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Research research

Developing students' scientific competence in biology education

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Abstract: This study examined the key factors supporting the development of scientific competence among secondary school students in biology. A theoretical analysis identified three core components of scientific competence: theoretical knowledge, practical skills, and analytical abilities. An experimental study conducted at M. Lomonosov Secondary School No. 5 in Taldykorgan, Zhetysu Region, Republic of Kazakhstan, assessed the effectiveness of selected pedagogical conditions in supporting these components. Following the introduction of changes to the learning environment, the experimental group showed improvements across all three components. The proportion of students demonstrating a basic level of theoretical knowledge decreased from 45.65% to 32.20%, while the proportion attaining a very high level increased from 1.49% to 12.70%. The proportion demonstrating very high practical skills rose from 4.67% to 12.47%, and the corresponding proportion for analytical abilities increased from 2.36% to 9.79%. These changes suggest that the revised pedagogical practices supported students' understanding of biological concepts, application of practical skills, and analytical thinking. The findings highlight the potential of targeted pedagogical approaches to strengthen scientific competence in secondary school biology education.

Keywords: educational process, learning efficiency, level of preparation, pedagogical conditions, skills development

1. Introduction

The modern educational process requires students to be prepared for independent and active engagement in a rapidly changing world. Scientific competence—which encompasses theoretical knowledge, practical skills, and the ability to think critically—is becoming a vital component in the education of schoolchildren. From the perspective of critical pedagogy, science education should extend beyond the transmission of factual knowledge and encourage students to analyze information, interpret evidence, and actively construct understanding. Giroux [1] emphasized that education should promote critical engagement with knowledge and support students' ability to participate actively in the learning process. This is particularly relevant in the study of biology, where understanding natural processes and applying knowledge in practice are essential for academic development and the cultivation of environmental awareness. However, within the traditional school system, there is often a significant gap between the recognized need to foster scientific competence and the teaching methods actually employed. This highlights the pressing issue of improving the effectiveness of the educational process. Previous studies in science education have demonstrated that competence-oriented approaches are increasingly important for developing students' ability to apply knowledge, conduct investigations, and solve complex problems [2,3].

The mismatch between outdated teaching approaches and modern educational demands presents a serious challenge, as many methods remain focused on the transmission of large volumes of information rather than on the development of analytical thinking and independent problem-solving skills. In the context of biology education, this discrepancy is evident in the limited use of practical tasks, a lack of laboratory experiments, and the weak integration of interdisciplinary connections. Furthermore, low student motivation in science is frequently linked to the absence of applied, real-world examples that could make learning more engaging and relevant. As a result, a substantial proportion of students fail to develop comprehensive scientific competence, which, in turn, limits their future educational and professional opportunities. Similar challenges have been reported in biology education, where insufficient practical activities and limited opportunities for inquiry-based learning may reduce students' ability to transfer theoretical knowledge into scientific practice [4,5].

Research into the formation of scientific competence is a crucial step in addressing these challenges. It enables the identification of factors influencing key competence components and supports the design of more adaptive and practice-oriented teaching methods. In biology, where the integration of theoretical and practical knowledge is especially critical, such research can inform the adoption of innovative teaching strategies, including project-based learning, laboratory work, and the use of modern technologies. The importance of interdisciplinary approaches in biology education has also been demonstrated by Županec et al. [6], who found that integrating concepts from different scientific fields can improve students' understanding of biological phenomena and support more comprehensive learning outcomes. Moreover, evaluating the effectiveness of specific educational conditions can help address motivational gaps among students by increasing their interest in science and building confidence in their abilities. Ultimately, these efforts can enrich the theoretical foundations of biology education while also improving the quality of teaching and learning in practice. Moreover, students' attitudes toward biology represent an important factor influencing their engagement and willingness to participate in scientific learning activities. Toma [7] emphasized that positive attitudes toward biology are associated with greater student involvement and interest in biological learning. Biology education represents an important component of STEM education

because it integrates scientific inquiry, data interpretation, experimentation, and evidence-based reasoning. Therefore, the development of scientific competence in biology contributes to broader STEM-related skills required for solving interdisciplinary scientific problems. Research indicates that combining practical activities, digital technologies, and student-centered strategies contributes to the development of scientific literacy and analytical competence among learners [8,9]. Furthermore, modern biology education increasingly requires the integration of quantitative reasoning and interdisciplinary competencies, as biological research relies extensively on data analysis and computational approaches. Caughman and Weigel [10] demonstrated that students' values regarding mathematics and computer science are closely associated with their engagement in biological learning, highlighting the importance of interdisciplinary preparation in biology education.

The theoretical foundation of the present study is based on constructivist approaches to learning, which consider students as active participants who construct knowledge through experience, interaction, and problem-solving. In biology education, this perspective supports the use of inquiry-based activities, laboratory work, and practical tasks that enable learners to connect theoretical concepts with observable phenomena. In addition, embodied cognition theory emphasizes that learning is supported by interaction between cognitive processes and physical experiences. From this perspective, experimental activities and direct engagement with biological objects may facilitate deeper conceptual understanding and scientific reasoning [11,12].

Based on this analysis, the main conditions required for the successful formation of scientific competence in schoolchildren studying biology are illustrated in Figure 1.

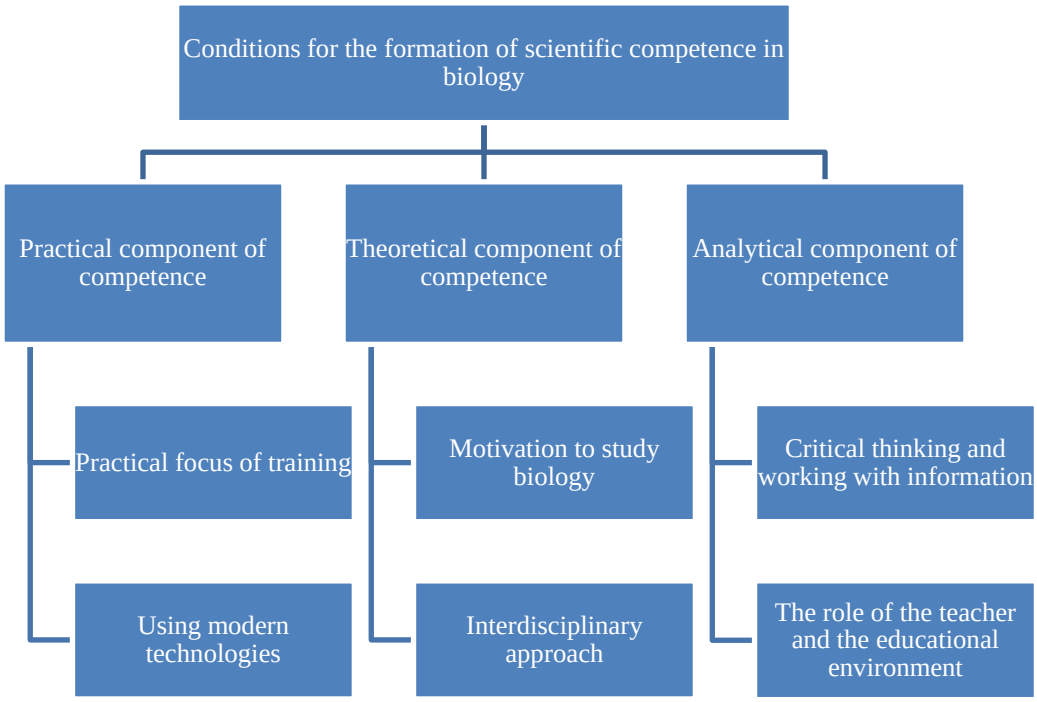


Figure 1. Key conditions for the successful development of scientific competence in the study of biology.

Various studies in the field of scientific competence formation show that the effective development of this component in students requires a combination of various teaching methods and approaches. In the study by Sukhova and Zhanburshinova [13], which examined hybrid education, it was found that the use of active educational strategies aimed at involving students in the research and analysis process has a positive effect on their theoretical training, but it was noted that this approach often requires significant time and highly qualified teachers. The study by Iminova and Abdimanapov [14] examined personality-oriented teaching methods that involve the individualization of the educational process, noting that adapting the content of lessons to the level of training of each student allows for progress in learning the material; a limitation of this approach was the absence of systematic recommendations for teachers in the context of mass education. The results of the work of Muller [15], focused on the use of information and communication technologies in educational practice, showed that such use of such technologies contributes to the deepening of knowledge and the development of analytical skills; however, the study was limited by insufficient technical support, which limited the availability of this method.

Also, in the process of forming scientific competence, it is important to pay attention to the development of students' skills on independent research and analysis of information. The results of the work of Pantiuk et al. [16] showed that the use of tasks focused on individual completion with the inclusion of problem-solving tasks increases the level of learning of the subject in students, but it was noted that the systematic inclusion of such methods in the curriculum limits their long-term effectiveness. In Nazira [17], it was found that an emphasis on student interaction during group work contributes to the development of communication skills and the ability to jointly solve problems; however, it was also noted that the lack of clear recommendations for teachers to assess the individual contribution of each student reduces the effectiveness of group work. In Murillo-Zamorano et al. [18], it was shown that the use of active learning methods promotes the development of critical thinking and helps students form their own opinions on complex issues, but it was noted that insufficient time in lessons for full discussion may require a revision of the curriculum and a redistribution of the workload.

An essential aspect of the educational process is the development of students' ability to solve practical problems that require the application of knowledge in non-standard situations. The findings of Toshpolatovich [19] demonstrated that the inclusion of complex and non-standard tasks in the curriculum can deepen students' understanding of biological processes and phenomena. However, the absence of a diverse selection of tasks across a wide range of topics limited students' opportunities for broader application of the knowledge acquired. In the study by Colomer et al. [20], emphasis was placed on reflective teaching methods, which supported the development of students' analytical skills and their capacity to evaluate their own actions and draw conclusions. Nonetheless, the lack of clear criteria for assessing task quality occasionally reduced the effectiveness of these methods in educational practice. Similarly, research by Yell et al. [21] explored the impact of individual projects on the formation of scientific competence. The study found that working on personal projects encouraged students to develop skills in independent planning. However, due to insufficient preparation, outcomes among students varied significantly, highlighting the need for additional guidance and scaffolding.

The aim of the present study was to analyze the factors contributing to the formation of scientific competence among school students studying biology and to experimentally evaluate the

effectiveness of specially designed pedagogical conditions. Based on this aim, the following research questions were formulated:

RQ1: Do students exposed to innovative pedagogical conditions demonstrate higher levels of theoretical knowledge compared with students following the standard biology curriculum?

RQ2: Do students exposed to innovative pedagogical conditions demonstrate higher levels of practical biological skills compared with students following the standard biology curriculum?

RQ3: Do students exposed to innovative pedagogical conditions demonstrate higher levels of analytical abilities compared with students following the standard biology curriculum?

Based on previous research demonstrating the positive influence of inquiry-based learning, practical activities, and digital learning approaches on scientific competence development [22,23], the following alternative hypotheses were proposed:

H1: Students participating in the innovative methodology will demonstrate significantly higher levels of theoretical knowledge than students following the standard curriculum.

H2: Students participating in the innovative methodology will demonstrate significantly higher levels of practical skills than students following the standard curriculum.

H3: Students participating in the innovative methodology will demonstrate significantly higher levels of analytical abilities than students following the standard curriculum.

2. Materials and methods

The methodological approach of the study was based on a quasi-experimental educational design, which is widely applied in educational research to evaluate the effectiveness of instructional interventions in authentic learning environments where complete randomization is often difficult to implement. This approach allows researchers to compare groups exposed to different educational conditions while maintaining the natural organization of classroom learning. In science education, quasi-experimental designs are commonly used to examine the influence of innovative teaching strategies, practical activities, and student-centered approaches on learning outcomes.

The methodological approach of the study was based on a quasi-experimental educational design, which is commonly used when researchers investigate the effects of instructional interventions in authentic school environments where complete randomization is not always feasible. Such designs allow comparison between groups receiving different educational approaches while maintaining the natural organization of the learning process. In science education research, quasi-experimental approaches are frequently applied to evaluate the effectiveness of new teaching strategies, particularly when interventions are implemented within existing classroom structures [23,24].

As part of the research, an in-depth theoretical analysis of academic literature concerning the development of competencies in school education was conducted. This included the study of pedagogical, psychological, and methodological sources, which facilitated the identification of the core components underpinning the formation of scientific competence in students. Through this analysis, three primary components of scientific competence were identified: theoretical knowledge, practical skills and abilities, and the capacity for critical thinking and independent scientific problem-solving. Theoretical knowledge refers to the assimilation of fundamental concepts, laws, and theories that provide a foundation for understanding biological processes. Practical skills and abilities encompass students' capacity to engage in experimental work, analyze data, and carry out research tasks. Critical thinking includes the ability to interpret information, assess its reliability, and

draw well-reasoned conclusions. Another key area explored in theoretical analysis was the role of the educational environment in developing scientific competence. This included the use of laboratory equipment, virtual tools, and modern technologies as pedagogical conditions that enhance the assimilation of content and support the development of research skills. In addition, particular attention was given to understanding the role of student motivation in the learning process. This comprehensive analysis contributed to a nuanced understanding of the structural and functional aspects of scientific competence, as well as the factors that influence its development. On the basis of these findings, key principles and assumptions were formulated to guide the design of the experimental phase of the study.

To analyze the effectiveness of pedagogical conditions for the formation of scientific competence among schoolchildren in biology, an experimental study was conducted at Secondary School No. 5 named after M. Lomonosov (Republic of Kazakhstan, Zhetysu Region, Taldykorgan), involving 124 students from Grades 6 to 11. The participants represented students enrolled in biology courses at the selected secondary school. The sample was formed using a convenience sampling approach because participation was determined by accessibility within the existing educational environment. The participants were students aged approximately 12–17 years who were enrolled in Grades 6–11 during the research period. This sampling strategy corresponds to educational intervention studies conducted in authentic school settings, where researchers evaluate pedagogical approaches within naturally formed student groups. The inclusion of students from Grades 6–11 was determined by the organization of biology education in the selected school, where biology is taught continuously across these educational levels.

The study focused on evaluating general changes in scientific competence formation rather than differences between individual age groups. For the purpose of objective analysis, the participants were divided into two groups: the original group (n = 60) and the test group (n = 64). The assignment of students to groups was based on existing school classes and was not conducted through individual random allocation. Therefore, the study should be interpreted as a quasi-experimental design, and possible selection effects related to pre-existing differences between groups were considered as a limitation of the research. To minimize this influence, the initial assessment of scientific competence was conducted before the intervention, and statistical tests were used to confirm the comparability of the groups. Students in the test group were taught using specially designed pedagogical conditions aimed at enhancing cognitive activity and personal motivation, developing research skills, integrating theoretical and practical knowledge, and incorporating digital technologies into the learning process.

These conditions were developed based on student-centered and inquiry-oriented approaches, which emphasize active participation, independent investigation, and application of knowledge in practical contexts. Such approaches have been shown to support the development of scientific competence by improving students' ability to analyze information, conduct investigations, and apply theoretical concepts to biological problems [23,24]. In contrast, students in the original group followed the standard biology curriculum, which was primarily based on conventional classroom instruction, including teacher explanations, textbook-based learning, and reproductive tasks aimed at knowledge acquisition. Although this approach provides a foundation for understanding biological concepts, it provides fewer opportunities for systematic research activities, experimental practice, and independent analysis compared with student-centered approaches.

The innovative methodology implemented in the test group was based on a student-centered and activity-oriented approach, which emphasized active knowledge construction, practical application of biological concepts, research activities, and the integration of digital learning tools. These principles correspond to contemporary approaches in science education, where learning is considered more effective when students actively engage in inquiry, experimentation, and interpretation of scientific information rather than only receiving theoretical explanations. The implemented methodology included inquiry-oriented activities, practical tasks, and digital learning tools aligned with the identified components of scientific competence.

To evaluate the theoretical component, a series of standardized test tasks was administered to assess the depth and completeness of students' knowledge. This testing method was selected because of its objectivity, standardization, and capacity to reflect a broad spectrum of academic achievements. It allowed for the identification of students' mastery of core biological concepts, terminology, and laws, as well as their ability to apply knowledge in explaining natural phenomena. The practical component was assessed through the completion of applied tasks designed to evaluate students' research abilities and their capacity to use theoretical knowledge in real-life contexts. These tasks included modeling biological processes, analyzing data, and conducting simple experiments. Evaluation criteria included the accuracy of task completion, adherence to procedural guidelines, and the ability to interpret experimental outcomes.

The analytical component was measured using situational tasks that required students to demonstrate critical thinking skills and provide reasoned explanations of biological phenomena. The assessment instruments were developed according to the three identified components of scientific competence. The theoretical component was measured using biology knowledge tests assessing students' understanding of concepts, terminology, and biological processes. The practical component was evaluated through applied tasks requiring students to interpret biological situations, analyze experimental results, and apply theoretical knowledge. The analytical component was assessed through problem-based tasks requiring interpretation of scientific information, justification of conclusions, and evidence-based reasoning.

All assessment instruments were evaluated according to predefined criteria corresponding to the three components of scientific competence. The theoretical assessment focused on conceptual understanding, the practical assessment examined the application of biological knowledge in experimental and problem-solving contexts, and the analytical assessment evaluated students' ability to interpret information and justify conclusions. These tasks aimed to assess students' abilities to interpret scientific data, draw logical conclusions, and propose evidence-based solutions. To ensure the comparability of the two groups, statistical data analysis was conducted using Student's t-test and Pearson's chi-square test (1):

$$x^2_{emp} = \sum \frac{(\int emp - \int crit)^2}{\int crit} \quad (1)$$

The statistical analysis was conducted to test the alternative hypotheses formulated in the Introduction. Student's t-test was used to examine the initial comparability of the groups, whereas Pearson's chi-square test was applied to identify statistically significant differences after the intervention. The combined use of these statistical tools ensured the precision of the data analysis and reinforced the reliability of the interpretation of the research findings.

3. Results

The initial level of students' scientific competence before the implementation of the pedagogical conditions was assessed for both groups. Obtained results are presented in Table 1.

Table 1. Assessment of students' scientific competence levels prior to the implementation of the pedagogical conditions.

Component of scientific competence formation	Level of students' competence (%)							
	Elementary		Intermediate		Advanced		Expert	
	Original group	Test group	Original group	Test group	Original group	Test group	Original group	Test group
Theoretical training	44.73	45.65	39.28	40.14	12.67	12.72	3.32	1.49
Practical results	42.14	42.96	39.72	38.72	13.90	13.65	4.24	4.67
Analytical skills	46.02	44.13	38.42	40.56	12.25	12.95	3.31	2.36
Average value	44.29	44.24	39.14	39.81	12.94	12.96	3.62	2.84

The analysis of Table 1 indicates that, at the initial stage of forming students' scientific competence (prior to the implementation of specific pedagogical conditions) both the original and test groups demonstrated a comparable level of competence development. The results obtained after the implementation of the pedagogical conditions are presented in Table 2.

Table 2. Assessment of students' scientific competence levels following the implementation of pedagogical conditions.

Component of scientific competence formation	Level of students' competence (%)							
	Intermediate		Intermediate		Intermediate		Intermediate	
	Original group	Test group	Original group	Test group	Original group	Test group	Original group	Test group
Theoretical training	43.56	32.20	38.90	35.18	13.05	19.92	4.04	12.70
Practical results	44.18	35.74	39.25	32.65	13.56	19.14	3.01	12.47
Analytical skills	44.25	35.16	39.75	34.80	12.90	20.25	3.10	9.79
Average value	44.00	34.36	39.30	34.21	13.17	19.77	3.38	11.65

The analysis of the presented data reveals significant differences in the dynamics of scientific competence development between students in the original and test groups following the implementation of new pedagogical conditions. In the original group, where the educational process remained unchanged, the indicators of competence development showed minimal variation. For instance, the proportion of students with a basic level of theoretical training decreased only slightly, from 44.73% to 43.56%. Similarly, the percentage of students with an advanced level of theoretical knowledge increased marginally, from 12.67% to 13.05%. These changes were relatively small and did not indicate substantial improvement. By contrast, the test group, in which new pedagogical strategies were introduced, exhibited notable positive changes. The proportion of students with a basic level of theoretical knowledge significantly declined from 45.65% to 32.20%, indicating that a substantial number of students progressed beyond the initial level of understanding. Concurrently,

the percentage of students achieving a very high level of theoretical knowledge rose from 1.49% to 12.70%. This improvement indicates a shift toward higher levels of theoretical knowledge among students in the test group after the implementation of the pedagogical conditions.

Similar trends were observed in the development of practical skills. In the original group, almost no change was detected; the proportion of students with a very high level of practical skills increased only slightly from 4.24% to 4.67%. In contrast, the test group experienced a marked improvement in this area, with the proportion rising from 4.67% to 12.47%. Additionally, the number of students with a basic level of practical competence in the test group decreased from 42.96% to 35.74%, further indicating enhanced ability to apply theoretical knowledge in practice. In the domain of analytical skills, the original group again demonstrated little change. The proportion of students with a very high level of analytical skills decreased slightly from 3.31% to 3.10%. Conversely, the test group showed a substantial increase in this area, with the proportion rising from 2.36% to 9.79%. This change indicates an increase in the proportion of students demonstrating higher levels of analytical competence after the intervention. Similar results were reported by Matanıarı et al. [25], who showed that research-oriented learning activities contribute to the development of students' critical thinking skills in biology education. Their findings confirm the importance of tasks requiring interpretation of scientific information and evidence-based reasoning. Overall, the results demonstrate differences in the distribution of competence levels between the original and test groups following the implementation of the pedagogical conditions. Students exposed to the revised methodology demonstrated deeper theoretical knowledge, improved practical abilities, and stronger analytical thinking skills. Meanwhile, students in the original group, who continued with the standard curriculum, exhibited no comparable progress, indicating differences in competence development between the groups.

Figure 2 presents a graphical representation of the dynamics of change in scientific competence levels before and after the pedagogical intervention.

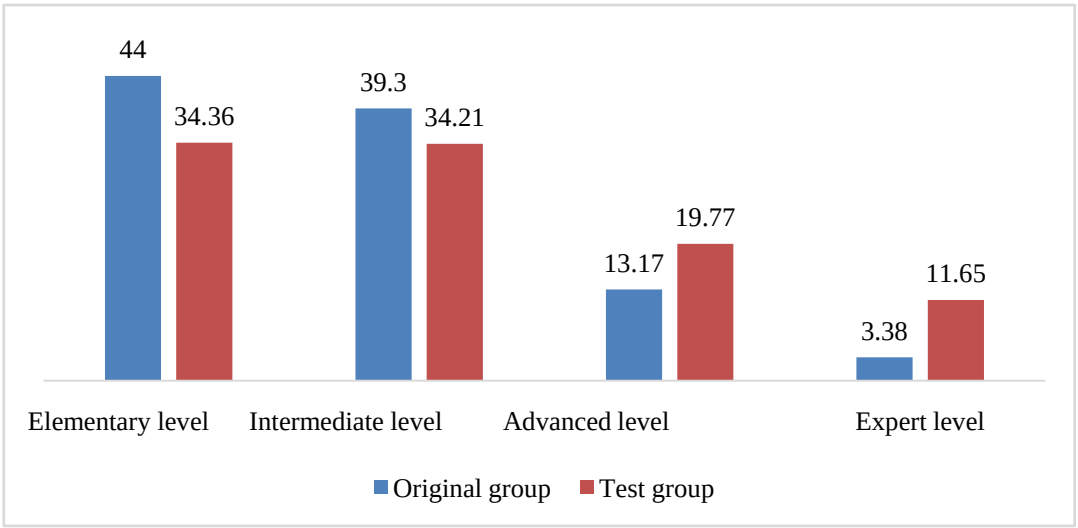


Figure 2. Dynamics of changes in the level of scientific competence as a result of changes in the educational process.

To determine whether significant differences exist in the levels of scientific competence

development between the original and test groups, the data presented in Table 3 were subjected to statistical analysis.

Table 3. Indicators of the formation of scientific competence of the original and test groups.

No.	$\int emp$, %	$\int crit$, %	$\int emp - \int crit$	$(\int emp - \int crit)^2$	$\frac{(\int emp - \int crit)^2}{\int crit}$
1	34.36	44.00	-9.64	92.93	2.11
2	34.21	39.30	-5.09	25.91	0.66
3	19.7	13.17	6.60	43.56	3.31
4	11.65	3.38	8.27	68.39	20.23
Total	100%	100%			x^2_{emp} = 26.31

To test the assumption that the observed data correspond to theoretical expectations, the empirical value of the chi-square statistic was calculated: $\chi^2_{emp}=\frac{(\int emp-\int crit)^2}{\int crit}/\int crit) = 26.31$. Given that the number of degrees of freedom is v = n−1 = 3, and the significance level is α = 0.01, the critical value is χ^2_{crit} = 11.345. Since $\chi^2_{emp} > \chi^2_{crit}$, the differences between the original and test groups in terms of students' scientific competence were statistically significant at the selected significance level. The obtained result corresponds to $\chi^2(3) = 26.31$, $p < 0.001$, confirming statistically significant differences between the groups after the intervention. This finding suggests that the observed differences between groups are unlikely to be explained by random variation alone. In this analysis, the null hypothesis (H_0), which posited that there would be no significant differences between the original and test groups, was tested. The rejection of this hypothesis indicates that the level of scientific competence differed significantly between the groups after the implementation of the new pedagogical conditions. Consequently, the alternative hypothesis (H_1), which assumes that the differences between the groups are statistically significant, was accepted.

This conclusion is further supported by the fact that the observed improvements spanned all key components of scientific competence: theoretical knowledge, practical skills, and analytical abilities. Overall, the results demonstrated statistically significant differences between the groups after the intervention. The results also highlight the critical role of changes in both the educational environment and instructional methods. The improvements observed in the test group indicate that the proposed pedagogical strategies not only enhanced students' theoretical understanding but also fostered the development of practical application skills and analytical thinking. The outcomes of the statistical analysis demonstrate that the observed differences between groups were statistically significant and corresponded with the proposed alternative hypothesis. This confirms the effectiveness of the implemented methods and supports their application in efforts to improve educational outcomes in schools.

4. Discussion

In the present study, scientific competence was analyzed through three components: theoretical knowledge, practical skills, and analytical abilities. This highlights that scientific competence is a multifaceted construct, with each component playing a distinct and essential role in students' educational and personal development. The findings of Sharpe et al. [26] support the importance of

the relationship between theoretical knowledge and practical skills. Their research showed that students with stronger theoretical foundations performed better in laboratory tasks. However, the limited sample size restricted the generalizability of the results to a broader population. Similarly, Irwan et al. [27] investigated the development of critical thinking through project-based learning and demonstrated that the regular integration of analytical tasks significantly enhanced students' ability to independently solve problems and justify conclusions. Nevertheless, their study provided limited insight into the influence of the educational environment and teacher involvement, which constrained the overall accuracy of the findings.

In another study, Hendriarto et al. [28] examined the role of practical activities in developing scientific competence. Their results revealed that students who were actively involved in laboratory work exhibited higher levels of engagement and confidence in their abilities. However, the lack of longitudinal analysis on the retention and sustainability of acquired knowledge and skills limited the broader applicability of the conclusions. In contrast to the aforementioned studies, the present research examined the combined development of theoretical knowledge, practical skills, and analytical abilities within one educational intervention. This perspective provides additional evidence regarding the relationship between different components of scientific competence within biology education. The findings also highlight the importance of teacher support during competence-oriented learning. Shen et al. [29] demonstrated that teacher leadership is positively associated with student achievement, indicating the significant role of teachers in creating effective educational conditions. These findings also correspond with research emphasizing the role of the educational environment in competence development.

Karpova et al. [30] demonstrated that an information and educational environment supports the formation of students' digital competencies and creates conditions for more effective learning. These findings also contribute to STEM education by demonstrating how biology-based learning environments can integrate scientific reasoning, practical investigation, and technology-supported activities to promote transferable scientific competencies.

The analysis of changes in the level of theoretical training among students in the original and test groups conducted during this study enables conclusions to be drawn regarding the impact of different pedagogical approaches on the development of scientific competence. In the original group, where educational conditions remained unchanged, students' results showed little to no improvement. However, following the introduction of experimental methods in the test group, a marked improvement was observed. This suggests that pedagogical strategies focused on enhancing motivation and promoting research activities—particularly through an interdisciplinary approach—were effective in engaging the most capable students and enabling them to achieve higher academic outcomes. The findings are consistent with those of Amin et al. [24], who reported that problem-based learning effectively supports the development of critical thinking skills, especially among highly motivated students. However, their study lacked a detailed analysis of the approach's impact on students with lower levels of academic preparation, limiting the applicability of the findings across diverse student populations.

Similarly, the study by Komalasari et al. [31] found that students using blended learning strategies during theoretical training performed better overall, although the influence of external factors—such as the broader educational environment—was not fully accounted for, thereby affecting the precision of the results. In a related study, Salybekova et al. [23] noted that the integration of project-based activities into theoretical instruction increased students' interest in subject content. However, the study paid limited attention to the method's effectiveness among

students with low motivation, leaving open the question of whether additional support mechanisms are necessary to engage all learners effectively. In contrast to the aforementioned studies, the present research undertakes a more comprehensive exploration of the factors influencing the development of scientific competence. This approach enabled a deeper investigation into how various pedagogical and contextual elements impact changes in students' levels of theoretical preparation, thereby offering more holistic insights into effective strategies for fostering scientific competence across a broad spectrum of learners. The influence of motivational factors and students' self-confidence should also be considered when analyzing learning outcomes. Rafiola et al. [32] found that learning motivation, self-efficacy, and blended learning approaches are important factors associated with students' academic achievement.

When analyzing the changes in students' practical outcomes before and after the introduction of targeted pedagogical methods, significant improvements must also be acknowledged. Notably, the observed decrease in the proportion of students with an initial level of preparation in the test group may indicate that, as a result of the new teaching approaches, more students began achieving higher outcomes. This reduction in lower-level results may reflect deeper comprehension of the material and improved quality of practical skills, despite a decline in the proportion of those initially categorized at the foundational level. The increase in the number of students who attained advanced and very high levels of practical competence in the test group further supports the conclusion that pedagogical strategies that stimulate cognitive engagement—alongside the use of digital technologies—enhance the development of robust practical skills. These findings align with the study by Kervinen et al. [4], which reported improvements in students' practical abilities through methods that integrated theoretical instruction with hands-on activities. However, that study also noted limitations in students' ability to apply the acquired skills in non-standard or unfamiliar situations, suggesting a lack of flexibility in transferring learning to new contexts.

Similarly, Matanıarı et al. [25] observed positive trends in students' practical competencies when specialized classes were incorporated but also highlighted that the limited depth of application in complex tasks constrained the overall effectiveness of the skills developed. In the study by Pratiwi et al. [33], an increase in competence was reported following the integration of theoretical knowledge with practical activities. Nonetheless, the authors stressed that inadequate opportunities for repeated practice created challenges in transferring these skills to real-life scenarios. In contrast to the aforementioned studies, where the improvement of practical skills appeared to be context-dependent and limited when applied in non-standard situations, the present study demonstrated higher indicators of practical competence development. This supports the conclusion that the pedagogical methods implemented—characterized by cognitive activation, digital integration, and a practice-oriented approach—are effective in promoting both the acquisition and flexible application of practical skills in biology education. In addition to cognitive factors, emotional experiences during learning activities may influence students' engagement and persistence. Zhang et al. [34] emphasized that students' emotions in design-based learning environments play an important role in shaping their interaction with educational tasks.

The analysis of the results related to the development of analytical skills also reveals a significant improvement in competence levels following the introduction of new educational conditions. Prior to the implementation of these methods, the majority of students in both the original and test groups were classified at the initial or intermediate levels of competence, as reflected in the similar baseline indicators. However, after the pedagogical changes were applied, a notable shift occurred. The reduction in the number of students at the initial and intermediate levels in the test group indicates a

redistribution toward higher competence categories. This suggests a qualitative enhancement in students' analytical abilities and confirms the value of the newly introduced teaching strategies. In the study conducted by Francisco et al. [35], key methods contributing to the development of analytical skills were identified, including the use of problem-oriented tasks. However, the authors also noted the constraints posed by limited time for practical application, which hindered the full implementation of these strategies.

Similarly, the work of Yusuf and Widyaningsih [22] demonstrated that the use of interactive tools—such as simulations and virtual laboratories—can significantly enhance students' analytical capabilities. Nevertheless, the requirement for substantial technical resources was identified as a barrier to widespread adoption. The research by Funa and Talaue [36] emphasized the importance of modular learning programs in fostering analytical thinking. However, their study also highlighted challenges in adapting these programs to meet individual student needs effectively. Unlike these studies, which focus on specific elements—such as problem-oriented tasks, interactive materials, or modular training—this study examined changes in several components of scientific competence within one educational intervention.

The findings of this study underscore the effectiveness of an integrated pedagogical approach that combines digital technologies, motivational strategies, and the active linkage of theoretical knowledge with practical application. Research in this area is essential for advancing educational practices that prepare students to address complex challenges in science and society. It provides a framework for evaluating the effectiveness of different instructional methods and fosters a deeper understanding of the conditions necessary for the successful development of scientific competence. Ultimately, such research contributes to the enhancement of the education system as a whole by promoting evidence-based strategies that support student achievement and scientific literacy.

5. Conclusions

The study demonstrated that the implementation of specific pedagogical conditions was associated with improvements in students' scientific competence indicators. Based on both theoretical analysis and experimental data, the study identified the key components influencing the development of scientific competence: theoretical knowledge, practical skills, and analytical abilities. Together, these components determine the overall level of students' scientific training and are central to the development of scientific thinking.

The experimental phase of the study revealed substantial differences between the original and test groups. In the original group, where the educational process remained unchanged, students' competence levels showed minimal progression. In contrast, the test group, where new pedagogical conditions were introduced, demonstrated clear and measurable improvements. The proportion of students with an initial level of theoretical knowledge decreased from 45.65% to 32.20%, indicating a shift toward higher levels of mastery. Simultaneously, the percentage of students achieving a very high level of theoretical knowledge rose from 1.49% to 12.70%, indicating improvements associated with the implemented strategies. Similar positive changes were observed in the area of practical skills. In the test group, the proportion of students with a very high level of practical competence increased from 4.67% to 12.47%, whereas the corresponding indicators in the original group remained largely unchanged.

Notably, the development of analytical skills also showed improvement in the test group, with

the percentage of students reaching a very high level rising from 2.36% to 9.79%. These results indicate improvements in analytical competence indicators among students who participated in the intervention. Overall, the findings confirm that the introduction of innovative pedagogical conditions—such as revised teaching methods and the reinforcement of theoretical instruction—was associated with higher indicators of students' scientific competence.

It is important to acknowledge certain limitations of this study. The research was conducted within a specific educational setting, which may restrict the generalizability of the findings to other contexts or age groups. Therefore, the results should not be interpreted as universally applicable to all school populations. However, the identified pedagogical conditions provide a transferable framework that may be adapted to other biology education contexts after considering differences in curriculum structure, available resources, teacher preparation, and student characteristics. Furthermore, the study focused primarily on short-term outcomes, without examining the potential long-term effects of the implemented pedagogical strategies. Future research could usefully explore the sustainability of the acquired knowledge and skills over time and assess the adaptability of the proposed methods across various educational systems and student ability levels. The development of more universal, flexible pedagogical approaches remains a promising direction for enhancing scientific competence in diverse learning environments.

Author contributions

Conceptualization, ZK; methodology, KT, OY; software, ZK; investigation, OY, KT, ZK; resources, OY; data curation, KT; writing—original draft preparation, KT, ZK, OY; writing—review and editing, KT, ZK, OY; visualization, OY, ZK.

Use of Generative-AI tools declaration

The authors declare that generative AI or AI-assisted technologies were not used in any way to prepare, write, or complete this manuscript. The authors confirm that they are the sole authors of this article and take full responsibility for the content therein, as outlined in COPE recommendations.

Conflict of interest

The authors declare no conflict of interest.

Ethics declaration

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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