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Effects of a Professional Development Program for the Integration of Phylogenetic Software in Biology Class on Professional Knowledge of Teachers

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Abstract

To promote young talents in STEM careers and enhance students' scientific literacy, more than 460 out-of-school student labs have been established across Germany. In these non-formal places of learning students conduct experiments using authentic laboratory equipment - resources often unavailable in regular school settings. Many of these labs also contribute to teacher education by offering courses to students and to teachers at university. Despite ongoing digitalization, many teachers still lack digital competencies. The project *LFB Labs digital* addresses this gap by leveraging the expertise of out-of-school student labs to further develop teachers in digital learning settings. In the professional development (PD) program *Working with Phylogenetic Software - Integrating Genetics and Evolution* teachers learn about the digital tool *MEGA* while connecting Genetics and Evolution, which is considered to be beneficial for learning.

This study evaluated the PD program, which aimed to enhance biology teachers' technological pedagogical content knowledge (TPACK). A pre-post design revealed significant improvements in teachers' technical knowledge (TK) about phylogenetic software, pedagogical content knowledge (PCK), and technological content knowledge (TCK), while no significant changes were found for technological pedagogical knowledge (TPK) or TPACK. Compared to a control group, participants showed higher initial PCK, intrinsic motivation in teaching contexts, self-efficacy in subject-specific use of digital media, and technology commitment, whereas there were no significant initial differences in TK, TCK, TPK, and TPACK. The results highlight the value of out-of-school student labs as effective settings for professional development, particularly in supporting subject-specific digital integration.

Keywords: professional development program; TPACK model; digital education; phylogenetic software; out-of-school student labs

1. Introduction

Access to information and knowledge through Information and Communication Technologies (ICTs) is essential for lifelong learning and social participation (UNESCO, 2018). Students and teachers must learn to use technology effectively to succeed in an increasingly complex, knowledge-based society (UNESCO, 2008). Despite growing digital integration in schools, teachers still show low levels of digital competence (Eickelmann et al., 2019). Targeted support measures are therefore crucial for professional development (Bonnes et al., 2021; Huber et al., 2020). A review by Fernández-Batanero et al. (2020) highlights insufficient ICT qualifications among teachers and stresses the need to integrate Technological Pedagogical Content Knowledge (TPACK) into training programs. The TPACK model by Mishra and Koehler (2006) emphasizes combining pedagogy, content, and technology (Rodríguez Moreno et al., 2019).

In Germany, only about one-third of teachers developed digital competencies during their studies (Diepolder et al., 2021). Although interest in training is high, participation remains low - likely due to inadequate offerings (Diepolder et al., 2021). In STEM education, out-of-school student labs play a key role: They provide authentic lab experiences often unavailable in schools (Haupt et al., 2013). Beyond their work with students, many of these labs also contribute to teacher education by offering specialized training programs for both pre-service and in-service teachers. These labs are well positioned for digital transformation, as digital media are integral to their operations (Haupt & Stamer, 2023). The LFB-Labs-digital project was launched to strengthen subject-specific digital skills in STEM education. Seven labs developed professional development programs for in-service teachers (Kirchhoff et al., 2024).

Building on this, the program *Working with Phylogenetic Software – Integrating Genetics and Evolution* was created by teutolab-biotechnology at Bielefeld University. It introduces teachers to MEGA (Molecular Evolutionary Genetics Analysis), a tool for analyzing evolutionary relationships using genetic data. The goal is to enable teachers to integrate this software into classroom instruction in a pedagogically sound and content-appropriate way.

2. Theoretical Background

2.1 Teachers' Professional Knowledge

The TPACK framework, developed by Mishra and Koehler (2006), defines the professional knowledge teachers need to integrate technology effectively into classroom teaching. Using technology can be challenging because digital tools are often complex and unstable, leaving many educators feeling unprepared (Koehler & Mishra, 2009). Teachers need an approach that considers their existing knowledge, its application, and the classroom context, while also developing strategies to manage technological complexity. At the core of successful integration are three components - pedagogy, content, and technology - combined in the TPACK framework, which emphasizes their interaction across diverse educational settings.

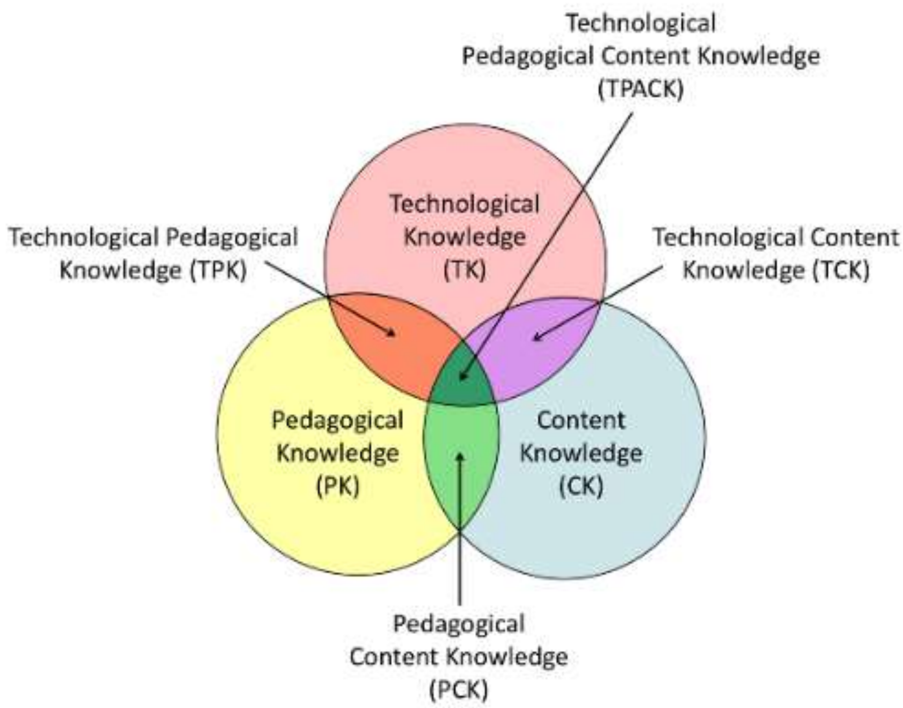
Building on Shulman's (1986) concept of pedagogical content knowledge, Mishra and Koehler (2006) expanded it by adding technology, creating a comprehensive model. It combines content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK), with overlapping domains: PCK, TCK, and TPK. At the center lies TPACK, representing full integration of all three.

- PK: Understanding teaching and learning practices, educational goals, classroom management, assessment, and student development. Strong PK enables effective lesson design and skill development (Koehler & Mishra, 2009).

- CK: Specialized subject-matter knowledge, including concepts, theories, and proven methods for instruction (Koehler & Mishra, 2009).
- TK: A dynamic domain similar to Fluency of Information Technology (FITness), requiring adaptable mastery of technology for problem-solving and communication (Koehler & Mishra, 2009).
- PCK: Applying subject knowledge to teaching by interpreting and adapting content to students' prior knowledge and misconceptions (Shulman, 1986).
- TPK: Understanding how technology changes teaching and learning, recognizing tool affordances, and adapting them creatively for education.
- TCK: Knowing how technology and content influence each other, enabling teachers to select tools that enhance subject learning.
- TPACK: Knowledge emerging from the interaction of content, pedagogy, and technology, requiring flexibility and context-specific adaptation.

Figure 1 illustrates these domains and their overlaps.

Figure 1: TPACK – Model (Mishra & Koehler, 2006)



2.2 Studies on TPACK

In recent years, the TPACK framework has guided the redesign of teacher preparation programs and development workshops (Chai, 2010) and has been widely applied to study teacher professionalization. Most research focuses on pre-service teacher education at universities, reporting effective approaches such as educational technology courses, longitudinal integrated coursework, and content-specific methods courses (Hofer & Grandgenett, 2012). For instance, ICT-based courses for meaningful learning increased TK, PK, CK, and TPACK (Chai, 2010), while cross-semester media projects also improved TPACK (Max, 2021). Integrating digital media into science teacher education within existing curriculum modules led to significant gains across all TPACK dimensions (Stinken-Rösner et al., 2021).

In-service teachers' TPACK can be enhanced through ICT training. Runge et al. (2024) found that PD programs combining technological and pedagogical content were more effective than general technology-focused ones. Online PD programs that included active experimentation with ICT tools and subsequent redesign of teaching modules substantially improved TPACK (Rientjes et al., 2013). Similarly, physics teachers' TPACK was fostered by learning multimedia applications and classroom adaptation strategies (Mayer et al., 2021).

Wu (2013) reviewed 24 studies (2002–2011), noting most targeted preservice teachers (54.2%), with fewer on high school (20.8%), elementary (16.7%), and university teachers (8%). Over half (66.7%) addressed domain-general TPACK. Between 2010 and 2021, Irwanto (2021) identified 106 studies, mostly in the US, with only two in Germany. These findings reveal a lack of domain-specific PD programs for in-service teachers in Germany. Out-of-school student labs could help address this gap by supporting teachers' TPACK development.

2.3 Out-of-School Student Labs

Out-of-school student labs have existed in Germany since the 1980s, with rapid growth from the early 2000s (Haupt & Hempelmann, 2015), partly triggered by the "PISA shock" after Germany's poor performance in the 2000 PISA study. This expansion reflects the rising importance of natural and engineering sciences in industrial societies, where innovations like biotechnology and nanotechnology play key roles (Dähnhardt et al., 2009). To meet labor market and societal demands, a solid understanding of scientific concepts is essential (Euler, 2001). Schools face challenges in STEM education, and authentic, hands-on experiences can help develop these competencies (Euler, 2001). Consequently, out-of-school learning environments emerged at universities, research centers, and industry partnerships (Haupt et al., 2013).

Today, over 460 student labs operate across Germany (Haupt, 2023), aiming to spark interest in STEM and promote scientific literacy (Haupt & Hempelmann, 2015). They complement school instruction by offering curriculum-relevant experiments with high-quality equipment often unavailable in schools due to cost and complexity. Visits are usually one-time events, though repeated participation reinforces learning. Labs also support teacher education: university students supervise school groups during practical phases, adapting or creating experiments to strengthen didactic skills and subject knowledge (Haupt & Hempelmann, 2015). Studies show these experiences improve teaching routines, instructional quality, and foster student-centered approaches (Völker & Trefzger, 2011; Elsholz, 2018; Scharfenberg & Bogner, 2016). Inquiry-based learning enables pre-service teachers to apply theory in practice and integrate insights back into their studies (Röllke et al., 2021). Well-structured practical phases at universities have been shown to make a substantial contribution to the professional development of pre-service teachers (Röllke, 2019).

Student labs also offer opportunities for in-service teacher PD, providing authentic, innovative settings supported by university experts (Kirchhoff et al., 2024). They act as drivers of educational innovation beyond rigid school systems (Euler & Schüttler, 2020) and are well equipped for digital transformation. Most labs use modern technology; two-thirds employ digital tools in courses, and half actively integrate them to enhance students' digital competencies (Haupt & Stamer, 2023).

2.4 Research Questions and Hypotheses

In response to the demands on supporting in-service teachers' TPACK, the project *LFB-Labs-digital* was initiated. Within this initiative, a network of out-of-school student labs spanning most STEM disciplines developed PD programs aimed at enhancing teachers' digital competencies. As part of this project, the *teutolab-biotechnology* student laboratory designed a PD program on working with phylogenetic software to integrate genetics and evolution, targeting the following research question:

Research Question 1:

Does the PD program *Working with Phylogenetic Software - Integrating Genetics and Evolution* foster teachers' professional knowledge in terms of TPACK?

As the PD program addresses the implementation of a specific digital tool in biology class, the attendance should lead to an improvement of professional knowledge in terms of TPACK (cf. Runge et al., 2024; Rientjes et al., 2013; Mayer et al., 2021). Specifically, the domains of TK, PCK, TPK, TCK, and TPACK should be fostered, as the handling of a specific technical tool is introduced and applied in an educational context.

Hypothesis 1:

The PD program *Working with Phylogenetic Software - Integrating Genetics and Evolution* leads to an improvement of teachers' TK, PCK, TPK, TCK, and TPACK.

For a deeper understanding of the findings in the specific sample of participants, we followed the supplementary research question:

Research Question 2:

Do teachers who decided to participate in the PD program report higher involvement regarding digital media and higher professional knowledge in terms of TPACK than teachers who did not want to participate?

Although the Conference of the Ministers of Education in Germany emphasizes the importance of PD programs for in-service teachers and generally mandates participation, most federal states - including North Rhine-Westphalia, where our study was conducted - do not specify the required scope of participation, nor is it systematically monitored (Daschner, 2023). Hence, the decision for participation is voluntarily and we infer that these teachers demonstrate a higher level of general involvement as well as technological professional knowledge.

Hypothesis 2:

The participating teachers of the PD program *Working with Phylogenetic Software - Integrating Genetics and Evolution* command a higher TK, PCK, TPK, TCK, and TPACK as well as a higher level of technology commitment, higher self-efficacy in subject-specific use of digital media, and higher intrinsic motivation in teaching contexts than other teachers who decided not to take part in the program.

3. Material and Methods

3.1 Material Design: Professional Development Program for the Integration of Phylogenetic Software in Biology Class

The professional development program *Working with Phylogenetic Software – Integrating Genetics and Evolution* trains teachers in using MEGA, a tool for phylogenetic analysis of DNA data.

Module 1 – Introduction to Viral Evolution and MEGA

Participants independently complete the online course *Evolution of Coronaviruses* (https://teutolabbiotechnologie-online.de/evolution-von-coronaviren-2/), featuring interactive videos, quizzes, and tutorials on viral evolution, phylogenetic tree construction, and molecular genetics methods. A step-by-step guide explains how to align and analyze DNA sequences and build phylogenetic trees. Teachers work on four inquiry-based tasks, including mutation analysis of the S-gene, tracing SARS-CoV-2 origins, manual tree construction, and identifying sequences for PCR diagnostics and vaccine development. Originally designed for students, the course was adapted for teacher training with added instruction on retrieving genetic data from NCBI GenBank. Since this module was completed independently as a self-study unit, both the duration and the fidelity of implementation can only be estimated. It can be assumed that a conscientious completion of this online module requires approximately three hours.

Module 2 – Practical Implementation in the Student Lab

Teachers visit the out-of-school lab with their upper secondary biology classes for a full-day workshop, applying online content through MEGA-based analyses and PCR plus gel electrophoresis experiments. Equipped workstations and a slide-based presentation support alternating theory, hands-on lab work, and software exercises. The visit also offers teachers the opportunity to exchange ideas with experts from the teutolab-biotechnology, particularly regarding lesson planning and classroom implementation.

Module 3 – Lesson Planning and Reflection

Teachers design lesson plans integrating MEGA and discuss them in a final video conference. To address time constraints, additional teaching materials offer further contexts for DNA sequence analysis. Selected activities are explored during the reflection session. The final session conducted via videoconference lasted two hours. The development of lesson sequences during the self-study phase required varying amounts of individual time; however, an average of approximately three hours can be regarded as a realistic estimate.

For a deeper insight into the design of the material, see Röllke et al. (in press).

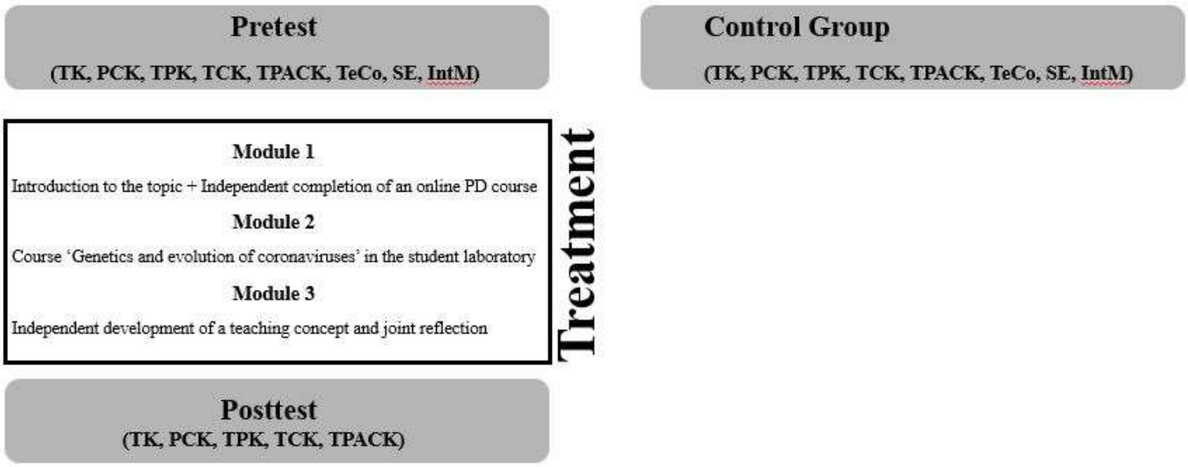
3.2 Study Design and Sample

In a pre-post design, changes in teachers' technological professional knowledge were measured by assessing TK about phylogenetic software, PCK, TPK, TCK, and TPACK by a validated questionnaire with a 6-point Likert scale. Participants were recruited by offering the PD program to more than 300 teachers who regularly visit the student laboratory with their biology classes. Participation in both the professional development and the questionnaire study was entirely voluntary.30 teachers took part in the programme (M_{age}: 41,6 years, SD_{age}: 10,1 years, 66,7 % female). During the post-test administration, nine teachers dropped out, resulting in a final sample of 21 respondents. Moreover, only 19 teachers completed the items in the ‘Technological Knowledge’ subscale. All cases that did not provide complete responses for the respective subscales were excluded from the analysis. We conducted a Wilcoxon Signed Rank test to compare the paired samples and calculated the effect size *r*. According to Cohen (1988,

S. 83), values about 0.1 are considered as weak, values about 0.3 are graded as moderate, and values about 0.5 are rated as strong.

In a control group design, we asked other biology teachers who visited the *teutolab-biotechnology* with their biology class, but did not take part in the PD program. We assessed their TK about phylogenetic software, PCK, TPK, TCK, and TPACK as well as their technology commitment, self-efficacy in subject-specific use of digital media, and intrinsic motivation in teaching contexts by validated questionnaires with a 6-point-Likert scale. The control group comprised 33 teachers (M_{age}: 45,1 years, SD_{age}: 11,7 years; 45,5 % female). For comparison, the treatment group answered the same questions at the outset of the PD program. To compare the independent samples, we performed an analysis of variance (ANOVA) on composite Likert-scale scores, checked all required assumptions, and calculated the effect size *r*. Figure 2 gives an overview about the study.

Figure 2: *Study Design (TK: Technical Knowledge about Phylogenetic Software, PCK: Pedagocical Content Knowledge, TPK: Technological Pedagogical Knowledge, TCK: Technological Content Knowledge, TPACK: Technological Pedagogical Content Knowledge, TeCo: Technology Commitment, SE: Self-Efficacy in Subject-Specific Use of Digital Media, IntM: Intrinsic Motivation in Teaching Contexts)*



3.3 Measurement Instruments

To investigate TPACK in the domains described above, we used a self-assessment questionnaire of Stinken-Rösner (2021). It is based on Chai (2013), adapted to natural sciences class and translated into German.

For the assessment of technology commitment, we used a scale developed by Neyer et al. (2012) and selected six out of the twelve items that specifically reflect the domains of technology acceptance and technology competence beliefs.

To measure self-efficacy regarding the subject-specific use of digital media, we adapted the 3-item scale developed by Beierlein et al. (2012) to specifically address the use of digital media within subject-specific contexts.

For the investigation of intrinsic motivation in teaching contexts, we selected three items from validated scales on motivational regulation in university learning (Thomas et al., 2018) and adapted their wording and perspective to address teaching instead of learning.

Table 1 gives an overview about the applied scales with sample items and reliabilities.

Table 1: Sample Items (translated) and Internal Consistency for the Pretest Data and for the Posttest Data of the Used Scales

Scale	Sample Item	*n* of Items	Cronbach's alpha (α)
Technical Knowledge about phylogenetic software (TK)	I have the necessary technical skills to use phylogenetic software effectively.	4	.86 (pre) .71 (post)
Pedagogical Content Knowledge (PCK)	I can help students to learn subject content in different ways.	5	.87 (pre) .79 (post)
Technological Pedagogical Knowledge (TPK)	I can use digital media to familiarize my students with everyday examples.	4	.77 (pre) .82 (post)
Technological Content Knowledge (TCK)	I can select and use appropriate digital media to present subject content.	4	.69 (pre) .86(post)
Technological Pedagogical Content Knowledge (TPACK)	I can design student-centered learning environments in which subject content, pedagogical principles, and digital media are appropriately integrated.	5	.83 (pre) .90 (post)
Technology Commitment (TeCo)	I am interested in using the latest technical equipment.	6	0.81 (pre)
Self-Efficacy in subject-specific use of digital media (SE)	I can rely on my own abilities in difficult situations when using digital media in my subject.	3	0.94 (pre)
Intrinsic Motivation in teaching contexts (IntM)	I really enjoy teaching.	3	0.93 (pre)

4. Results

Comparison of the Pretest and the Posttest

Teachers who had participated in the PD program showed an increase in the professional knowledge dimensions TK, PCK, TCK, and TPACK. The differences between the pretest and the posttest were significant with high effect sizes in TK and PCK, and with a medium effect size in TCK. The change in TPK and TPACK was not significant (see Table 2).

Table 2: Comparison of Teachers' Professional Knowledge Before and after the Participation in the PD Progam

	Pretest		**Posttest**					
Variables	***M***	***SD***	***M***	***SD***	***N***	***Z***	***p***	***r***
Technical Knowledge about phylogenetic software (TK)	2.17	0.91	3.64	0,83	19	3.466	< .001	.795
Pedagogical Content Knowledge (PCK)	4.99	0.50	5.39	0,45	21	2.917	.004	.637
Technological Pedagogical Knowledge (TPK)	4.61	0.82	4.62	0,80	21	0.044	.965	.010
Technological Content Knowledge (TCK)	4.55	0.57	4.93	0,89	21	2.102	.036	.459
Technological Pedagogical Content Knowledge (TPACK)	4.08	0.87	4.18	1,13	21	0.546	.585	.119

Note. Significant differences are highlighted in grey

Comparison of the Treatment Group and the Control Group

Teachers who had decided to participate in the PD program reported higher PCK, TPK, TCK, TPACK, technology commitment, self-efficacy in subject-specific use of digital media, and intrinsic motivation in teaching contexts when they started than teachers in a control group who had not planned to attend. The differences between the two groups were significant with medium effect sizes in PCK, technology commitment, self-efficacy in subject-specific use of digital media, and intrinsic motivation in teaching contexts. The difference in TPK, TCK, and TPACK was not significant. Participating teachers showed lower - but statistically non-significant - levels of TK compared to the control group (see Table 3).

Table 3: Comparison of Teachers Who Had Decided to Participate in the PD Program (Treatment Group) With a Control Group Regarding Their Professional Knowledge, Technology Commitment, Self-Efficacy in Subject-Specific Use of Digital Media, and Intrinsic Motivation in Teaching Contexts

	Treatment Group		**Control Group**					
Variables	***M***	***SD***	***M***	***SD***	***N***	***F***	***p***	***r***
Technical Knowledge about phylogenetic software (TK)	2.23	0.86	2.62	1.07	56	2.256	.139	0.200
Pedagogical Content Knowledge PCK)	4.95	0.46	4.44	0.88	60	7.918	.007	0.346

Technological Pedagogical Knowledge (TPK)	4.63	0.73	4.34	0.83	59	1.986	.164	0.184
Technological Content Knowledge (TCK)	4.54	0.61	4.41	0.82	50	0.494	.485	0.089
Technological Pedagogical Content Knowledge (TPACK)	4.03	0.83	3.68	1.04	60	2.141	.149	0.190
Technology Commitment (TeCo)	3.48	0.47	3.09	0.56	60	8.147	.006	0.351
Self-Efficacy in subject-specific use of digital media (SE)	4.57	1.07	3.99	1.15	60	4.158	.046	0.259
Intrinsic Motivation in teaching contexts (IntM)	5.34	0.57	4.56	0.88	60	16.549	<.001	0.471

Note. Significant differences are highlighted in grey

5. Discussion

This study examined whether a PD program developed by an out-of-school student lab could enhance teachers' professional knowledge for integrating educational technology into classroom instruction. The program comprised three modules: an introduction to the phylogenetic software MEGA, practical application in a student lab workshop with biology classes, and support for designing additional lessons. A control group of non-participating teachers was included. We assessed professional knowledge, technology commitment, self-efficacy in subject-specific digital media use, and intrinsic motivation.

Pretest–Posttest Comparison (Hypothesis 1)

Participants showed significant gains in TK, PCK, and TCK, indicating general effectiveness. TPK and TPACK did not improve significantly, so Hypothesis 1 is only partially confirmed. The demanding nature of the biological concepts (linking genetics and evolution) made pedagogical integration harder, even as technical and content knowledge increased. Prior work suggests TK can bolster TPK and TCK, which in turn support TPACK (Chai, 2013; Lehiste, 2015; Koh, 2011), yet different TPACK dimensions may develop at different rates (Hofer & Grandgenett, 2012).

Additionally to the quantitative analysis, we asked the participants to identify the constraints they were confronted with and to provide a personal summary at the end of the PD program. Teachers reported a lack of time and the challenge of finding suitable topics with suitable contexts to develop new coursework for - especially since exam tasks must not be too open-ended. Additionally, appropriate genes must be selected, with scientifically recognized sequences available in the NCBI database. These underscore the difficulty of pedagogically meaningful presentation. These statements underscore that especially the pedagogical meaningful presentation to their students is difficult. Nevertheless, one teacher summarized "Dealing with specialized software that is also used in scientific research is time-consuming, but incredibly beneficial for subject teaching in schools. I have experienced that students' motivation to engage with this topic increases. Especially the time-consuming comparison of gene segments is greatly simplified by the presented software, making it more accessible for students. The provided instructions significantly ease the teacher's onboarding process." The out-of-school student lab environment was especially praised for providing practical, well-guided access to cutting-edge scientific practices, ultimately enhancing lesson quality and student engagement.

Control Group Comparison (Hypothesis 2)

According to Hypothesis 2, the teachers who participated in the PD program demonstrated significantly higher PCK, as well as greater technology commitment, higher self-efficacy in the subject-specific use of digital media, and stronger intrinsic motivation in teaching contexts, compared to the control group. Thus, Hypothesis 2 can be partially confirmed. While both participating and non-participating teachers rated their knowledge for teaching specific content as high, the participating teachers reported even higher levels of PCK.

Although the treatment group also showed higher mean values in the dimensions of TPK, TCK, and TPACK, these differences were not statistically significant. Interestingly, the teachers who chose to participate in the PD program already started with a higher level of knowledge, yet still expressed a desire to further improve. This motivation may be explained by their awareness of specific deficits - particularly in the area of TK about phylogenetic software. In this dimension, both groups showed low mean values, but the treatment group scored even lower than the control group. This suggests that participating teachers were particularly aware of this shortcoming and were motivated to address it through the PD program.

A curricular change in North Rhine-Westphalia - merging genetics and evolution since 2022 (MSB NRW, 2022) - created urgency for targeted support. Recruitment went to >300 teachers with prior teutolab-biotechnology visits; 30 enrolled, all attended the kick-off and the lab visit, but 21 joined the final video conference. Eligibility (current biology teaching in Qualification Form 2) and extra time outside regular duties likely reduced completion. Schulze-Vorberg et al. (2021) identified different teacher profiles through latent profile analysis, using variables such as TK, TPK, self-efficacy, and the use of digital media. Their study distinguished between types such as the “Digital Forerunning” teachers - who were three times more likely to participate in PD programs focused on digital media - and the “Standing Apart” group, who preferred beginner-level PD programs. Our findings suggest that we were more successful in reaching the first group, despite efforts to make the training as accessible as possible to a wider range of teachers.

Nonetheless, the feedback we received was encouraging. For example, one teacher praised the high-quality guidance which fit with needs of the participants: “The professional development was very helpful and educational. It motivated me to try out new technical possibilities. The guidance during the training was great - engaging and on equal footing. There was no boredom, and we had many practical phases. If something didn’t work or there was no time, that was not a problem.”

Limitations

While this study provides valuable insights into the effectiveness of a PD program focused on integrating phylogenetic software into biology education, some limitations must be acknowledged.

First, we used in our study self-report questionnaires to assess participants’ knowledge, motivation, and attitudes. While validated scales were employed, self-assessments are inherently subjective and may be influenced by social desirability bias or inaccurate self-perception. Moreover, self-ratings may be affected by response shift bias, whereby participants' internal standards or understanding of the assessed constructs change over the course of the program, potentially distorting perceived changes.

Second, the study involved a relatively small number of participants, which limits the generalizability of the findings. Moreover, the sample in the treatment group as well as in the control group was self-selected. This introduces potential selection bias, as teachers who chose to visit an out-of-school student lab may have higher intrinsic motivation, stronger digital affinity, and greater openness to innovation than the general teacher population. As a result, the findings may not be representative of all biology teachers. Additionally, the self-selection bias limits the external validity of the findings.

Third, the PD program was centered around the integration of the phylogenetic software MEGA and the combined teaching of genetics and evolution - a highly specific and cognitively demanding topic usually covered in upper secondary education. This narrow focus restricts the applicability of the program to broader content areas or to teachers of lower secondary levels. Additionally, the complexity of the topic may have contributed to the limited development of integrated TPACK, as pedagogical application of such abstract content requires more extended support and practice. For further research on the development of professional knowledge in terms of TPACK through PD programs designed by out-of-school student labs across various STEM fields and formats, see the joint findings of the *LFB Labs Digital* project (Reher et al., 2015).

6. Conclusions and Outlook

The PD program *Working with Phylogenetic Software – Integrating Genetics and Evolution*, developed by the *teutolab-biotechnology*, proved effective in enhancing in-service teachers' professional knowledge, particularly in the dimensions of TK, PCK, and TCK. Although no significant gains were found in TPK and TPACK, the observed improvements suggest a positive development toward integrating phylogenetic software meaningfully into biology instruction. Teachers who chose to participate in the PD program demonstrated higher initial levels of PCK, technology commitment, self-efficacy in using digital media and intrinsic motivation in teaching contexts than their peers in the control group. These findings indicate that especially motivated and digitally engaged teachers are more likely to participate in such programs and benefit from them. Overall, the results emphasize that out-of-school student labs are not only valuable learning environments for students, but also important partners in the professionalization of teachers amid ongoing digital transformation.

To further enhance the integration of digital tools in biology education, future PD programs should aim to address the diverse needs and starting points of in-service teachers by offering differentiated formats for varying levels of digital competence. Expanding access beyond the most motivated and digitally confident teachers is essential. More targeted outreach, institutional incentives, and systemic support - such as mandatory participation quotas or recognition within career advancement - could help increase participation. In addition, future programs should intentionally include outreach strategies tailored to less digitally confident teachers and systematically compare participant characteristics with those of the wider teacher population to strengthen representativeness. Given the ongoing digital transformation in education, such formats should be systematically embedded into teacher training programs and supported through institutionalized partnerships between universities, out-of-school student labs, and schools.

Further research should explore long-term effects of such training on teaching practices and student outcomes, as well as how to best support sustained implementation of digital tools like phylogenetic software in everyday classroom instruction. To strengthen practical applicability, future PD iterations should incorporate exemplar lesson sequences using MEGA, including time estimates for classroom implementation and suggestions for assessing students' understanding of phylogenetic reasoning. Out-of-school student labs, with their access to authentic scientific tools and environments, will continue to play a key role in fostering innovation and bridging the gap between scientific research and school education.

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Data availability statement

The data presented in this article are not readily available because this study is part of an ongoing research project in which further analyses are planned. Requests to access the datasets should be directed to the corresponding authors.

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