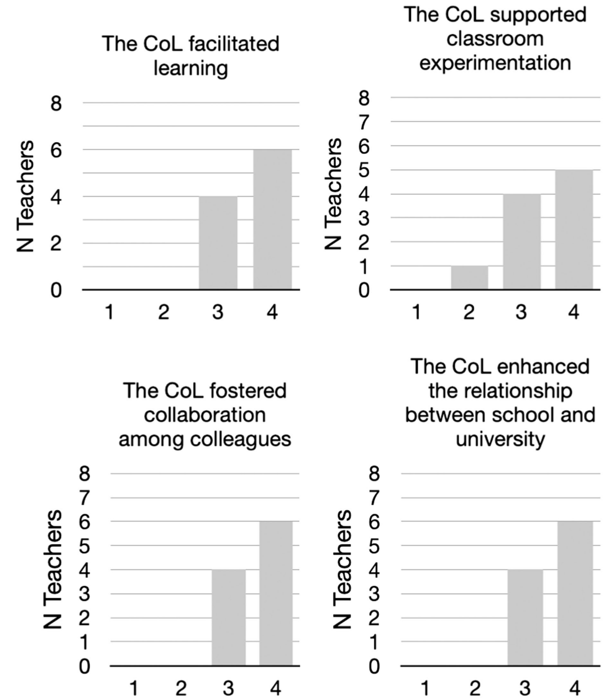

FIG. 6. Participants' assessment of the effectiveness of the CoL approach in addressing some broader professional development goals. The data pertain to the group of 11 teachers who completed the second year.

3. Action research

Participants highly valued the opportunity to experiment in their own classrooms, a component that is not typically included in professional development courses:

> In my opinion, teacher training courses should be like this, practical. If a methodology is introduced, I'd also like to have the chance to put it into practice, understand its strengths, how to use it, and in what contexts. (Sylvia)

Some participants valued the opportunity to conduct research in a systematic manner, which involved using data collection tools and gathering feedback from students. A crucial factor in this process was the guidance offered to teachers as they navigated their way through experimentation in the classroom. Lisa, for instance, reiterated this aspect on multiple occasions:

> I truly appreciated the way you guided us step by step in formulating our action research question, starting from where we were, from our strengths and weaknesses. (Lisa)

And later,

> In most courses, even when there is a practical assignment, you cannot prepare for it. But if I don't try, and I don't get feedback while experimenting, it's useless. The thing that made the difference here is that you guided us along the way. (Lisa)

Despite the recognition of the value of action research, its role in the first year of the program was less significant than expected, compared to other activities (Fig. 4). Many teachers reported that the most beneficial aspect of participating in action research was "cultivating a research mindset" (Adam), "concentrating on a question" (Gordon), "finding a focus within ourselves" (Margot), whereas it was difficult to develop an action research plan and put it into practice. Some of the difficulties were as follows:

- Selecting a "wrong" target: I got the target class just wrong. I had something in mind for the fifth year, but I soon realized that such an action research plan was better suited for younger classes. (Gordon)
- Starting too big: I aimed a bit too high. Instead of focusing on a single laboratory sequence, I attempted to devise a whole new strategy for instructional labs that I never actually put into practice. (Fred)
- Lack of a defined deadline: For me, the difficulty was the absence of a strict deadline; I didn't feel the pressure to finish something. (Gordon)

These insights prompted us to revise the action research component by providing teachers with a more precise focus and timeline through the development of a TLS. Unfortunately, the emergence of the COVID-19 pandemic coincided with teachers starting to implement their TLSs in the classroom. This represented of course a challenge, given the laboratory focus of the TLSs. Reactions to the situation were varied:

- Three teachers restructured the entire TLS for the online context, restarting from the identified learning outcomes and modifying the activities for the new situation. One of these TLSs was documented in a prior publication [82].
- Six teachers implemented only a few elements of the planned TLS, adapting the activities to the online context. The action research potential of the TLS was not fully realized, but they did report using some experiments, adopting the rubrics, etc.
- Finally, two teachers stated that the demands of distance teaching overwhelmed them, resulting in them not implementing any aspects of their planned TLS. Specific reasons were increased workload and the characteristics of the online instructional space which was particularly hard to reconcile with a laboratory focus.

These circumstances complicate the assessment of the role of action research in the program; nevertheless, the development of a TLS was identified as one of the most beneficial activities, as discussed earlier.

B. Reported changes

1. Group evolution

Figure 7 displays the changes reported by participants after each year of the course, and the number of teachers who mentioned each change. The analysis is limited to the 11 teachers who completed both years. Besides the total count of changes for each of the three domains (personal, practice, and consequence), the figure also presents the specific changes that were mentioned within each domain. The darker bar represents teachers who reported each change already after the first year, while the lighter bar represents teachers who reported each change only in the second year. This visualization allows us to appreciate the group's progression from the first to the second year.

After the first year, the majority of reported changes were related to the personal domain (nine teachers) and the domain of practice (ten teachers), while only three teachers reported changes in the domain of consequence. After the second year, improvements were observed in all three

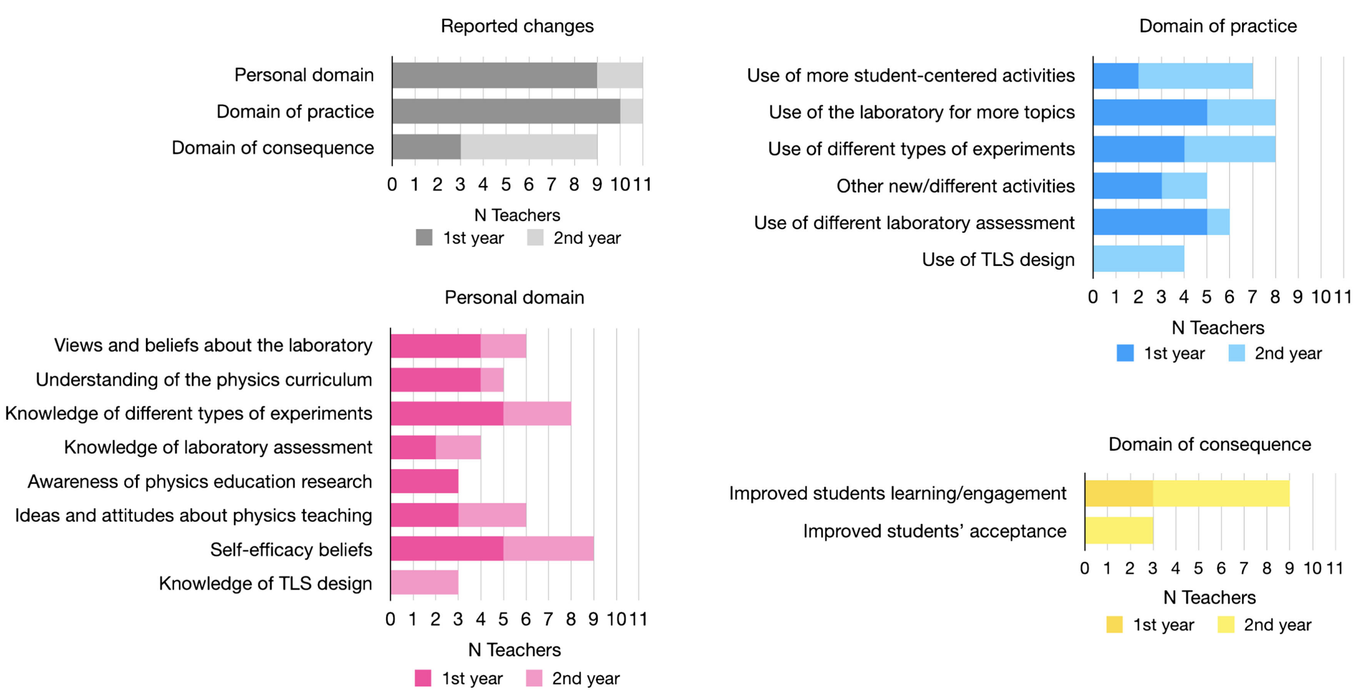

FIG. 7. Reported changes in the three domains after the first year (darker color) and at the end of the program (full bar). The analysis is limited to the 11 teachers who completed both years of the program.

domains, with a notable enhancement in the domain of consequence. In this domain, 9 of the 11 teachers reported positive students' outcomes.

Personal domain. Within this domain, the two most frequently reported changes were related to gaining knowledge about different types of experiments (observational, testing, and application experiments as described in the ISLE model) and improved self-efficacy. A teacher highlighted the significance of differentiating among experiments:

> The course has provided me with a broader perspective on laboratory work. It helped me understand the diversity of laboratory activities and appreciate the different moments of an experimental activity. (Sophie)

Regarding self-efficacy, teachers aspects of enhancing confidence in conducting laboratory activities, as well as greater self-confidence in defending the new methodologies with colleagues at school:

> Now I even retrieve instruments from the cabinets, something would never have done before. I no longer rely on the technician to lead and explain the activity for me. (Margot)
>
> In my school, the laboratory is understood in a traditional way. I disagreed with that, and I had tried to approach it differently. But my colleagues and even some parents criticized my methods. And I began to think, 'Maybe I am the wrong one, perhaps it's because I am a mathematician'. This course gave me encouragement. It was vital for me to see that I was not doing everything wrong. (Lisa)

The impact of the program on self-efficacy was discussed in greater detail in a previous publication [85].

In the second year, these two aspects remained important and continued to develop. In addition, there was an evolution in teachers' views and beliefs about the laboratory. For example, a teacher commented about the educational value of unexpected outcomes:

> If something doesn't work out, it's an opportunity to analyze and understand what went wrong, investigate it, try to figure out what the problem might be. (Gordon)

Other changes included new ideas or attitudes about physics teaching and a better understanding of the physics curriculum.

Domain of practice. After the first year, the most frequent reported change was using laboratory activities for a wider range of topics, and adopting a different approach to assessment, especially concerning the use of assessment rubrics for scientific abilities:

> Laboratory work is often seen as cliché. Instead, I've come to realize that each activity, each rubric offers a unique aspect to value. This is what I tried to do: in each lab, I tried to value and assess certain specific abilities. (Gordon)

Some participants began to consistently incorporate the different types of experiments into their teaching, and their number increased after the second year:

> Having different types of experiments, I had this idea in my mind, but it wasn't as well-structured as you proposed it. This thing, I have made it my own stably in my teaching practice, and every time I tell the students, 'Now we're doing this or this other type of experiment'. (Lisa)

Teachers also reported incorporating more student-centered activities in their lessons, not only for laboratories but also for other classroom activities.

Domain of consequence. While a few teachers reported positive effects on students even after the first year, the majority began to observe positive outcomes by the end of the second year. Teachers correlated the use of different types of experiments and a more student-centered approach with increased student engagement and understanding of scientific processes:

> This shift from providing a cooking recipe to having students design their experiment is something I have incorporated in nearly all of my labs. It works very well, and the students find it much more enjoyable. And [even when] the experiments are somewhat recipe-like, if students are trained to design experiments, the way they follow the recipe changes, because they understand the underlying logic. (Ethan)

Some also noted a shift in student behavior:

> In the lab, students are more active; their engagement is different compared to the classroom. They are more focused, ask questions, stand up and ask the technician for the materials they need. They are also more independent. (Gordon)

2. Participants' growth pathways

To complete the discussion on changes, it is interesting to look at the growth pathways of individual participants. As a first visualization of the differences among them, Fig. 8 shows the number of reported changes by each teacher after each year of the program.

To add nuance to these findings, we analyze three case studies (Lisa, Gordon, and Sophie) in order to gain insight into possible trajectories and to better appreciate the variance

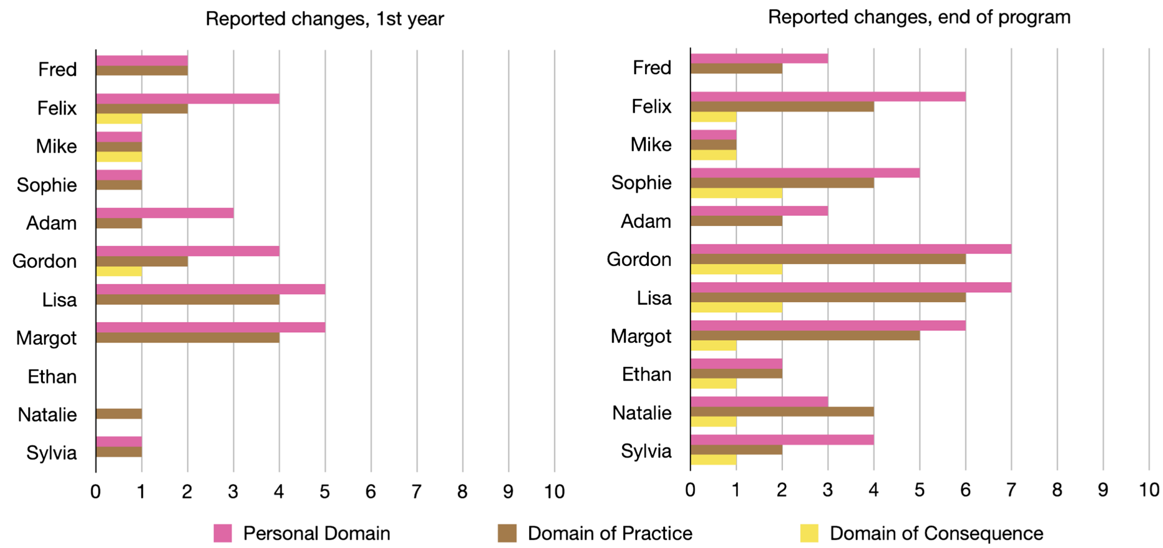

FIG. 8. Number of reported changes in each of the three domains for each participant in the sample, (left) after the first year and (right) at the end of the program.

among participants. To visualize the results, we employ an approach akin to the one utilized by Levy *et al.* [18]. For each case study, in the narrative, we outline different steps or "moves" in the participant's trajectory, making reference to participant's quotes which are tabulated and sequentially numbered. For each move, we identify which domains of the interconnected model of professional growth [56] are involved, as well as the process (enactment or reflection) connecting them. We then visualize the trajectory on a map that includes the four domains, representing each "move" with an arrow connecting the domains involved: solid arrows denote enactments, while dashed arrows are used for reflections. Each arrow is assigned a number corresponding to the respective quote. When a quote contains multiple moves, the first one is shaded in gray to help the reader follow the trajectory. The maps for the three teachers are displayed together in Fig. 9.

Gordon. During the first year, Gordon [Table VI and Fig. 9(a)] focused on observing his students to figure out how to change the *status quo* (1). At the same time, he collected insights from the program, enriching his

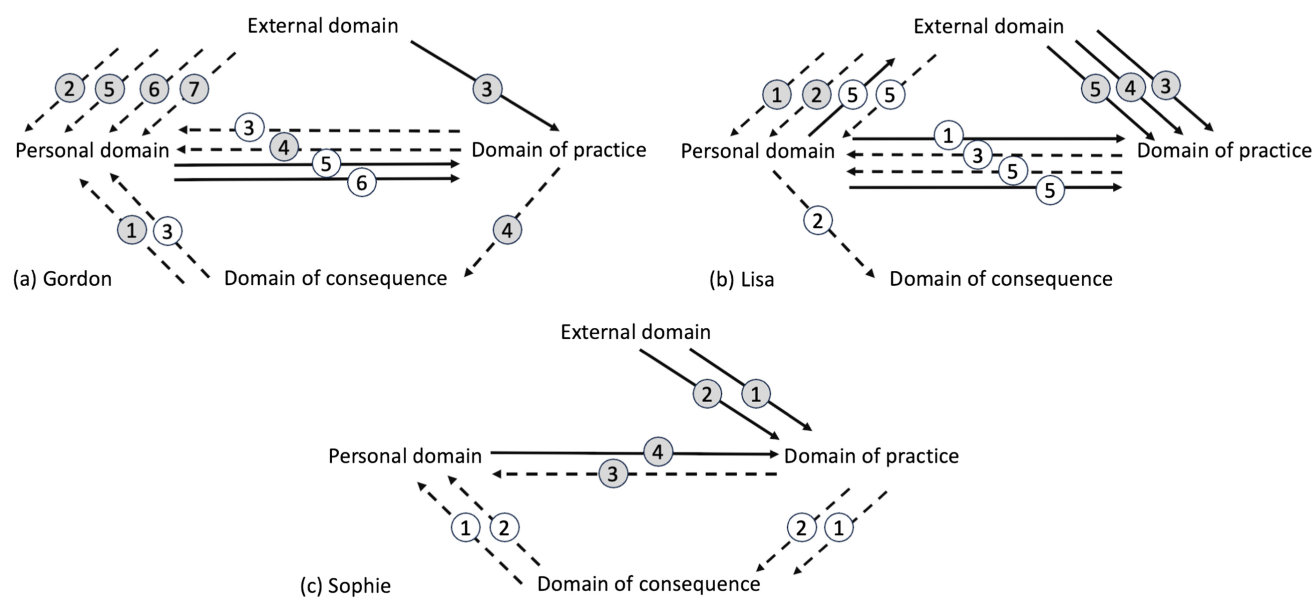

FIG. 9. Participants' trajectories across the different domains of change, mediated by the processes of enactment (solid lines) and reflection (dashed lines): (a) Gordon, (b) Lisa, (c) Sophie. Numbers refer to the quotes reported in the tables for each participant. The gray color marks the first move for each instance.

TABLE VI. Gordon’s growth pathway.

Quote	Move(s)
(1) “I didn’t apply the methodology directly. But here’s what I did, perhaps in retrospect: I observed the students more closely and tried to figure out how to modify the lab. I sensed that something wasn’t working as the students appeared somewhat restrained, and at the same time, it was challenging to maintain their focus and keep them quiet during the activities.” (final interview)	Domain of consequence → reflection → personal domain
(2) “You provided us with the materials, the references…so one could see that there is someone who is thinking about a teaching aspect. Even if you can’t read it all this year, next year you’ll know that Etkina’s group has done this or that, and perhaps you’ll pull something out.” (first year focus group)	External domain → reflection → personal domain
(3) “[I tried to implement my action research plan, but] I chose the wrong target class. I came to realize that a research project requiring ongoing feedback is better suited for younger classes, as they have more time and availability, and you can spread it out over time.” (first year focus group)	External domain → enactment → domain of practice → reflection → personal domain
(4) “First, there was an increased frequency to [familiarity with] with the laboratory [environment]. I began conducting my regular classes in the lab as well. By changing both the frequency and the nature of my classes, I observed that the students stand differently. And it works, because, firstly, I’ve wasted less time and I’ve done more experiments. And the students…in the short term, they appear to remember more, in the long term we’ll see.” (final interview)	Domain of practice → reflection → personal domain and domain of consequence
(5) “Perhaps the most important thing was the concept of laboratory design, of planning beyond traditional lab worksheet. Equipping us with tools like the ISLE model, or backward design… When you tasked us with completing the matrix, it greatly aided our planning, enabling us to concentrate on the essential elements. And I was actually able to do something, the experiment with diffraction and the thick hair.” (second year focus group)	External domain → reflection → personal domain → enactment → domain of practice
(6) “The first year, I sort of put them [the rubrics] in a drawer…printed them out and stored them away. Later on I revisited them, and I found it valuable to review my notes as well. This year I started actively using the rubrics as I was felt more at ease, more confident. I began modifying some of the experiments and creating assessment rubrics for them as well.” (final interview)	External domain → reflection → personal domain → enactment → domain of practice
(7) “I was a little reluctant about being evaluated by peers, but I must admit it turned out to be highly beneficial and productive. It helped me confront my fear of making mistakes or constantly needing to be fully prepared. By nature, I tend to be that kind of person, so the realization that I don’t have to know everything and that you can create something through interaction and constructive criticism was very helpful for me personally.” (final interview)	External domain → reflection → personal domain

knowledge about the findings of research on instructional laboratories. He consistently emphasized the importance of a solid research foundation for introducing innovations (2). It is worth noting that Gordon holds a Ph.D. in physics, which makes him especially sensitive to the value of a robust research underpinning. In the first year, Gordon attempted to implement his action research plan, but he was not able to fulfil it due to what he called a “wrong” target classroom. Nevertheless, this experience further stimulated his reflection (3). In the second year, Gordon reported implementing practical changes that quickly became habitual. He began to use the lab more frequently, including for regular classes; he observed positive effects both on himself (e.g., better time management) and on the students, particularly in terms of attitude, compared to his initial observation (4). In parallel, the introduction of tools designed to support TLS planning (such as the backward design matrix) enabled him to engage in classroom experimentation in a more focused way (5). Gordon’s inclination to engage in personal reflection before implementing the innovation reemerges as he reports about his experience with assessment rubrics. Once more, their integration in classroom practice was not straightforward; rather, it occurred when his confidence had matured (6). Concurrently with enactments in the classroom, during the second year, Gordon reported further growth in the personal domain. In particular, he reported restructuring his self-efficacy thanks to the peer feedback activity (7).

Lisa. For Lisa [Table VII and Fig. 9(b)], progress in the two domains (personal and practice) was more aligned. On a personal level, a key element was a methodological grounding that encouraged her to apply the proposed innovations in the classroom (1) and boosted her self-efficacy, a factor that she associated with increased student acceptance (2). The connection between methodological grounding and self-efficacy has been documented in previous literature [86]. In parallel, Lisa began integrating the proposed innovations in the classroom, starting already in the first year. Engaging in action research allowed her to

TABLE VII. Lisa's growth pathway.

Quote	Move(s)
(1) "Ever since I started teaching, one thing I lacked was a little bit of research, I mean real research, with data. So, it gave me a sense of relief to discover that I'm not alone and that there is somebody out there working on this, getting results that I can also research, I can attempt to implement what they've tried. So that was also a pat on the back." (first year focus group)	External domain → reflection → personal domain → enactment → domain of practice
(2) "One thing that has changed completely is the solidity, the confidence I have acquired in approaching laboratory work. This course allowed me to refocus, revisit ideas that I had previously abandoned, and restructure them properly. The students…perhaps because I am more confident now, they have also become more receptive to these changes." (first year focus group)	External domain → reflection → personal domain → reflection → domain of consequence
(3) "I was tired of doing things for pretend. This time, I had a real classroom where I could experiment, so this attacking right into reality instead of just dealing with theory also helped me." (first year focus group)	External domain → enactment → domain of practice → reflection → personal domain
(4) "Seeing others experiment with the same thing boosted my confidence and sparked new ideas. For example, a colleague had already employed the rubrics before Christmas, and I thought, 'Ah, why not give that a try?'. So I experimented with the rubrics before fully implementing the entire experiment structure. The opportunity to try in practice, with a monthly deadline throughout the year, allows you to try things in bits and pieces and eventually put it all together." (first year focus group)	External domain → enactment → domain of practice
(5) "If I try to do it [apply ideas from the program] on my own, at the first obstacle I don't know how to proceed. So, the [community] environment is very useful for engaging with others and then getting back into it, revisiting, reformulating, or restructuring certain elements." (final interview)	External domain → enactment → domain of practice → reflection → personal domain → enactment → external domain → reflection → personal domain → enactment → domain of practice

experiment with the innovations rather than merely studying them in theory, facilitating the development of a sense of ownership. (3). Lisa was also motivated to try new things in her practice by learning about other teachers' experiences (4). Later on, she once again emphasized the significance of the community in her professional development journey, describing a cyclical process involving classroom experimentation and feedback within the

TABLE VIII. Sophie's growth pathway.

Quote	Move(s)
(1) "[The rubrics] were valuable for the end-of-year [school] competency assessment, they came in handy for that purpose. And it's definitely a win-win in the sense that the feedback was overwhelmingly positive. And I think it should become a regular practice and potentially extended. So, it's definitely something that I intend to make more systematic. You've given me insights, I've used them to some extent, now I'd like to systematize them so that I can use them more consistently." (first year focus group)	External domain → enactment → domain of practice → reflection → domain of consequence → reflection → personal domain
(2) "[I tried to implement something in the lab and] what we did in the lab is what the students remembered the most. And they consistently highlighted it in their presentations, so it's effective. It's something I'm not going to discard, as the students remember it with enthusiasm." (first year focus group)	External domain → enactment → domain of practice → reflection → domain of consequence → reflection → personal domain
(3) "The experimentation part, I really enjoy that. Designing and experimenting, that's something I feel…when I try it, when I actually do it…obviously supported by the content, the models, and researchers, but it's also something that keeps me alive, in a nutshell. And that's also the part that I know sticks with me the most. When I try, I also understand myself better." (final interview)	Domain of practice → reflection → personal domain
(4) "For next year, I am considering refining a few more rubrics to use them more seamlessly. Because once you get a little deeper into the mindset…you know." (final interview)	Personal domain → enactment → domain of practice

CoL (6). Lisa represents a participant who fully exploited the potential of the community and was mindful of the process.

Sophie. In the case of Sophie [Table VIII and Fig. 9(c)], most of the changes occurred in the second year. Her approach involved initially implementing innovations in her classroom and then reshaping her ideas based on the outcomes. Her attitude was pragmatic: she recognized assessment rubrics as a tool that could help her fulfill the school's requirements for competency assessment, used them for this purpose, and after seeing positive results, she decided to further explore their use (1). She described a similar approach regarding the use of laboratory activities: once again, positive feedback from students was the deciding factor in her adoption of the new approach (2). While students' outcomes remain a key factor for Sophie, active involvement in experimentation also enriched her personal domain through a direct pathway (3). Equipped with new ideas and beliefs, at the end of the program, Sophie was ready to move forward with further experimentation in the classroom (4).

VII. DISCUSSION

The aim of this research was to develop an approach to teacher professional development that could promote improvements in the use of the laboratory for physics teaching in secondary schools. Our study responded to calls in literature for further research on professional development about laboratory work [87] and on the role of communities in supporting the integration of PER findings in teachers' training [18,36,37].

Our first research question (RQ1) examined the role and relevance of the different program features for facilitating professional development on laboratory instruction. These included the structural features supported by the literature (content focus; active learning opportunities; coherence; and sufficient duration) [12] and two foundational pillars: the learning community and action research. It also entailed a robust grounding in physics education research.

While all of the identified features were important, the learning community emerged as the pivotal factor. It provided a space for cultivating professional discourse about instructional laboratories, fostered authentic collaboration in designing laboratory-based teaching-learning sequences, and enabled reciprocal training in each teachers' lab activities. This catalyzed personal and professional growth, regarding both program-specific aspects and broader elements such as an enhanced understanding of the physics curriculum, or how to achieve a better alignment of learning goals, instruction, and assessment. Reciprocal training was identified as the "truly developmental" element, as it held participants accountable for their peers' learning and it bridged ideas from the program to teachers' reality. Positive results accomplished in the classroom were no longer seen as "private" experiments but as the collective achievement of the entire group. Our findings also support the importance of feelings of belonging and confidence, contributing to the expanding body of evidence that advocates a holistic view of teachers' growth [38,88].

The findings also offer insights into the role of action research. Engaging in classroom experimentation during the program, with ongoing support from researchers and opportunities for comparison with colleagues, provided a sense of purposeful progress in learning how to design effective laboratory activities for the classroom. The participatory approach enabled customization to the various contexts' needs and nurtured a sense of ownership over the proposed innovations. However, engaging in participatory action research demands substantial support, patience, accommodation, and time. A tension exists between adopting this approach and the goal of achieving a certain standard of quality for all. In the second year of the program, we introduced a tradeoff by proposing the development of a teaching-learning sequence incorporating laboratory work. This facilitated classroom experimentation; however, we feel that further research is required to understand how best to integrate the action research component into the model.

Regarding the other program features, our results support prior research recommendations also in the context of high-school laboratory instruction, indicating that a clear content focus, the incorporation of active learning strategies, an extended duration, and coherence with teachers' backgrounds and needs are essential core features. Teachers' narratives offered insights into the role and relevance of the various features: for instance, choosing a single foundational physics topic in the first year established a common ground for discussion about the laboratory that encouraged collaboration; the extended duration of the program, combined with its monthly rhythm, was crucial for sustaining the community and action research.

Finally, in line with the viewpoint put forth by Etkina *et al.* [36,37], we argue that the core features suggested by the literature can be understood through the lens of two essential components: the community of learners and action research. In fact, a CoL encompasses sufficient duration, coherence with participants' needs, and a shared content focus; on the other hand, action research inherently includes opportunities for active learning and reflection. While these considerations, as suggested by Etkina *et al.*, may extend beyond the specific domain of laboratory work, we have found evidence of the effectiveness of this perspective for professional development in this context. We have also provided an example of how this lens can be adopted in shaping an in-service professional development program on laboratory instruction.

Our second research question (RQ2) examined teachers' changes in the use of the laboratory. The reported changes included various aspects in both the personal domain and the domain of practice, with changes in the students also beginning to emerge. Frequent categories of change were knowledge and use of different types of experiments, knowledge and use of assessment strategies focused on scientific abilities, and the incorporation of more student-centered activities. Collectively, these changes reflect a shift toward a revised understanding of laboratory goals more focused on the development of scientific practices, aligning with contemporary literature recommendations [2]. Extending the program for an additional year intensified these changes, and some became "habits" of practice [36]. Effects on the students included improved engagement, a better attitude in the lab, and enhanced understanding of the experimental process. Another element of change was enhancement of self-efficacy in the use of the laboratory. The program incorporated multiple potential sources of self-efficacy (mastery and vicarious experiences, verbal persuasion and affective states [89]; simulated modeling, content and methodological mastery [86]). While some of these findings were discussed in a previous publication [85], further research is needed in order to discern which program elements were most effective and to elucidate the interplay between self-efficacy beliefs and other reported changes.

Finally, an analysis of personal participants' trajectories captured the complexity of teachers' growth, revealing multiple possible pathways toward developing an enhanced use of laboratory work in the classroom. The teachers whose trajectories were examined in the individual case studies experienced complex journeys of professional growth over the 2 years, each following a distinct pathway. This aligns with recent findings in the literature [18]. Multiple transitions between the four domains of the interconnected model of professional growth were found, mediated by the processes of "enactment" and "reflection." The program's structure facilitated these processes through various mechanisms: a stimulating, safe, and motivating environment; inspiration from peers; engagement in action research and sharing within the community; and the monthly rhythm. The variety of productive pathways suggest the presence of multiple zones of proximal development: teachers could find their personalized ways of implementing program ideas in the classroom, with ongoing support. Each teacher's journey was characterized by different types of transitions between the various domains of change, but they all moved forward from their initial position. Our deliberate approach was to embrace the diversity of starting points and to accompany each teacher in their unique pathway of growth. The learning community setting made this perspective explicit and engaged all participants in this collective endeavor.

VIII. CONCLUSIONS AND PERSPECTIVES

The Collabora project aimed to identify the features of effective in-service training on laboratory instruction for high school physics teachers and to assess its impacts.

An approach that emphasizes scientific practices and skills, strongly supported by literature on undergraduate laboratories [2], appears to be effective in the high school context as well. It is also valuable for teachers to reflect on the role of experiments in constructing scientific knowledge and to utilize assessment tools, such as scientific abilities rubrics, that help them better focus on the identified learning outcomes and evaluate the development of experimental skills across various topics. In this regard, it is important to use design approaches that emphasize the alignment between learning goals, assessment, and instruction. A learning community setting and the opportunity for structured, ongoing, and gradual experimentation in the classroom seem to be vital. According to our results, the combination of these approaches can promote teachers' growth on multiple dimensions, with different possible individual trajectories, therefore requiring time for full development. Long-term impacts and replicability in different contexts remain open research questions.

The Collabora project also served as an initial step toward rethinking professional development opportunities for physics teachers offered by our university, with the broader goal of fostering the infusion of PER-based approaches within the community of Italian physics teachers. Indeed, one of the outputs of the project was the Collabora model (Fig. 1) that we are now applying in our teacher training courses and we are sharing with colleagues in other institutions.

For example, a national project recently funded by the Italian Ministry of Education (ADELANTE—Adopting Digitally-Enhanced Laboratories in a Network of Teachers) will expand the model to include two more universities in central and southern Italy, besides our own which is located in the north. As recommended by Van Driel *et al.* [90], testing similar professional development programs in different contexts is good practice for better understanding the quality attributes of the proposed models. This project will also entail the participation of teachers at different levels—a core group of teacher leaders, local learning communities, and a broader online community of practice. We expect this approach to enable a more nuanced use of, and insights into, the learning community construct for physics teacher professional development, particularly regarding laboratory instruction, and to allow reaching a larger number of teachers.

Another study conducted with colleagues from the Department of Education [91] explored the potential of (virtual) communities of practice for preservice and early-career teachers, in the context of a joint project with Monash University in Australia [92]. In that case, changes in teachers' ideas and beliefs were examined using a quantitative tool, Epistemic Network Analysis (ENA [93]), which shows significant promise for integrating "coding and counting"–based analyses [94].

Finally, we think that the best way to disseminate the Collabora approach consists in empowering teachers who have experienced the program to become promoters of the model in their contexts, transforming themselves into "change agents" and gradually establishing a wider community of "*Collabora*tive" teachers. We have evidence of this "seed effect," as we will discuss in an upcoming paper that will also assess the long-term impact of the Collabora project.

At the time of writing this paper, Italian universities, including our own, are in the process of developing new curricula for initial secondary school teacher training in response to the recent law mandating prospective teachers to earn 60 ECTS credits, as opposed to the previous 24, for professional qualification. Various stakeholders, such as the Italian Physical Society (SIF) and the "National coordination for physics education and the history of physics" (CooFIS08) have issued recommendations for the design of curricula. They emphasize the importance of grounding training actions in the findings of physics education research, aligning with calls published also in this journal [26,36]. We believe that the Collabora model serves as a concrete example of a professional development opportunity informed by such findings and represents a pragmatic application of the learning community paradigm within the context of physics teacher training, particularly in the Italian context where limited research in this area was available.

ACKNOWLEDGMENTS

The post-doctoral researcher involved in the project was recruited through funding provided by the university project 'Formazione Insegnanti' (Del. 52 Cons. Amm. 14/02/2017). Further project expenses were funded by resources from our research group and the PLS-Piano Lauree Scientifiche national project, supported by the Italian Ministry of Education, University and Research. We also thank technicians and colleagues for their support and fruitful discussions, and the anonymous reviewers for their valuable feedback. Above all, we thank the Collabora teachers for their active participation and constructive conversations that inspired us during and after the program and continue to this day.

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