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Methodological framework for integrating sustainable development goals in pre-service biology teacher education

Akmaral Sharipova[1], Mahabbat Amanbayeva[2], Esenzhol Nazarov[3], Gulmira Nazarova[4], Aiman Karabalayeva[5], Sergey Sumatokhin[6]

[1]*Korkyt ata Kyzylorda University, Kyzylorda, Kazakhstan, ORCID ID: 0000-0002-0091-3980*
[2]*Abai Kazakh National Pedagogical University, Kazakhstan, ORCID ID: 0000-0001-6173-3564*
[3]*Senior lecturer at Korkyt Ata Kyzylorda University, Kazakhstan, ORCID ID: 0000-0003-2368-6466*
[4]*Senior lecturer at Korkyt Ata Kyzylorda University, Kazakhstan, ORCID ID: 0000-0002-3872-9951*
[5]*Astana international university, Astana, Republic of Kazakhstan, Corresponding Author,karabalayevaa@gmail.com , ORCID ID: 0000-0001-6539-2541*
[6]*Moscow City University, Russia, ORCID ID: 0000-0002-9027-4085*

ABSTRACT

This study explores how the Sustainable Development Goals (SDGs) can be meaningfully integrated into pre-service biology teacher education, with a particular focus on the development of sustainability-related competencies. A mixed-methods design combined survey data from 120 pre-service biology teachers with semi-structured interviews conducted with 15 university instructors involved in teacher training. The results suggest that although future teachers generally understand the concept of sustainable development and recognise its relevance to biology education, their readiness to apply the SDGs in practice remains at a moderate level. Paired-samples t-test analysis demonstrated statistically significant improvements across all measured competency dimensions following the SDG-orientated methodological intervention ($p < .001$). The largest improvement was observed in the ability to design SDG-based biology lessons ($\Delta M = +1.08$, Cohen's $d = 0.94$), indicating a strong practical effect. The main challenges were associated with lesson planning, interdisciplinary connections, and the assessment of sustainability competencies. Student-centred approaches, such as project-based learning, inquiry activities, and collaborative reflection, were linked to greater pedagogical confidence and methodological readiness, whereas traditional lecture-based methods had less influence. Interview data further revealed fragmented curriculum integration and an absence of clear methodological guidance. The study highlights the importance of systematically incorporating SDG-focused methodological components into biology teacher education programmes and offers practical suggestions for curriculum design and teaching practice in the context of education for sustainable development. It contributes to the literature by combining validated competency assessment, mixed-methods analysis, and intervention-based evidence within the under-represented Central Asian context of pre-service biology teacher education.

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Introduction

Contemporary education systems operate within a rapidly globalising world where economic, environmental, and social challenges increasingly intersect. Under these conditions, education is expected not only to transmit disciplinary knowledge but also to contribute to the long-term sustainability of societies (UNESCO, 2017). In this context, the Sustainable Development Goals (SDGs) have emerged as a key international framework guiding educational transformation and curriculum renewal, and higher education institutions are widely regarded as central actors in their achievement (Chankseliani & McCowan, 2021). Their integration into teacher education is especially significant, as teachers directly influence how future generations understand environmental responsibility, social justice, and civic engagement (Mulà & Tilbury, 2025). Biology occupies a distinctive position within this process. As a natural science discipline, it addresses fundamental issues related to ecosystem stability, biodiversity loss, human health, and climate change — areas that closely align with the core priorities of sustainable development (Jeronen et al., 2017; Jackson et al., 2023). Consequently, the professional preparation of future biology teachers represents a particularly appropriate educational context for embedding SDG principles in a systematic and pedagogically meaningful way. Nevertheless, despite this conceptual alignment, the integration of SDGs into pre-service biology teacher education remains uneven and insufficiently structured in many higher education institutions, and existing approaches often lack methodological coherence and a clearly articulated pedagogical rationale (Ferrer-Estévez & Chalmeta, 2021; Leal Filho et al., 2019).

Although international policy frameworks and strategic documents consistently emphasise the role of education in achieving the Sustainable Development Goals, their practical implementation within teacher education programs remains problematic (Bourn et al., 2017). A substantial body of research has examined the sustainability competencies future teachers require and the pedagogical approaches capable of developing them: seminal frameworks by Wiek et al. (2011) and Rieckmann (2012, 2018) identified the core competencies underlying sustainability-orientated practice, while Lozano et al. (2017, 2019, 2022) demonstrated that active, student-centred methods such as project-based and problem-based learning are more effective than traditional instruction for developing these competencies. In biology education specifically, Bezeljak et al. (2020) found that pre-service teachers are relatively confident in the environmental dimension of sustainability but struggle to connect it with its economic and social dimensions, and a recent bibliometric review by Jeronen et al. (2026) confirmed that holistic studies at the intersection of biology and Education for Sustainable Development (ESD) remain limited. This gap is particularly visible in the preparation of future biology teachers: a systematic review of 158 publications by Fischer et al. (2022) found that the assessment of learning outcomes and the promotion of systemic change remain the least developed areas of research on teacher ESD, and current teacher training curricula continue to introduce SDG-related content in a fragmented manner, without consistent methodological support. Instructional strategies often remain predominantly theoretical, while assessment practices are rarely aligned with the evaluation of sustainability-related competencies, producing a disconnect between curriculum content, teaching methods, and assessment tools that limits future biology teachers' ability to translate sustainability concepts into effective classroom practice (Sinakou et al., 2018).

What remains largely absent from this literature, however, is empirical evidence from Central Asia. Existing regional studies indicate that ESD implementation across universities is uneven and that student awareness of the SDGs remains low (Bespalyy et al., 2024), that teacher preparation in Kazakhstan is affected by fragmented curricula and weak institutional support (Yelubayeva et al., 2023), and that motivational and reflective aspects of professional readiness among biology students are frequently underestimated (Nurgaliyeva et al., 2022). More recent Kazakhstani studies have identified a persistent gap between declared attitudes and actual teaching skills among pre-service biology teachers (Abiltayeva et al., 2025), as well as a weak representation of critical thinking, a key competence of Target 4.7, in the stated learning outcomes of teacher education programmes (Kabysheva, 2025). None of these studies, however, combines validated competency measurement with an intervention-based

design capable of demonstrating whether structured methodological training can change this picture, and this is the gap the present study addresses. The study is grounded in the conceptual understanding of sustainable development as a multidimensional phenomenon that encompasses economic, environmental, and social dimensions. Education is viewed as a central mechanism for fostering the knowledge, values, and competencies required to support sustainable societal development. From this perspective, teacher education plays a mediating role between global sustainability agendas and classroom-level educational practice. The pedagogical framework of the study draws on constructivist learning theory, the competency-based approach, and principles of interdisciplinary education. Constructivist theory emphasises that learning occurs through active engagement and meaning-making rather than through passive knowledge transmission. The competency-based approach enables the evaluation of future teachers' readiness for professional practice, particularly in complex and value-laden domains such as sustainable development (Rieckmann, 2012). Interdisciplinary learning, in turn, facilitates the integration of biological knowledge with broader ecological, social, and ethical contexts, which is essential for addressing sustainability challenges (Wiek et al., 2011). The originality of this study lies in several important aspects. First, the study examines SDG integration specifically within pre-service biology teacher education, an area that remains under-represented in current ESD research. Second, the study combines quantitative, qualitative, and quasi-experimental intervention data within a single mixed-methods framework. Third, the research adapts and validates SDG-related competency instruments for the educational and cultural context of Kazakhstan. Finally, the study provides empirical evidence from Central Asia, a region that remains insufficiently represented in international literature on Education for Sustainable Development.

Research Questions

This study addresses the following research questions:

1. What is the level of readiness of pre-service biology teachers to integrate SDGs into teaching practice?

2. Which pedagogical approaches most effectively support the development of SDG-related competencies?

3. What methodological challenges hinder the implementation of SDGs in biology teacher education?

Research Hypotheses

H1. Structured SDG-orientated methodological training significantly improves pedagogical competence.

H2. Active learning approaches (e.g., project-based and inquiry-based learning) enhance pedagogical confidence in SDG implementation.

H3. Interdisciplinary and reflective instruction improves overall readiness for integrating SDGs into teaching practice.

Aim of the Study

The aim of this study is to identify and empirically validate the methodological foundations for integrating Sustainable Development Goals (SDGs) into pre-service biology teacher education. In particular, the study seeks to examine the effectiveness of SDG-orientated pedagogical approaches in developing sustainability-related competencies, including pedagogical confidence, methodological competence, and interdisciplinary teaching skills among future biology teachers.

Literature Review

The issue of integrating the SDGs into the preparation of future biology teachers has emerged at the intersection of three research areas. These include education for sustainable development (ESD),

subject specific teacher training methods, and the competence-based approach in teacher education. These areas developed relatively independently over several decades. However, the adoption of the 2030 Agenda and its Target 4.7 gave them a common direction. A review of existing studies makes it possible to trace how the academic community gradually moved from general frameworks to more specific questions of pedagogy, competencies, and assessment. It also allows us to identify the gaps that justify the need for the present study. The theoretical foundation of ESD was formed in works that appeared before the adoption of the 2030 Agenda. Sterling (2001) introduced an important distinction between education about sustainability as an update of content and sustainable education as a transformation of values and meanings within the system. Tilbury (2011), working under UNESCO, summarized global experience and identified five key pedagogical principles of ESD. She emphasized the role of teacher preparation as a strategic factor for systemic change. UNESCO (2017) further developed these ideas by outlining learning objectives and suggested activities for each of the 17 SDG. Vare and Scott (2007) proposed an analytical distinction between ESD 1 and ESD 2. The first focuses on informed behavior, while the second aims to develop critical thinking and the ability to act in conditions of uncertainty. This framework is widely used in current research on teacher education. Wals (2015) developed the idea of transgressive learning and argued that environmental and social crises require not simple adaptation but a deeper reconsideration of existing models. Later studies that focus on higher education practice show that the institutional response remains uneven. Chankseliani and McCowan (2021) identified significant differences in how universities support the full range of the SDGs. Ferrer-Estévez and Chalmeta (2021) showed that active teaching approaches are still not sufficiently represented in official curricula. Leal Filho et al. (2019) found that the main barriers to integrating the SDGs into higher education include limited teacher training, inflexible curricula, and weak institutional support.

At the same time, a separate line of research focused on sustainability competencies was formed. The work of Wiek et al. (2011) became one of the most widely cited frameworks. It identified five core competencies. These include systems thinking, anticipatory competence, normative competence, strategic competence, and interpersonal competence. A decade later, Brundiers et al. (2021) updated this framework based on a Delphi study. They added competencies of integration and implementation. Rieckmann (2012, 2018), in a series of studies, defined eight key competencies in ESD. He placed strong emphasis on values and critical reflection. Barth et al. (2007) showed that sustainability competencies in higher education are most effectively developed through interdisciplinary and self-directed learning. Bertschy et al. (2013) made an important distinction. They separated competencies for learners in sustainability from the professional competencies of teachers in ESD. This distinction was further developed by Cebrián and Junyent (2015). They proposed a seven-component professional model and showed that students in teacher education programs have a limited awareness of their own competencies in this field. Lozano et al. (2017, 2019, 2022) created a matrix that links competencies with teaching approaches. Their findings confirmed that case studies, problem-based learning, and project-based learning are more effective than traditional lectures for developing sustainability competencies. Mogensen and Schnack (2010) pointed out that the tradition of action competence, rooted in the German concept of Bildung, offers a democratic alternative to an instrumental view of competencies.

A separate line of research focuses on teacher education in the context of sustainable development. Mulà and Tilbury (2025) identified eight catalytic entry points for embedding ESD into teacher education programs across European countries. Fischer et al. (2022) conducted a systematic review of 158 publications and found that the assessment of learning outcomes and the promotion of systemic change remain the least developed areas in research on teacher ESD. Bourn et al. (2017) documented a persistent gap between policy declarations on ESD and actual teaching practice in teacher education programs. Sinakou et al. (2018, 2019) showed that even academics working in this field often rely on partial rather than holistic understandings of sustainable development. This affects what they communicate to their students. Vare et al. (2019) described the Rounder Sense of Purpose project, where twelve professional competencies for teachers in ESD were defined for European teacher education programs. Darling-Hammond et al. (2017) identified seven features of effective professional

development for teachers. These features are closely aligned with active learning approaches that are widely used in ESD.

Biology education has been studied in the context of sustainable development less often than other natural science disciplines. However, interest in this topic has grown in recent years. Bezeljak et al. (2020) compared Slovenian and Austrian student teachers and found that future biology teachers are confident in the environmental aspects of sustainability but have difficulty linking them with economic and social dimensions. Jeronen et al. (2017), in a review of teaching methods in biology and ESD, concluded that outdoor learning, fieldwork, and project-based learning are the most effective for developing environmental literacy. A later bibliometric analysis by Jeronen et al. (2026) confirmed that holistic studies at the intersection of biology and ESD remain limited. Jackson et al. (2023) described the redesign of the school biology curriculum around socio-scientific issues aligned with the SDG. Their study showed that disciplinary rigor and a value-orientated focus on sustainability do not contradict each other. Boeve-de Pauw et al. (2015), based on a sample of more than 2,000 Swedish students, demonstrated that holistic and pluralistic approaches to teaching ESD can significantly influence students' ways of thinking. Active and student-centred teaching methods form one of the most developed areas in this body of literature. Krajcik and Blumenfeld (2006) identified five key features of project-based learning that are still used as a reference in curriculum design. Pedaste et al. (2015) synthesized research on inquiry-based learning into a five-phase cycle, which has become a standard planning tool in science teacher education. Markula and Aksela (2022) examined how teachers implement project-based learning in school science courses and noted that environmental and sustainability-related topics often serve as the driving questions of projects. Strat et al. (2024), in a systematic review of 142 studies, found that future science teachers learn inquiry-based learning successfully as students, but face difficulties when applying it in their role as teachers. Kalsoom and Khanam (2017) showed, using data from Pakistan, that inquiry activities related to the SDG significantly increase environmental awareness among teacher education students. Lozano et al. (2019, 2022) summarized data from 13 European universities and confirmed that problem-based and project-based learning consistently appear as the most effective approaches for developing sustainability competencies. Rieckmann (2012) and Cebrián et al. (2020) emphasized the role of reflective and interdisciplinary practices in the development of professional identity in ESD.

Issues of assessment and curriculum integration in ESD form a separate problem area in the research literature. Sinakou et al. (2018) found that even among teacher educators, a simplified and mainly environmental understanding of sustainability prevails. This narrows the range of competencies that are developed. Leal Filho et al. (2019) systematized institutional barriers that hinder the implementation of ESD and identified the lack of targeted teacher training as the main challenge. Lozano et al. (2019) showed that the assessment of sustainability competencies remains the weakest element in university teaching practice. Boeve-de Pauw et al. (2015) warned that positive changes in values do not always lead to corresponding changes in behavior. For this reason, assessment tools should address several levels of readiness. Cebrián et al. (2020) identified the development of reliable diagnostic tools as one of the key priorities in current research. The context of Kazakhstan and Central Asia requires special attention, since international studies rarely focus on this region. Yelubayeva et al. (2023), in a qualitative study, identified the main challenges of ESD in Kazakhstan. These include insufficient teacher preparation, fragmented curricula, and weak institutional support. Nurgaliyeva et al. (2022) examined practice-orientated training of biology students in Kazakhstani universities and showed that motivational and reflective aspects of professional readiness are often underestimated. Abiltayeva et al. (2025) conducted a survey of future biology teachers in Kazakhstan and revealed a clear gap between declared attitudes and actual teaching skills. This finding is consistent with international research that points to a mismatch between knowledge and teaching confidence. Kabysheva (2025) carried out a computer-based analysis of bachelor's level teacher education programs in Kazakhstan and found that critical thinking, as a key competence of Target 4.7, is weakly represented in stated learning outcomes. Saparbaikyzy et al. (2026) provided quasi-experimental evidence that project-based environmental education significantly improves social and environmental values and

behavior among school students in Kazakhstan. This supports the potential of active learning methods in this national context. Bespalyy et al. (2024) conducted a comparative study in four Central Asian countries (Kazakhstan, Tajikistan, Kyrgyzstan, and Uzbekistan) and concluded that student awareness of the SDGs remains low, while the integration of ESD into university programs is uneven.

The review makes it possible to identify several key gaps that justify the need for the present study. First, although the international knowledge base on sustainability competencies and active learning methods is extensive, studies that focus specifically on teacher education in biology remain limited. The Central Asian context is also almost absent in this field. Second, in cases where the preparation of biology teachers has been examined, researchers consistently report that environmental knowledge is well developed. At the same time, the integration of economic and social dimensions of sustainability remains weak. Third, there is a clear lack of data on the actual use of project-based and inquiry-based learning by Kazakhstani students in biology teacher education programs, despite existing policy declarations. Fourth, the field requires more intervention-based studies that combine the content of the SDGs, competence frameworks, and active teaching methods within a single instructional design with measurable outcomes. Finally, there is a shortage of assessment tools that are sensitive to the educational and linguistic context of Kazakhstan. Such tools are needed to track the development of professional readiness among future biology teachers. These gaps define the research focus of the present study.

Methods

Research Design

This study employed a mixed-methods research design integrating quantitative and qualitative strands within a convergent parallel model (Creswell & Plano Clark, 2018). Quantitative data captured the distribution and magnitude of SDG-related readiness across the full participant sample, while qualitative data from instructor interviews illuminated pedagogical conditions and institutional constraints shaping that readiness. A quasi-experimental pre-post component was embedded within the quantitative strand to evaluate the effect of the authorial instructional module on a volunteer subgroup. Combining these two strands with the embedded quasi-experimental component allowed methodological triangulation, strengthening the credibility and interpretive depth of the findings.

Institutional Context and Participants

The study was conducted at Korkyt Ata Kyzylorda University (Kazakhstan), an institution offering an accredited pre-service programme for biology teacher education. The quantitative phase involved 120 pre-service biology teachers (female 74%, male 26%; mean age = 20.8 years, SD = 1.4) enrolled across Years 2, 3, and 4: Year 2 (n = 38, 31.7%), Year 3 (n = 45, 37.5%), and Year 4 (n = 37, 30.8%). Purposive sampling ensured variation in academic year and prior exposure to sustainability-related coursework.

The qualitative phase involved 15 university instructors responsible for biology pedagogy, environmental education, or curriculum design courses. Purposive sampling criteria included a minimum of five years of experience in pre-service teacher education, direct involvement in biology methodology or ESD-related courses, and willingness to reflect critically on current practice. A subgroup of 60 students drawn from Years 3 and 4 also participated in the instructional intervention. Participation was voluntary and had no bearing on academic assessment.

Instructional Intervention

The SDG-focused instructional intervention was built around two interlocking components developed by the lead author specifically for pre-service biology teacher education in Kazakhstan. The

first component was the authorial course "Kazakhstan Bioresources and Sustainable Development," comprising 30 contact hours and approximately 40 hours of independent and collaborative project work, delivered over one academic semester (15 weeks). The course was structured in three sequential blocks. The first block (Weeks 1–3) consisted of thematic seminars in which students analysed linkages between seven SDGs (2, 3, 4, 6, 13, 14 and 15), together with Targets 4.7 and 4.c of SDG 4, and core biology curriculum topics, drawing on Kazakhstani ecological contexts: the Aral Sea crisis, Tian Shan glacier retreat, steppe ecosystem degradation, and regional biodiversity loss. The second block (Weeks 4–11) centred on project-based learning, during which students, in groups of three or four, identified a locally relevant sustainability problem, formulated a driving question, conducted inquiry activities, and developed a complete biology lesson sequence that integrated SDG content with active teaching strategies. Projects were subject to structured peer feedback. The third block (Weeks 12–15) focused on reflective practice through written reflective journals, group discussions, and individual professional development plans.

The second component was the School EcoClub, implemented during the students' teaching practicum at general education schools in Kyzylorda. Operating under the methodological supervision of the university department, students planned and led club activities aligned with the UN 2030 Agenda across two formats. Within biology lessons, SDG-orientated content was integrated into the existing curriculum in agreement with the mentor teacher. In extracurricular sessions, students organised thematic meetings, field observations of local ecological sites, and project-based environmental initiatives that addressed regional sustainability challenges. EcoClub activities were documented through reflective diaries, mentor evaluations, and a portfolio of completed events.

Prior to the main study, the course tasks and instruments were piloted with five students not included in the main sample. Minor revisions were made to task instructions and two questionnaire items on the basis of pilot feedback.

Research Instruments

Three instruments were used. The first was the SDG Readiness Questionnaire (SRQ), a structured 24-item measure given to all 120 participants. Items assessed six dimensions on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree): knowledge of SDGs, understanding of sustainability concepts, ability to integrate SDGs into biology lessons, use of SDG-orientated teaching methods, ability to design interdisciplinary SDG tasks, and assessment of sustainability competencies. The questionnaire was developed with reference to prior ESD research (Cebrián & Junyent, 2015; Sinakou et al., 2019) and reviewed for content validity by three experts in biology education and ESD. Internal consistency was satisfactory (Cronbach's α = .81), with subscale reliabilities ranging from α = .73 to α = .79.

To further ensure construct validity, exploratory factor analysis (EFA) was conducted prior to the main analysis. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was .82, indicating good suitability for factor analysis, while Bartlett's Test of Sphericity was statistically significant (χ^2 = 846.31, $p < .001$). Factor loadings for all retained items exceeded .60, confirming acceptable construct validity of the instrument.

The second instrument was the SDG Competency Self-Assessment Scale (SCAS), an authorial adaptation of the Instrument for Measuring Student Sustainability Competencies (Waltner et al., 2019) developed for the Kazakhstani context. The original instrument was translated, content-adapted to local ecological referents (Aral Sea, Tian Shan glaciers, steppe ecosystems), subjected to expert review by eight specialists, piloted with 24 students, and refined on the basis of item analysis. The finalised 20-item scale comprises four subscales measuring gnosological (G), praxiological (P), axiological (A), and motivational (M) dimensions of SDG-related competency. Internal consistency of the adapted scale was acceptable at both time points (pre: α = .83; post: α = .85). The SCAS was administered to the intervention subgroup (n = 60) one week before the course began (M-0) and one week after its conclusion (M-4). A five-point monitoring system spanning checkpoints M-0 through M-4 tracked competency trajectories

across the full semester, with M-1 and M-2 providing formative mid-course data and M-3 capturing teaching practicum outcomes evaluated by the mentor teacher, the university supervisor, and the student's own reflective report.

The third instrument was a semi-structured interview protocol used with the 15 teacher educators. The 12-question protocol addressed three thematic areas: current practices and challenges in SDG integration, perceptions of effective pedagogical approaches, and recommendations for curriculum reform. The protocol was informed by Fischer et al. (2022) and piloted with two instructors outside the main sample. Interviews lasted 35–55 minutes (M = 44 min), were audio-recorded with participants' consent, and were conducted in participants' preferred language (Kazakh or Russian). Transcripts were produced verbatim and translated into English by a certified bilingual translator, with back-translation by a second independent translator; discrepancies were resolved through consensus.

Procedure

Data collection unfolded in three sequential stages within one academic semester. In Stage 1, the SRQ was distributed electronically to all 120 participants via an institutional survey platform. Participants had two weeks to complete the questionnaire; one reminder was sent at the midpoint. The response rate was 100%. In Stage 2, the one-semester instructional intervention was delivered to the volunteer subgroup of 60 students. The SCAS was administered at M-0 (one week before the first session) and M-4 (one week after the final session). To minimise response bias, both administrations used anonymous participant codes. Monitoring checkpoints M-1, M-2, and M-3 were embedded at fixed points during the semester. In Stage 3, semi-structured interviews were conducted with the 15 teacher educators in an online or in-person format according to participant preference.

Data Analysis

Quantitative data from the SRQ were analysed using descriptive statistics (means, standard deviations, frequency distributions) to characterise SDG readiness across dimensions and years of study. Pearson product-moment correlations examined associations between reported frequency of specific teaching methods and overall SRQ scores. For the pre-post comparison of SCAS data, paired-samples t-tests were applied to each of the four subscales (G, P, A, M), with effect sizes calculated using Cohen's d. All quantitative analyses were conducted in IBM SPSS Statistics (Version 27) with α set at .05.

Qualitative interview data were analysed through reflexive thematic analysis following Braun and Clarke's (2022) six-phase procedure. Initial coding was conducted by the lead researcher; a second researcher independently coded 30% of the transcripts. Inter-rater reliability was substantial (Cohen's κ = .76), and discrepancies were resolved through discussion. Quantitative and qualitative findings were integrated at the interpretation stage by mapping thematic categories onto the readiness dimensions identified quantitatively.

Ethical Considerations

The study was approved by the Research Ethics Committee of Korkyt Ata Kyzylorda University prior to data collection. All participants received a written information sheet detailing the study's purpose, procedures, data handling practices, and their right to withdraw at any time without consequence. Informed consent was obtained in writing before any data were collected. Students in the intervention subgroup were explicitly informed that participation was voluntary and would not affect their course grades or academic standing. All data were anonymised at the point of transcription and stored on a password-protected institutional server accessible only to the research team. No personally identifiable information is reported in this article.

Results

Preparation Level of Future Teachers for SDG Implementation

Quantitative analysis showed that the level of preparation of future biology teachers regarding the integration of the Sustainable Development Goals (SDGs) into pedagogical practice was heterogeneous. The level of preparation was assessed on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) according to several criteria. In particular, the levels of conceptual knowledge of SDGs, understanding of sustainable development principles, ability to integrate SDGs into the content of biology lessons, use of SDG-orientated teaching methods, development of interdisciplinary tasks and assessment of sustainable development competencies were considered. The results showed that future biology teachers' theoretical awareness and conceptual understanding of the concepts of SDGs and sustainable development were at an average level. However, it was found that the competencies related to methodological preparation and assessment were relatively poorly developed. In particular, participants showed high confidence in understanding the importance of SDGs for the biology subject, but they felt less confident in developing SDG-integrated lesson plans, systematically using active learning strategies, and assessing students' sustainable development competencies. This trend clearly demonstrates the imbalance between the level of knowledge-based preparation and practical pedagogical capabilities of future teachers. That is, there is a gap between awareness of sustainable development principles and the ability to effectively implement them in the actual teaching process. Overall, the results obtained confirm that future biology teachers have initial preparation for implementing SDG, but systematic methodological training is needed to translate this preparation into effective and sustainable classroom practice.

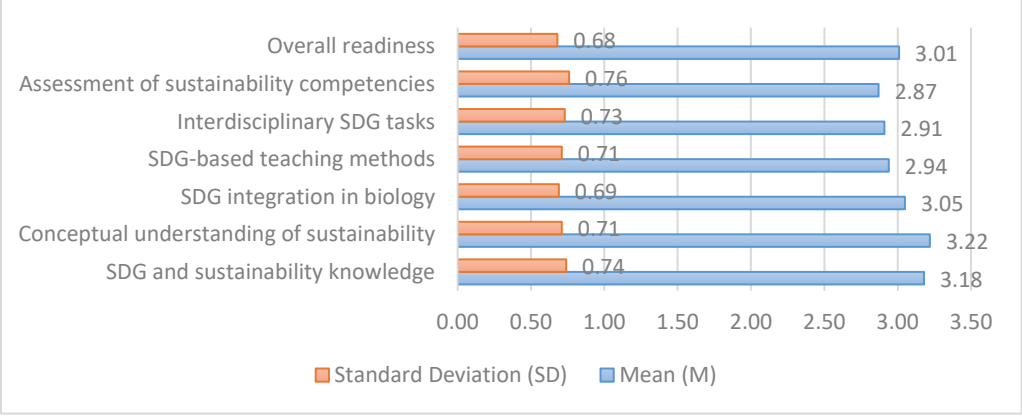
Table 1

Mean indicators of SDG-related preparation (N = 120)

Dimension of Readiness	Mean (M)	Standard Deviation (SD)
Knowledge of SDGs	3.18	0.74
Understanding of sustainability concepts	3.22	0.71
Ability to integrate SDGs into biology lessons	3.05	0.69
Use of SDG-oriented teaching methods	2.94	0.71
Designing interdisciplinary SDG tasks	2.91	0.73
Assessment of sustainability competencies	2.87	0.76
Overall readiness	3.01	0.68

Figure 1

Mean scores of SDG-related readiness among pre-service biology teachers



The results indicated that the overall level of preparation of future biology teachers was average across all measured dimensions (M = 3.01, SD = 0.68). Relatively high averages were observed in dimensions related to conceptual understanding, namely, the level of knowledge of the Sustainable Development Goals (M = 3.18, SD = 0.74) and understanding of the concepts of sustainable development (M = 3.22, SD = 0.71). These results indicate that the respondents have a basic theoretical understanding of the principles of sustainable development. In addition, lower averages were found for methodological and practical dimensions. In particular, the indicators of the use of teaching methods focused on SDG (M = 2.94, SD = 0.71), the development of interdisciplinary SDG tasks (M = 2.91, SD = 0.73) and the assessment of sustainable development competencies (M = 2.87, SD = 0.76) remained at a low level. This means that, although future biology teachers have theoretical preparation on sustainable development issues, their skills for effective implementation and assessment in the teaching process are insufficiently developed.

Distribution of Preparation Levels

To better illustrate differences in the level of preparedness for implementing the Sustainable Development Goals (SDGs), respondents were classified into three groups based on their composite readiness scores: low, moderate, and high. This categorisation made it possible to examine not only overall trends but also the extent to which future biology teachers differ in their capacity to apply SDG-related principles in educational practice. The analysis indicates that the largest group of respondents falls within the moderate readiness category. The analysis indicates that many pre-service biology teachers possess a general awareness of the SDGs and recognise their relevance to biology education; however, their ability to apply these principles in a methodologically confident manner remains limited. Such respondents appear to be at a transitional stage between theoretical understanding and practical implementation. At the same time, a considerable proportion of participants demonstrated a low level of readiness. This group is characterised by insufficient practical experience and uncertainty in selecting appropriate SDG-orientated instructional and assessment strategies. These respondents are likely to require substantial methodological support to move beyond declarative knowledge toward effective classroom application. Only a smaller segment of the sample reported a high level of readiness. This finding suggests that comprehensive and systematic competence in integrating SDGs into biology teaching is not yet common among future teachers. Overall, the distribution pattern reflects uneven preparation levels and points to structural gaps in current teacher education programmes.

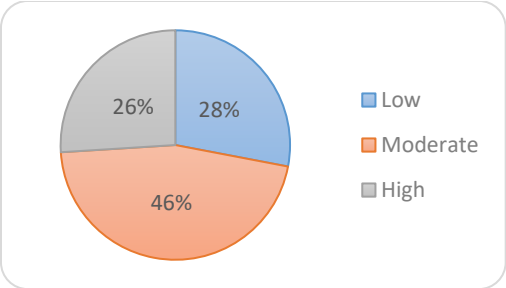
Table 2

Distribution of preparation levels of pre-service biology teachers for SDG implementation

Readiness Level	Score Range	Percentage
Low	1.0–2.4	28%
Moderate	2.5–3.4	46%
High	3.5–5.0	26%

Figure 2

Distribution of pre-service biology teachers' readiness levels for SDG implementation



As shown in Table 2 and Figure 2, nearly half of the respondents (46%) fall within the moderate readiness category. This suggests that while many future biology teachers have acquired basic knowledge and general awareness of the Sustainable Development Goals, they do not yet demonstrate sufficient methodological confidence for consistent classroom implementation. In addition, more than one quarter of participants (28%) display low readiness, indicating limited experience and hesitation in applying SDG-orientated teaching and assessment approaches. Only 26% of respondents report a high level of preparedness, confirming that advanced competence in systematically integrating SDGs into biology instruction remains relatively rare. Taken together, these findings underscore the need for targeted and structured methodological training within teacher education programmes.

Relationship between Teaching Methods and Competency Development

To examine the relationship between instructional approaches and the development of SDG-related competencies, a Pearson correlation analysis was conducted. The analysis focused on identifying associations between commonly used teaching methods and indicators of pedagogical confidence, methodological preparedness, and sustainability-orientated competence among pre-service biology teachers.

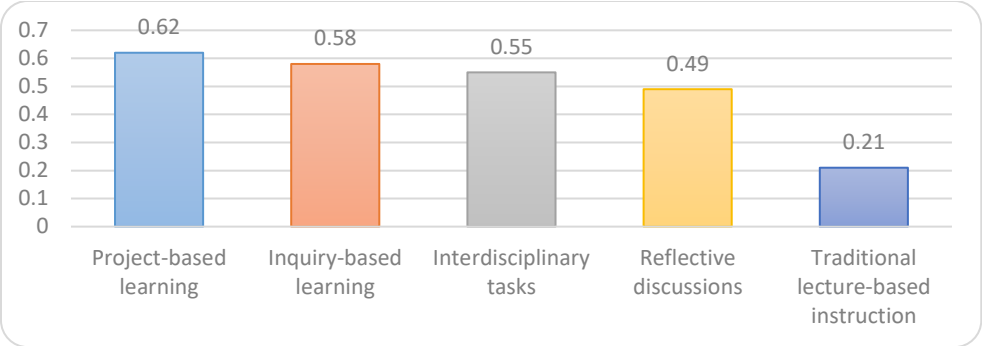
Table 3

Correlations between teaching methods and SDG-related competencies

Teaching Method	r	Significance (p)
Project-based learning	0.62	< .01
Inquiry-based learning	0.58	< .01
Interdisciplinary tasks	0.55	< .01
Reflective discussions	0.49	< .01
Traditional lecture-based instruction	0.21	> .05

Figure 3

Correlation between teaching methods and SDG-related competencies



Active, student-centred teaching methods–project-based learning, inquiry-based learning and interdisciplinary assignments–were found to have strong positive correlations with the development of SDG-related competencies in future biology teachers. These methods were found to be strongly associated with higher levels of pedagogical confidence, methodological preparedness and the ability to integrate sustainable development concepts into biology lessons. In contrast, traditional lecture-based teaching showed a weak and statistically insignificant association with the development of SDG-related competencies, indicating limited effectiveness in developing practical pedagogical skills for sustainable development.

Survey Results Students' Attitudes and Beliefs

The attitudes of future biology teachers towards the integration of the SDGs into the educational process were investigated through an extended survey in terms of their perception of the relevance of the subject, pedagogical confidence and methodological needs. The survey results indicated that the vast majority of respondents consider the SDGs important for biology as a subject and acknowledge that they increase the social and practical significance of their biology lessons. However, despite these positive views, only a significant minority of students noted that they felt confident in teaching topics related to SDG. At the same time, the majority of participants clearly indicated the need for additional methodological training aimed at implementing SDGs. These results point to a clear discrepancy between students' recognition of the importance of sustainable development and their perceived ability to teach it effectively, highlighting the necessity of structured, practice-orientated methodological preparation in biology teacher education programmes.

Table 4

Students' attitudes toward the integration of SDGs

Survey Statement	Strongly Agree	Agree	Neutral	Disagree
SDGs are relevant to biology education	48%	34%	12%	6%
SDGs increase the social relevance of biology lessons	41%	35%	16%	8%
SDGs help connect biology with real-life problems	45%	33%	14%	8%
I feel confident teaching SDG-related topics	12%	22%	36%	30%
I need more methodological training on SDGs	52%	36%	8%	4%
SDGs should be systematically included in teacher education programs	57%	31%	7%	5%

The findings presented in Table 4 indicate an overall positive orientation of prospective biology teachers toward the Sustainable Development Goals (SDGs). A substantial proportion of respondents

perceive SDGs as an essential component of biology education (82%) and agree that their integration enhances the social relevance of biology lessons (76%). In addition, most participants (78%) acknowledge that SDGs facilitate meaningful connections between biological content and real-world sustainability challenges, thereby increasing the applied value of the subject.

Despite this generally favourable perception, the level of self-reported pedagogical confidence remains comparatively low. Only 34% of respondents indicated that they feel confident teaching SDG-related topics, while a considerable share expressed neutral or negative responses, reflecting uncertainty in practical classroom implementation. At the same time, an overwhelming majority of participants (88%) emphasised the need for additional methodological training specifically focused on SDG integration. Strong support was also expressed for the systematic inclusion of SDGs in teacher education programmes, with 88% of respondents agreeing with this position.

Taken together, these results reveal a clear discrepancy between positive attitudes toward sustainable development and insufficient pedagogical confidence, emphasizing the necessity of structured and methodologically grounded support in preparing future biology teachers.

Qualitative Results

The thematic analysis of semi-structured interviews conducted with teacher educators (N = 15) revealed three closely related themes concerning the integration of Sustainable Development Goals in pre-service biology teacher education.

First, participants consistently pointed to deficiencies within existing curricula, including the fragmented and episodic inclusion of SDG-related content, the absence of coherent methodological guidance, and limited emphasis on assessing sustainability-related competencies. As one respondent noted, "SDGs are formally mentioned in the curriculum, but teachers lack concrete methodological tools for their effective implementation."

Second, teacher educators identified several pedagogical practices as particularly effective for integrating SDGs. These included project-based learning centred on local environmental issues, inquiry-orientated laboratory activities addressing real-life sustainability challenges, and reflective group discussions that connect biological knowledge with ethical and social considerations. Such approaches were viewed as enabling more profound engagement with sustainability concepts and supporting applied learning.

Third, the interview data revealed clear expectations on the part of students. According to participants, future teachers seek more practice-orientated and classroom-focused preparation, access to concrete examples of SDG-integrated biology lessons, and transparent criteria for evaluating sustainability-related competencies. Collectively, these themes highlight both existing methodological gaps and significant pedagogical potential for strengthening SDG integration in biology teacher education programmes.

Table 5

Main themes identified in teacher educator interviews

Theme	Description	Representative Quote
Curriculum fragmentation	SDGs are integrated inconsistently across courses	"SDGs are formally mentioned in the curriculum, but teachers lack concrete methodological tools."
Methodological limitations	Lack of assessment criteria and practical teaching models	"There are few examples of SDG-oriented biology lesson plans."
Importance of active learning	Project-based and inquiry approaches increase engagement	"Students learn sustainability concepts more effectively through practical activities."
Need for practice-oriented training	Students require classroom-focused methodological preparation	"Future teachers need more opportunities to apply SDGs in real teaching contexts."

Comparative Analysis of Pre- and Post-Intervention Competency Levels

A subgroup of participants (n = 60) completed a self-assessment of SDG-related competencies before and after participation in SDG-orientated instructional activities designed to enhance methodological readiness. This pre–post comparison aimed to examine changes in pedagogical confidence, methodological competence, and overall preparedness to integrate SDGs into biology teaching practice.

Table 6 presents the comparative results of competency levels before and after the intervention.

Table 6

Pre- and Post-intervention changes in SDG-related competencies among pre-service biology teachers

Competency Dimension	Before (M)	After (M)	Change
Pedagogical confidence	2.96	3.87	+0.91
Methodological competence	2.88	3.79	+0.91
Ability to design SDG-based lessons	2.74	3.82	+1.08
Interdisciplinary teaching skills	2.81	3.76	+0.95
Overall SDG readiness	2.92	3.83	+0.91

Figure 5

Comparison of competency levels before and after SDG-oriented methodological training

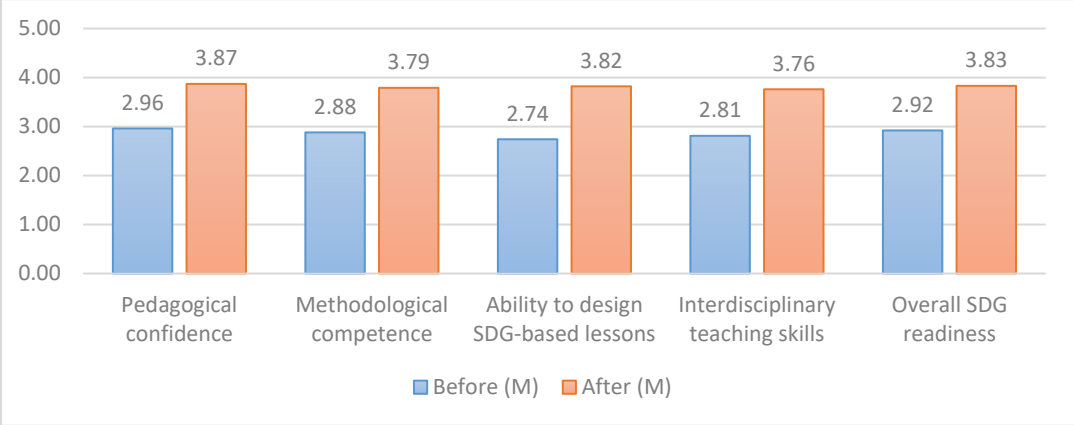


Table 7

Paired-Samples t-Test results for pre- and post-intervention competency scores

Competency Dimension	t	p	Cohen's d
Pedagogical confidence	8.42	< .001	0.91
Methodological competence	8.17	< .001	0.88
Ability to design SDG-based lessons	9.11	< .001	0.94
Interdisciplinary teaching skills	8.36	< .001	0.89
Overall SDG readiness	8.58	< .001	0.92

To examine the statistical significance of the observed changes, paired-samples t-tests were conducted for all competency dimensions measured before and after the intervention. The results demonstrated statistically significant improvements across all variables ($p < .001$). Effect size analysis using Cohen's d indicated moderate to strong practical effects of the intervention.

After the methodological training focused on SDGs, a clear and consistent increase was observed in all competence dimensions. This suggests that structured training interventions effectively

increase future biology teachers' pedagogical confidence, methodological competence and ability to design lessons based on sustainable development ideas. The observed positive changes indicate that targeted training focused on SDGs contributes to the development of not only the theoretical understanding of future teachers but also the practical pedagogical skills necessary to integrate sustainable development principles into the teaching process of biology. Overall, the results indicated that the readiness of future biology teachers to implement the Sustainable Development Goals is at an average level. Although this readiness rests on a sufficient theoretical understanding of the concepts of sustainable development and the SDGs, methodological and assessment competences remain insufficient. The results of the study clearly showed that active, student-centred teaching methods, such as project-based learning, research tasks and interdisciplinary activities, play an important role in the development of professional competences related to SDGs. It was also found that there is a clear gap between students' positive attitudes towards sustainable development ideas and their low pedagogical confidence in teaching topics related to SDG, which indicates gaps in practical training. Most importantly, the results of the "before-after" analysis proved that structured methodological training focused on SDG has a statistically and practically significant positive impact on pedagogical confidence, methodological competence and the level of general professional training, demonstrating the effectiveness of targeted teaching interventions in the training of future biology teachers.

Integration of Quantitative and Qualitative Findings

The integration of quantitative and qualitative findings revealed strong convergence across the data strands. Quantitative findings identified moderate overall readiness and weak methodological competencies among pre-service biology teachers, while qualitative interview data helped explain the underlying reasons for these patterns, including fragmented curriculum implementation and insufficient methodological guidance. At the same time, both data strands consistently highlighted the effectiveness of active, student-centred pedagogical approaches in supporting SDG-related competency development. The integration of findings therefore strengthened the interpretive validity of the study through methodological triangulation.

Discussion

The results of this study revealed several important patterns related to the implementation of the Sustainable Development Goals (SDGs) in the process of training future biology teachers. In general, the data obtained indicate that the readiness of future biology teachers to integrate SDGs into pedagogical practice is at an average level. Although this readiness rests on a relatively high conceptual understanding of sustainable development and the SDGs, methodological and assessment-related competencies remain weak. The results of the quantitative analysis showed that active, student-centred pedagogical approaches, such as project-based learning and inquiry-based learning, are closely associated with a high level of pedagogical confidence and competencies related to sustainable development, while the impact of traditional lecture-based teaching was limited. In addition, the qualitative data not only revealed persistent problems such as inconsistency in curricula and insufficient methodological guidelines but also showed a high demand from students for practice-orientated and reflective forms of learning. The significant positive changes identified during the "before-after" comparison prove that targeted methodological training focused on SDGs can significantly enhance professional readiness. On this empirical basis, the aim of the study was to identify methodological foundations for implementing the SDGs in the training of future biology teachers and to analyse pedagogical practices that contribute to the formation of sustainable development competencies. Accordingly, the discussion is structured around three main aspects: comparison with previous research, explanation of the effectiveness of individual teaching methods, and analysis of the results in terms of the proposed hypotheses (H1–H3). The results of the study are largely consistent with previous international research in the field of Education for Sustainable Development (ESD) and teacher training.

Many works note that prospective teachers have a positive attitude towards sustainable development ideas and an average level of theoretical understanding but face difficulties in implementing these ideas in concrete pedagogical practice and assessment systems (Anyolo et al., 2018; Evans et al., 2017; Imara & Altınay, 2021). The average level of preparation found in this study supports these findings and suggests that the challenges of integrating SDG are not specific to individual countries or institutions but rather a common trend across teacher education systems. Research in science and biology teacher education also shows that sustainable development topics are often presented in a fragmented manner and are not sufficiently integrated into methodological training (Borg et al., 2014; Büssing et al., 2019). The qualitative findings of this study also support these findings by identifying a lack of coherence in curricula, a lack of systematic methodological guidance, and insufficient attention to assessing sustainable development competencies. This study also fills the gaps in the literature empirically by combining quantitative indicators with qualitative teacher opinions through a mixed-methods design.

One of the central outcomes of the present research is the clearly articulated relationship between active, learner-orientated instructional practices and the development of SDG-related competencies among future biology teachers. The pedagogical value of project-based and inquiry-based learning can be interpreted through the lens of constructivist learning theory, which conceptualises learning as an active process of meaning-making grounded in engagement with authentic problems (Rieckmann, 2012; Sterling, 2010). Within such learning environments, sustainability is no longer treated as an abstract or declarative concept but is explored through concrete environmental, biological, and social contexts. In particular, project-based learning demonstrates a strong capacity to connect biological knowledge with both local and global sustainability challenges. By engaging students in the analysis and resolution of real-world issues, this approach enhances applied understanding and reinforces the professional relevance of sustainability-orientated instruction. These findings resonate with the conclusions of Leal Filho et al. (2016), who emphasise the potential of project-based learning to foster sustainability competencies in higher education settings. Inquiry-based learning complements this process by promoting analytical reasoning, critical thinking, and problem-solving skills, all of which are essential for addressing the complex and multifaceted nature of sustainable development. By contrast, the limited contribution of traditional lecture-based instruction observed in this study aligns with earlier research indicating that transmissive teaching models are insufficient for cultivating higher-order sustainability competencies (Cotton et al., 2007; Summers et al., 2005). Such approaches tend to prioritise content delivery over engagement, thereby restricting opportunities for reflection, application, and professional skill formation. The findings therefore reinforce the necessity of moving beyond content-centred instruction toward pedagogical models that emphasise participation, reflection, and contextualised learning. Qualitative evidence further demonstrates the importance of reflective group discussions and interdisciplinary learning in strengthening the integration of sustainability within teacher education. Reflective practices enable future teachers to critically reconsider their learning experiences, articulate their understanding of sustainable development concepts, and establish meaningful links between theoretical knowledge and pedagogical action. This reflective dimension has been widely identified as a key factor in the development of professional identity and pedagogical self-confidence in sustainability education (Tilbury, 2011; Wiek et al., 2011). Interdisciplinary learning, in turn, allows sustainability issues to be approached holistically, integrating biological perspectives with social, ethical, and environmental considerations. Such integration supports the development of systems thinking, which is consistently recognised as a core competence in education for sustainable development (Barth et al., 2007; Mogren et al., 2019). In this regard, interdisciplinary and reflective approaches emerge not as supplementary elements but as foundational components of SDG-orientated teacher preparation. The empirical results of the study provide consistent support for all three research hypotheses. The first hypothesis (H1), which assumed that the introduction of structured, SDG-orientated methodological modules would enhance pedagogical competence, was confirmed through significant improvements in methodological skills, lesson design capacity, and overall professional readiness. These outcomes correspond with earlier findings highlighting the importance of systematic methodological preparation in sustainability-focused teacher education (Anyolo et al., 2018; Sleurs,

2008). The second hypothesis (H2), proposing that the regular use of project-based and inquiry-based learning would increase pedagogical confidence, was likewise supported by strong correlations between active instructional methods and confidence indicators, as well as by notable gains following the instructional intervention.

The effect sizes observed in the pre-post analysis further indicate that the intervention produced not only statistically significant but also practically meaningful improvements in SDG-related competencies. In particular, the strongest effect was associated with the ability to design SDG-based biology lessons, suggesting that practice-orientated instructional experiences may play a decisive role in strengthening methodological readiness among future teachers.

This result is consistent with research demonstrating the role of experiential learning in strengthening teacher self-efficacy (Darling-Hammond et al., 2017). The third hypothesis (H3), which emphasised the role of interdisciplinary and reflective learning in enhancing overall professional preparedness, received full support from both qualitative evidence and measurable improvements in interdisciplinary teaching skills and general readiness for SDG implementation. These findings align with prior scholarship that identifies reflective and interdisciplinary experiences as critical for the formation of comprehensive sustainability competencies (Sterling, 2010; Wiek et al., 2011). Taken together, the discussion confirms that the primary objective of the study—namely, the identification of methodological foundations for integrating Sustainable Development Goals into the preparation of future biology teachers—has been successfully achieved. The findings indicate that meaningful SDG integration requires more than formal inclusion in curricular documents; it depends on methodologically grounded, practice-orientated pedagogical strategies. The combination of structured methodological modules with project-based, inquiry-driven, and reflective interdisciplinary approaches significantly strengthens sustainability-related competencies and prepares future biology teachers to respond effectively to global sustainable development challenges through educational practice.

Conclusion

The present study set out to examine the methodological foundations for integrating the Sustainable Development Goals (SDGs) into the preparation of future biology teachers and to identify pedagogical practices that support the development of sustainability-related competencies. The findings demonstrate that when SDGs are embedded in teacher education through a structured and methodologically grounded approach, this integration has a clear and positive effect on professional competence, pedagogical self-confidence, and overall readiness to address sustainability challenges in future teaching practice. The results indicate that prospective biology teachers generally possess a basic conceptual understanding of sustainable development and recognise the relevance of SDGs within biology education. However, in the absence of systematic methodological support, this conceptual awareness does not readily translate into effective classroom practice. In particular, persistent difficulties were observed in lesson planning, interdisciplinary integration, and the assessment of sustainability-related competencies. These findings confirm that declarative knowledge of SDGs alone is insufficient to ensure meaningful pedagogical implementation.

At the same time, the study provides empirical evidence that SDG-orientated methodological training, especially when grounded in project-based learning, research-orientated tasks, and reflective group activities, substantially enhances professional readiness. Improvements in pedagogical confidence, methodological competence, and interdisciplinary teaching skills highlight the importance of practice-orientated instructional approaches that allow future teachers to connect biological content with real-world sustainability issues. Such approaches create opportunities for students to move beyond abstract discussions and engage with sustainability as a concrete educational and professional concern. Despite these positive outcomes, several structural challenges remain. The analysis revealed a lack of coherent methodological guidelines and a limited availability of practical, SDG-integrated lesson models within existing curricula. These constraints continue to hinder the systematic implementation

of sustainability-orientated pedagogy and point to the need for stronger institutional support within teacher education programmes. The study also has certain limitations that should be acknowledged. The sample was drawn from a single higher education institution, which may restrict the generalizability of the findings. In addition, the analysis focused on a selected group of SDGs most directly related to biology education and did not address the full breadth of the SDG framework. Future research could expand the institutional scope, include a larger and more diverse participant pool, and explore SDG integration across other subject areas to provide a more comprehensive perspective. From a practical standpoint, the findings carry important implications for teacher educators, curriculum designers, and higher education institutions. The results suggest that SDGs should not be incorporated into curricula merely at a declarative level but should be supported by clearly defined methodological modules that explicitly address lesson design, instructional strategies, and assessment practices. Embedding SDG-focused modules within biology pedagogy courses may help position sustainable development as an integral component of professional training rather than an isolated topic. Such modules should include authentic project work linked to local and global sustainability challenges, inquiry-based tasks that foster critical thinking, and structured opportunities for reflection.

Equally important is the professional development of university instructors involved in teacher education. Providing educators with methodological resources, concrete examples of SDG-integrated lessons, and appropriate assessment tools can support more consistent and effective implementation of sustainability-orientated teaching. In addition, interdisciplinary collaboration among departments may further strengthen SDG integration by promoting systems thinking and a holistic understanding of sustainability. In conclusion, the study demonstrates that a coherent, methodologically sound, and practice-orientated approach to SDG integration represents an effective pathway for strengthening sustainability education in pre-service biology teacher training. By aligning curriculum content, teaching methods, and assessment practices with the principles of education for sustainable development, teacher education programmes can better prepare future biology teachers to contribute meaningfully to the achievement of the Sustainable Development Goals through school education.

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