




ISSN: 2617-6548

URL: www.ijirss.com



Organization of interdisciplinary integration in geography lessons using ChatGPT and digital technologies in shaping students' environmental culture

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Abstract

This study investigates the pedagogical potential of integrating ChatGPT, a large language model-based artificial intelligence tool, into secondary school geography education for the development of students' environmental literacy, critical thinking, and sustainability-oriented competencies. Employing a mixed-methods quasi-experimental design, the research combined qualitative thematic analysis with quantitative descriptive statistics. The participants were secondary school students who completed a series of interdisciplinary geography lessons on environmental sustainability, where ChatGPT-based tasks were integrated with traditional teaching methods. Data were collected from pre- and post-lesson questionnaires, student-written reflections, and teacher observations. The findings demonstrate that interaction with ChatGPT stimulated higher-order cognitive processes, particularly analysis, explanation, and structured argumentation. Student engagement and motivation increased markedly in project-based and collaborative tasks. Moreover, the integration of AI enhanced digital literacy and fostered the ability to critically evaluate environmental information. Teachers observed a noticeable rise in participation in classroom discussions and the depth of reasoning expressed in written work. The scientific novelty of this research lies in the development and testing of an integrated model that combines geography education with AI applications to cultivate environmental culture and sustainable thinking among secondary school students. The study contributes both theoretically, by advancing interdisciplinary approaches to education for sustainable development, and practically, by outlining strategies for responsible and critical integration of AI in school practice.

Keywords: Artificial intelligence, ChatGPT, Environmental literacy, Geographical education, Interdisciplinary learning.

DOI: 10.53894/ijirss.v8i6.9778

Funding: This study received no specific financial support.

History: Received: 24 July 2025 / Revised: 26 August 2025 / Accepted: 28 August 2025 / Published: 10 September 2025

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Competing Interests: The authors declare that they have no competing interests.

Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Publisher: Innovative Research Publishing

1. Introduction

In recent decades, environmental education has become a central component of global educational strategies in response to urgent challenges such as climate change, biodiversity loss, and environmental degradation. Schools play a crucial role in shaping students' environmental values and sustainable behaviors, thereby contributing to the formation of ecological culture as a foundation for long-term societal development [1, 2]. Ecological culture, understood as a humanistic approach to human interaction with both the biosphere and sociosphere [3], requires more than technological or cognitive solutions. Traditional approaches dominated by behaviorist and mass-oriented educational practices often fail to address the root causes of the ecological crisis. This underscores the necessity of culturally oriented and interdisciplinary educational models that foster critical awareness and value-based thinking [4].

The effective implementation of environmental education depends not only on administrative support but also on the availability of resources, methodological tools, and teacher readiness [5]. Global experience demonstrates that the introduction of education for sustainable development (ESD) is accompanied by methodological challenges, particularly the tension between anthropocentric and eccentric worldviews [6]. Nevertheless, embedding ESD in the classroom has been shown to strengthen students' environmental responsibility, civic values, and problem-solving skills essential for a sustainable society [7]. In Kazakhstan, despite the formal recognition of the importance of ESD, implementation remains inconsistent due to institutional and methodological barriers [8]. The low level of environmental culture among the younger generation is increasingly viewed as a potential threat to both national and global sustainability [9].

Among school subjects, geography holds particular potential for cultivating environmental culture because of its interdisciplinary character. By integrating environmental themes into content, fieldwork, and project activities, geography can effectively link natural sciences with social and cultural perspectives [10-14]. At the same time, the rapid development of digital technologies, particularly artificial intelligence (AI), opens new possibilities for interdisciplinary integration. Applications such as ChatGPT-4 are already being used in educational practice to support project-based learning, excursion planning, and resource preparation, thereby enhancing quality and reducing time investment [15]. Moreover, AI technologies have the capacity to personalize learning trajectories, stimulate spatial thinking, and promote inquiry-based learning [16]. However, the integration of AI also presents risks, including factual inaccuracies, over-reliance on automated responses, and limited contextual adaptation to regional realities. These challenges necessitate a hybrid pedagogical approach that combines innovative digital tools with critical evaluation and teacher guidance [17].

Despite the growing body of research on environmental education, interdisciplinary integration, and digital learning technologies, there remains a gap in understanding how AI can be systematically employed to strengthen environmental culture in secondary schools, particularly within the Kazakhstani context. Most existing studies treat these domains in isolation, without offering holistic models that combine environmental culture, spatial thinking, and critical engagement with AI-generated content.

The present study seeks to address this gap by analyzing the pedagogical potential of integrating environmental education and artificial intelligence within geography lessons. The scientific novelty lies in the development and testing of an integrated model that combines geographical content with AI tools while fostering a critical and value-oriented attitude towards digital information. This model aims to strike a balance between educational innovation and academic rigor, providing both theoretical and practical contributions to the advancement of sustainable education.

2. Literature Review

2.1. Environmental Education: Conceptual Foundations

The conceptual foundations of environmental education encompass a wide range of perspectives, from philosophical principles to practical methods of instruction. Schlottmann [18] argues that environmental education must go beyond knowledge transmission to cultivate moral consciousness, embedding values and ethical norms in human interactions with nature [18]. Similarly, through their cross-cultural research with teachers in the United States and Taiwan, they identified central constructs of environmental education, including environmental ethics, natural resource management, and the relationship between population and quality of life [19]. They further elaborated this framework by proposing a multidimensional conceptual model that distinguishes between value-based and relationally oriented environmental ethics, which can be applied to curricula, discourse, and educational policy [20]. Building on this, the concept of urban environmental education was introduced, linking school-based learning to civic environmental practices such as reforestation, waterway improvement, and urban gardening [21]. Taken together, these approaches highlight environmental education as a dynamic system in which ethical principles, socio-ecological interactions, and practices mutually reinforce the development of sustainable environmental awareness.

2.2. Environmental Education in the School Environment and the Kazakhstani Context

In Kazakhstan, the development of environmental culture has been prioritized within state education policy. The official Concept of Environmental Education establishes key principles and tasks, emphasizing integration into the general education system. Effective implementation requires a coherent legal framework, methodological support, and improved material infrastructure [22]. A key principle of Kazakhstan's transition to a "green economy" is the cultivation of ecological awareness among citizens and the business community, which demands the continuous modernization of curricula.

Recent innovations include the integration of STEAM methods into environmental education, demonstrating that combining ecology with STEAM fosters critical thinking, creativity, and problem-solving capacity, particularly when projects address regional environmental issues [23]. However, it notes that despite reforms such as the Environmental Code

and the “Zhasyl Kazakhstan” programme, environmental awareness among the population remains insufficient [24]. This suggests that government initiatives require closer alignment with educational institutions and more systematic pedagogical integration.

2.3. Geography as a Tool for Interdisciplinary Integration

Modern geography, as points out, is inherently interdisciplinary, linking natural and social sciences to address global environmental challenges [25]. In school practice, highlights indicate that successful integration in geography extends beyond content to include methodological frameworks that develop ecological thinking through both horizontal and vertical integration levels [26]. Digital tools, particularly Geographic Information Systems (GIS), significantly enhance this process. For example, it has been demonstrated that GIS fosters interdisciplinary connections between geography, history, and natural sciences, helping future teachers to develop spatial analysis and systemic thinking [27].

The integration of GIS in geography education has been shown to strengthen students’ research skills and critical thinking, while also enhancing their preparedness to address sustainability challenges. These studies collectively underline that geography provides a robust platform for interdisciplinary integration, particularly when supported by modern digital tools.

2.4. Digital Technologies and Artificial Intelligence in Geography Education

Recent scholarship highlights the transformative potential of digital technologies, particularly artificial intelligence (AI), in education. It notes that the use of neural networks, chatbots, and immersive technologies such as virtual and augmented reality can boost student motivation, linguistic competence, and metacognitive skills, thereby expanding classroom and extracurricular opportunities [28]. Similarly, show that AI applications can automate information retrieval and analysis, support teachers in planning, and enhance students’ environmental and engineering thinking, though concerns remain regarding algorithmic transparency and pedagogical oversight [29].

Other studies explore the broader pedagogical value of emphasizing its potential for personalizing learning and addressing global issues such as climate change, while also pointing to barriers related to access and teacher preparedness [30]. Provides experimental evidence that AI integration improves students’ academic achievement and higher-order thinking skills [31]. Further categorizes AI applications in geography education, including intelligent tutoring systems, natural language processing, and geospatial services, while stressing the need for infrastructure, teacher training, and ethical safeguards [32].

2.5. Synthesis and Research Gap

The reviewed literature demonstrates that environmental education has strong philosophical and ethical foundations and that geography, supported by digital technologies, is well-positioned to foster ecological awareness. Furthermore, emerging research underscores the potential of AI to enhance motivation, spatial reasoning, and critical thinking. However, significant gaps remain. Most studies focus on either environmental education, geography, or AI in isolation, while few examine their integration into a comprehensive pedagogical model. In the Kazakhstani context, despite policy recognition, the systematic application of AI to strengthen environmental culture in schools remains underexplored.

This study, therefore, addresses the identified gap by proposing and testing an interdisciplinary model that integrates environmental education, geography, and AI technologies to develop students’ environmental culture.

3. Methodology

3.1. Research Design

This study employed a quasi-experimental design in which the independent variable, the implementation of integrated lessons incorporating artificial intelligence, was controlled, but participants were not randomly assigned [33]. This design was selected because it balances internal and external validity, allowing pedagogical interventions to be evaluated under authentic classroom conditions while maintaining sufficient rigor for meaningful interpretation of outcomes. Similar approaches are reflected in Action Learning research, where experimental and control groups are compared to test the effectiveness of practice-oriented methods in stimulating students’ research interest.

The intervention included integrated ecology and geography lessons, the use of ChatGPT for completing assignments, the analysis of students’ written and digital work (posters, mind maps, infographics), as well as the administration of questionnaires and reflective notes. Such a design aligns with the argument that quasi-experimental research in education requires both quantitative and qualitative measures to provide a comprehensive understanding of complex educational processes [34].

3.2. Research Participants

The empirical study was conducted at the Nazarbayev Intellectual School of Chemistry and Biology in Kyzylorda City. A total of 48 pupils from classes 9B and 9D (24 students in each) participated. These classes were selected due to accessibility and the feasibility of conducting a pedagogical experiment within the established educational process. Nazarbayev Intellectual Schools were chosen as the research site because they are specialized institutions for gifted children where innovative teaching practices are systematically implemented. In addition, the authors’ affiliation with this school ensured organizational support and the effective management of the intervention.

3.3. Data Collection Instruments

Consistent with the quasi-experimental design, data were collected through a combination of digital tools, traditional resources, and interdisciplinary tasks.

Digital and interactive platforms:

- ChatGPT was applied to generate arguments, propose solutions, formulate rational questions, and comment on student responses.
- Twig Bilim, an educational video platform, was used to visualize complex ecological and geographical concepts. Previous studies confirm that such platforms enhance students' motivation and improve learning outcomes [35].
- Padlet was employed for collaborative assignments, enabling collective idea generation and group editing of materials.

Traditional and visual materials:

- Geographic maps and GIS elements were integrated for region-specific analysis.
- PISA-formatted tasks were used to assess and develop students' environmental literacy.

Questionnaires and sociological surveys were conducted, not only for reflection but also as pedagogical technologies. This approach is consistent with studies that demonstrated that the use of laboratory work and sociological surveys effectively promotes ecological culture and sustainable behavior among younger students [36].

The collected materials included students' written and digital products (posters, mind maps, infographics), responses to questionnaires, reflection sheets, and records of interactions on digital platforms. Figure 1 illustrates the interdisciplinary integration of the content of the tasks.

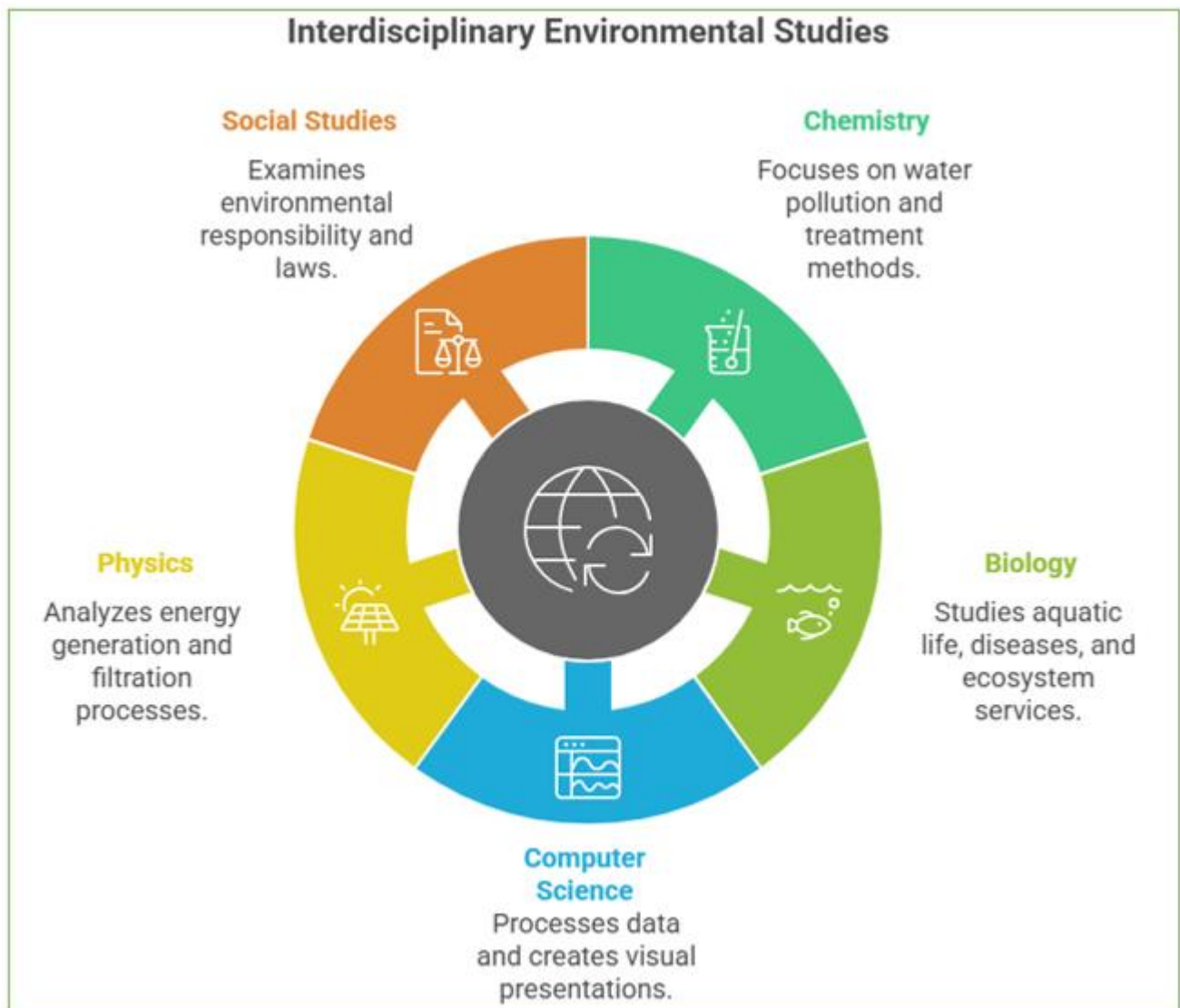


Figure 1. Interdisciplinary integration in the content of the tasks.

The materials collected included students' written and digital products (e.g., posters, mind maps, and infographics), responses to questionnaires, reflection pages, and records of interactions with digital platforms.

3.4. Data Analysis

Data analysis was conducted using a mixed-methods approach, combining quantitative and qualitative techniques to achieve greater depth and validity of interpretation. Quantitative data obtained from student questionnaires were processed using descriptive statistics to identify general trends and to compare results before and after the intervention. Qualitative data, including student work and observational records, were analyzed thematically through a systematic process of data familiarization, coding, theme generation, and interpretation in light of the research objectives.

To ensure methodological reliability, intercoder agreement procedures and triangulation were applied by comparing quantitative outcomes with qualitative themes. This strengthened the credibility of the findings and minimized the risk of interpretative bias. The use of mixed methods corresponds with the conclusion that integrating quantitative and qualitative approaches provides greater analytical breadth and depth than relying on a single methodological tradition [37].

4. Results

4.1. Conceptual Integration Scheme for Grade 9

The selection of integration topics for Grade 9 was based on the updated educational program content of the Republic of Kazakhstan, in which interdisciplinary links are considered an important tool for developing students' holistic worldview. According to the approach, sustainable development should be viewed through the lens of integrated, interrelated knowledge rather than within individual disciplines Chang and Kidman [38]. Widener et al. [39] emphasize that integrating content from different fields helps students to see the relationship between global issues and local contexts, which is particularly relevant in the context of Kazakhstan.

Table 1 presents topics that correspond to the goals and objectives of the school geography course and organically combine with the content of other disciplines. This allows students to apply their knowledge in practical and research situations.

Table 1.

Integration themes of the Year 9 geography course within the framework of the Kazakhstani school programme

№.	Geography lesson topic	Subjects related to the topic of the lesson	Integration content
1	Geographical database	Computer science	Visualization of data using ICT, mapping
2	Lithospheric cataclysms	Physics, Biology	Earthquakes, volcanoes, impact on life
3	The impact of climate on human life	Biology, literature	The influence of climate on the human body: examples from literary works
4	Atmospheric pollution	Chemistry, Biology	Gases, emissions, their impact on life, and air quality
5	Water resources and their pollution	Chemistry, Biology	Types of water pollution, purification methods, and impact on biodiversity
6	Water accidents and water supplies	Physics, computer science	Flood models, creating infographics
7	The influence of anthropogenic factors on natural complexes	Biology, Chemistry	Ecosystem change, pollutants, and biodiversity
8	Noosphere and sustainable development	Man, society, and law	Kindness, eco-culture, global thinking
9	Urbanization processes	Social studies, literature	Social consequences of urbanization, causes of migration
10	Natural resources	Chemistry, Economics	Rational use of natural resources, types of resources, and economic value
11	Scientific and technological revolution, human resources	Computer Science, history	Impact of NTR, population size, demography, and technology

Analysis of the presented topics shows that they correspond to the updated educational program content of Kazakhstan, covering key aspects of sustainable development. The combination of natural and human sciences in the selection of topics enables students to develop a comprehensive understanding of the interplay between environmental, social, and economic factors. This approach fosters critical thinking and the application of knowledge in interdisciplinary contexts.

4.2. Implementation of the Integrated Lesson Plan

Within the framework of the research, an integrated lesson on the topic “Atmospheric Pollution and its Consequences” was conducted for 9th-grade students. This lesson reflects the interdisciplinary approach of the Republic of Kazakhstan's updated educational program, which prioritizes environmental literacy, critical thinking, and digital skills. The choice of topic was influenced by its relevance to modern society and its alignment with the learning objectives of geography, chemistry, biology, informatics, and literature.

Learning objectives included:

- Geography (9.3.2.3): Assess the impact of human activities on the atmosphere.
- Chemistry (8.4.2.8): Knowledge of the main air pollutants (NO₂, SO₂, and CO) and an explanation of their origins.
- Biology: Describe the effects of pollutants on the human body.
- Computer Science: Presenting environmental data in the form of tables, charts, or infographics.

Literature: quoting literary works or creating a creative text on environmental topics.

The aim of the lesson was for pupils to:

- Identify the main sources of atmospheric pollution;
- Describe the impact of pollutants on humans and nature;
- Present information visually (infographics, diagrams);
- Express their personal position in defense of the environment.

The following resources were used during the lesson: an interactive whiteboard, ChatGPT, Google Forms/Jamboard, and laboratory videos on changes to the composition of air, as well as Canva and MS Word programs for creating infographics.

Lesson structure:

- Motivation (5 minutes): demonstration of a slide showing the air quality index (AQI) in Almaty, followed by a discussion of its importance.
- Learning new material (15 minutes): teamwork in four subject areas (chemistry, biology, informatics, and literature), using ChatGPT to find background information and examples (see Table 2).

Table 2.
Teamwork (with interdisciplinary orientation).

Group	Task	Discipline
№1	Identification of gases polluting the atmosphere and their sources	Chemistry
№2	How does air pollution affect human health?	Biology
№3	Converting urban pollution data into infographics	Computer science
№4	Writing a short fiction text or poem on the topic of conservation	Literature

Presentation of results (10 minutes): presentation of group work in the form of posters, infographics, or written texts.

Reflection and conclusions (10 minutes): writing a short essay on the topic “What can I do to reduce air pollution?” and completing a Google Forms survey.

Assessment will include peer assessment, feedback from the teacher, and checking the correct use of ChatGPT. The criteria covered were identifying sources of pollution, describing their impact on human health, suggesting specific solutions, and choosing a presentation method.

The results of the interdisciplinary integration are summarized in Table 3.

Table 3.
Results of interdisciplinary integration in the lesson on the topic of atmospheric pollution.

Subject	Contribution
Chemistry	Chemical composition and source of gases
Biology	Impact on human health
Computer science	Visualization of information

This lesson demonstrated how science and humanities disciplines can be integrated to develop a comprehensive understanding of environmental issues. Using artificial intelligence (ChatGPT) helped develop digital literacy and the ability to critically evaluate information, which aligns with the objectives of modern education in Kazakhstan.

4.3. Interaction with Generative Artificial Intelligence (ChatGPT)

Within the framework of the lesson, particular focus was given to using artificial intelligence to support the learning process. ChatGPT was employed as an interactive educational tool, offering quick access to reference information, generating examples, and stimulating cognitive activity among students.

One of the study's objectives was to identify the impact of working with ChatGPT on students' ability to formulate queries, critically evaluate the responses received, and incorporate them into final products such as infographics, texts, or oral presentations. To this end, real dialogues between students and ChatGPT were recorded to reflect the process of searching for and clarifying information on the topic under study.

A dialogue between a student and ChatGPT:

Student: What are the causes of water pollution in Kazakhstan?

ChatGPT: There are several causes of water pollution in Kazakhstan. For example:

1. Dumping industrial waste in rivers and lakes without treatment.
2. The excessive use of fertilizers and pesticides in agriculture.
3. Improper collection of municipal household waste.
4. Chemicals around deposits.

Student: Why does the Syr Darya River get polluted?

ChatGPT: The pollution of the Syr Darya River is caused by wastewater from irrigation systems in Uzbekistan and Tajikistan, as well as fertilizers and chemical waste from rice fields in the Kyzylorda region.

Student: What would you suggest to solve this problem?

ChatGPT: Here are some suggestions:

- Modernize water treatment systems.
- Application of environmentally friendly methods in agriculture
- Tight control of wastewater
- Increasing environmental awareness among the public to conserve water resources.

Through ChatGPT, students were able to clarify environmental issues, explain causes and effects, and suggest solutions. For example, they identified the causes of pollution in the Syrdarya River and recommended ways to modernize water-saving and purification systems.

4.4. Final Products and the Educational Impact of Integrated Learning

The study employed both qualitative and quantitative analysis methods. Quantitative data were collected through preliminary and final student surveys and processed using Google Forms and Excel. To visualize the results, diagrams were created to illustrate the dynamics of competence formation. Qualitative data included the analysis of students' projects (infographics, mind maps, essays, and presentations) and observations of their activities.

4.4.1. Improvement of Environmental Competences

Figure 2 shows a comparison of the pre- and post-survey results regarding knowledge of sources of water pollution. Initially, 42% of students could not name specific sources; however, after the integrated lessons, 91% of respondents could confidently provide examples of physical, chemical, and biological pollution. This growth reflects the effectiveness of combining a cross-curricular approach with digital tools.

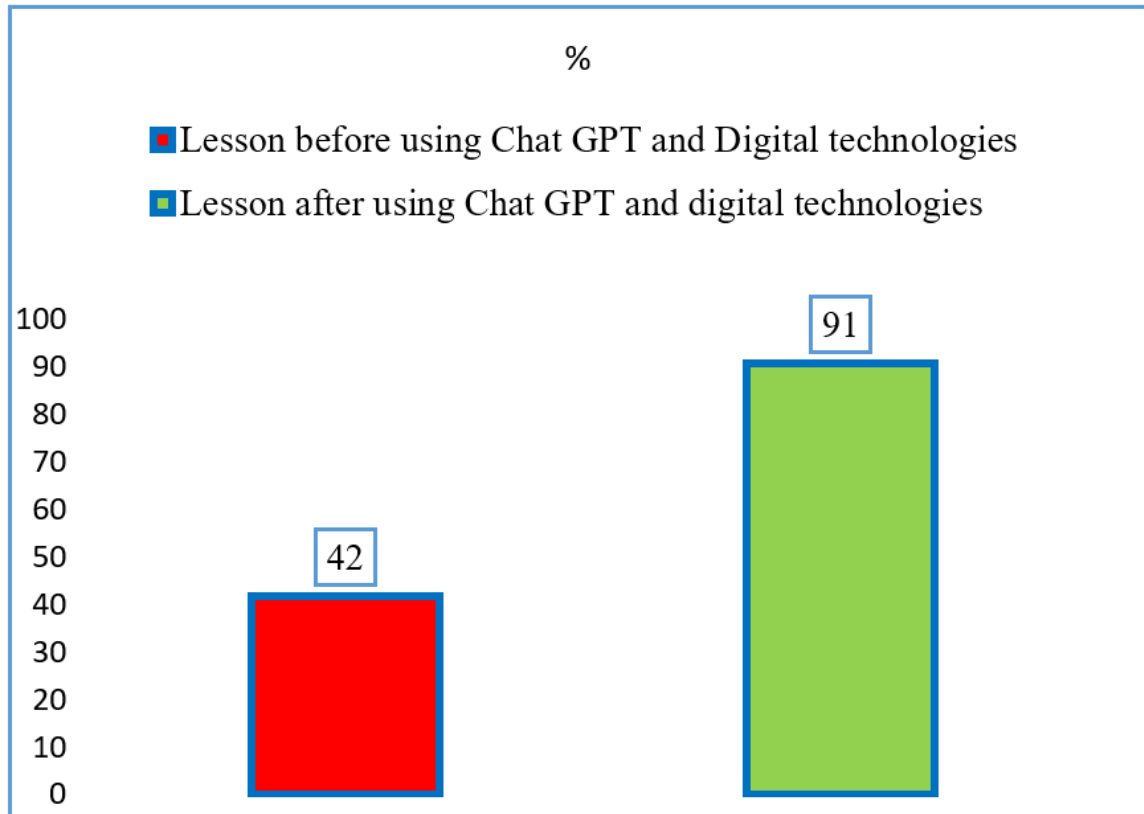


Figure 2. Comparison of survey results on knowledge of water pollution sources before and after integrated lessons.

In project tasks, students analyzed the environmental situation in Kyzylorda Province, highlighting factors contributing to water deficits, the specifics of rice farming, and the impact of industry. ChatGPT was then used to suggest solutions in scientific terms, such as 'sustainable irrigation systems' and 'biofiltration methods.'

4.4.2. Development of Digital Literacy and Reflective Skills

Figure 3 shows the distribution of digital tools used during project work. Canva and Google Forms were the most popular due to their accessibility and ability to create visual materials.

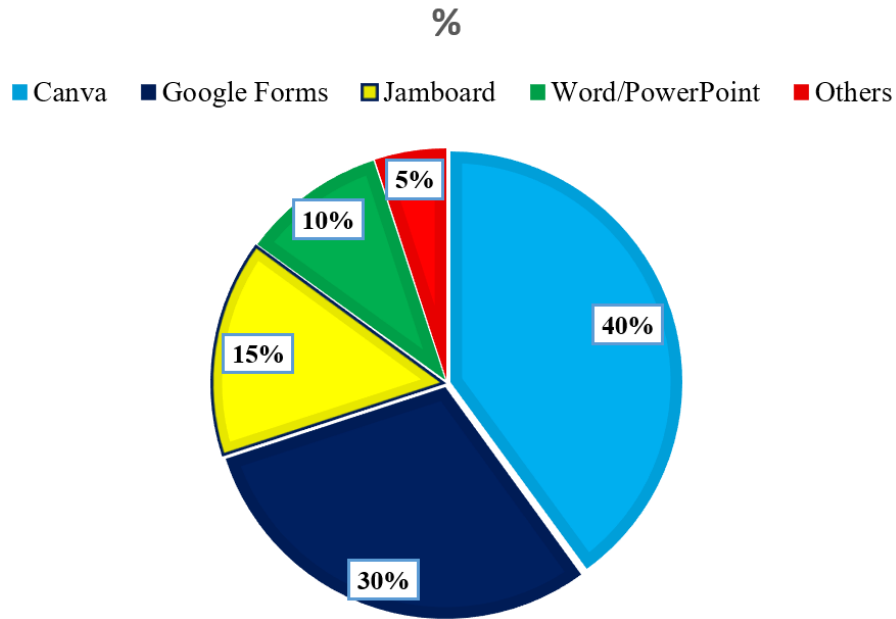


Figure 3.
Distribution of digital tools used by students in project work.

Completing tasks such as restating text using ChatGPT, clarifying terms, and constructing arguments enabled students to hone their clear and logical reasoning abilities.

4.4.3. Effectiveness and Limitations of ChatGPT

The diagram in Figure 4 reflects students' attitudes towards using ChatGPT in the learning process. While the majority noted its usefulness in providing simplified explanations of complex concepts, about one-third of respondents cited the risk of uncritical acceptance of information.

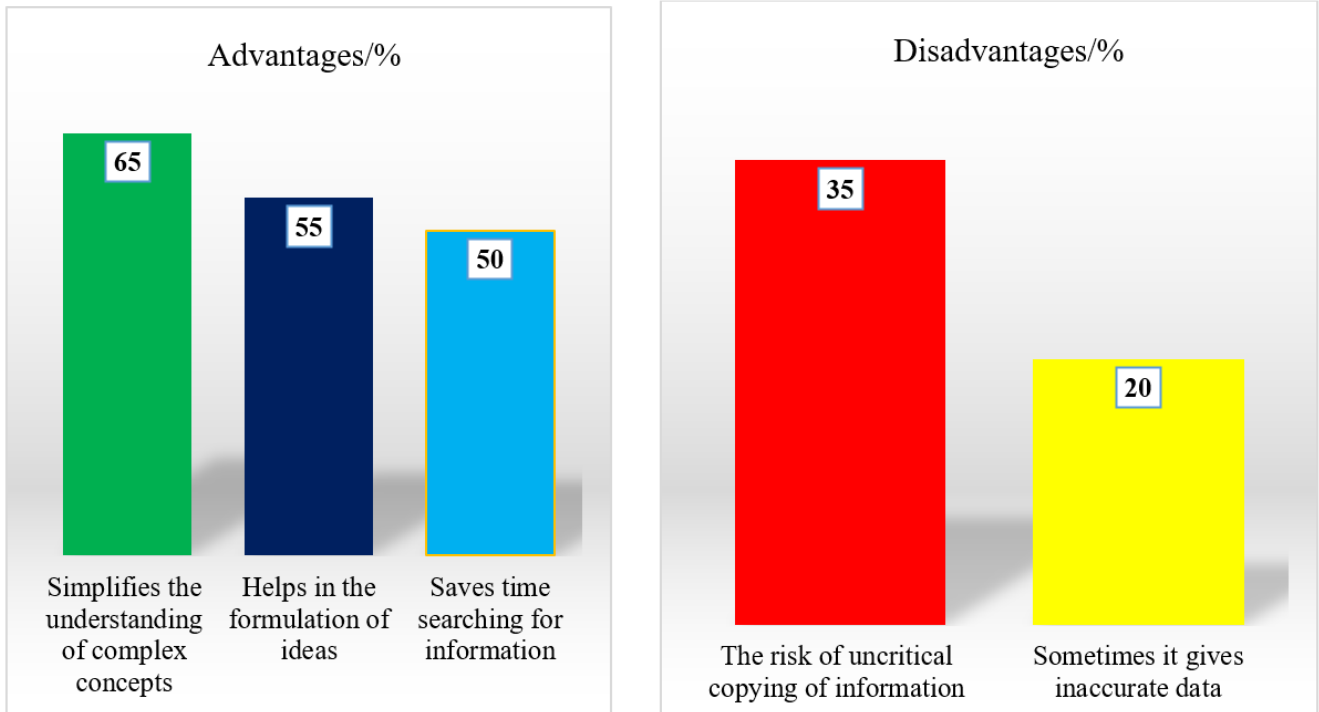


Figure 4.
Students' evaluation of the advantages and disadvantages of using ChatGPT.

4.4.4. Formation of a Holistic Ecological Approach

Analysis of the results of the activities has shown that students have learned to consider natural processes and anthropogenic impacts together, combining knowledge from geography, biology, and chemistry. One example of this was the preparation of science-based recommendations to mitigate the consequences of oil production and farming in the Kyzylorda region.

5. Discussion

The results of this study demonstrate that integrating digital tools, particularly ChatGPT, into environmental geography education promotes the development of environmental competencies and digital literacy in students while strengthening their critical thinking and interdisciplinary data skills. These findings are consistent with the research of those who emphasize that the effectiveness of sustainability education depends on both content and teaching methods [40]. In our study, the use of interactive assignments, group work, and project-based methods, supplemented by artificial intelligence, reflected the authors' identified trend of the need for active participation and the combination of several pedagogical approaches to foster systemic ecological thinking.

The observed increase in students' ability to analyze environmental problems and propose science-based solutions (e.g., "Sustainable irrigation systems" and "Biofiltration methods") corroborates Jeronen's [41] findings regarding the significance of interactive and exploratory learning in developing argumentation, critical evaluation, and knowledge application skills in real-world situations. Our data illustrate that this combination of methods promotes both factual learning and a holistic environmental approach: 91% of participants were able to recognize and classify types of pollution after the training module.

The role of digital tools in enhancing environmental literacy is consistent with the findings of Al Yakin et al. [42] who emphasize that digital citizenship and the ethical use of technology increase awareness of environmental issues and encourage responsible action. In our study, integrating ChatGPT into the process enabled students to not only receive information but also critically reinterpret it. This confirms the importance of technology as a mediator between knowledge and practical environmental solutions.

The critical thinking aspect deserves special attention. Alarcón-López et al. [43] demonstrated that using ChatGPT for sustainability-related tasks can improve the depth of analysis and quality of reasoning, particularly in urban schools. In our study, even when teacher supervision was required, we observed that students progressed from copying work mechanically to forming their own conclusions independently, which aligns with the aforementioned authors' findings regarding the gradual adaptation to technology and the strengthening of analytical skills.

Equally important is the interdisciplinary nature of the study. According to Hubert [44] interdisciplinary learning increases student engagement, develops integrated problem-solving skills, and promotes academic success. Our results, which involved integrating geography with biology and chemistry to analyze anthropogenic impacts in the Kyzylorda region, confirm that an interdisciplinary approach enables environmental problems to be considered in all their complexity, in line with the goals of sustainable development.

Furthermore, the results are consistent with the findings of a recent study on students' attitudes towards interdisciplinary learning, which emphasizes that experiencing the intersection of disciplines fosters positive attitudes towards interdisciplinary projects and increases interest in STEM subjects. In our project, this manifested itself in students' willingness to seek out additional data independently from related fields of knowledge and to combine it in their environmental proposals.

Thus, analysis of the obtained data confirms that combining qualitative and quantitative methods, using AI technologies, and relying on interdisciplinary approaches create an educational environment that transfers knowledge and shapes students' readiness to act responsibly for sustainable development. These findings correlate with Almalki [37] assertion that a combination of research and learning methods provides a more comprehensive and profound understanding of educational phenomena than a single approach. Taken together, our findings emphasize the need for an integrated approach to teaching geography and environmental studies, where pedagogical strategies, digital tools, and interdisciplinarity work together to provide academic and practical outcomes.

6. Conclusion

The findings of this study demonstrate that the integration of digital tools, particularly generative artificial intelligence, into environmental geography education effectively enhances the formation of environmental literacy, critical thinking, and student engagement. The quasi-experimental intervention confirmed that interdisciplinary and interactive teaching methods foster not only the acquisition of theoretical knowledge but also its practical application to real-world ecological challenges. Students demonstrated increased independence, collaborative initiative, and the ability to critically evaluate digital content, thereby validating the pedagogical potential of AI-assisted learning.

A key scientific contribution of the study lies in the development and testing of an integrated model that combines environmental education, geography, and artificial intelligence. This model advances existing scholarship by illustrating how AI can be employed not merely as a technical aid but as a catalyst for interdisciplinary integration and the cultivation of ecological culture. At the practical level, the research provides educators with concrete strategies for balancing technological innovation with critical reflection, thereby contributing to the broader goals of sustainable development in secondary education.

Despite these achievements, the study has several limitations. The quasi-experimental design did not permit full randomization, and the research was confined to a single school context, which may affect the generalizability of findings. Furthermore, differences in students' digital adaptation levels and the necessity of teacher supervision in AI-based tasks highlight structural and pedagogical challenges. Finally, the limited timeframe of the intervention prevented the assessment of long-term impacts on students' environmental values and behavior.

Future research should address these limitations by conducting longitudinal studies across diverse school types and social contexts, incorporating comparative cross-cultural analyses, and expanding the methodological framework to include

additional digital platforms. Such investigations will further clarify the role of AI in shaping environmental education and provide deeper insights into its contribution to fostering sustainable thinking and practices among young learners.

In conclusion, this research confirms the effectiveness of a holistic pedagogical approach in which digital technologies, interdisciplinary strategies, and active learning methods complement one another. The results highlight both the transformative potential and the necessary cautions of AI in education, offering theoretical and practical guidance for advancing sustainable education in Kazakhstan and beyond.

7. Suggestion

Based on the results obtained and the analysis of the study, the following recommendations are offered to practitioners, researchers, and educational program developers:

- Develop mini-methodological guidelines for science teachers on using ChatGPT. Such guidelines should include examples of dialogue, templates for teaching tasks, and assessment criteria for students' work. They should also include warnings about the ethical and methodological risks of using AI.
- Organize independent student research projects in ecology using AI. Involving ChatGPT and other digital tools for searching, analyzing, and systematizing information will improve project quality and develop independent planning and argumentation skills.
- A comprehensive course on digital information analysis and ecological literacy should be integrated into the curriculum from grade 7 onwards. Joint development of these competencies will enable students to work consciously with data, critically evaluate sources, and make informed decisions in the environmental sphere.
- Gradually introduce interdisciplinary projects linking geography, ecology, computer science, and the social sciences. Such projects strengthen the connection between educational material and real sustainable development issues, increasing student motivation.
- Professional development courses, seminars, and webinars on digital pedagogy and sustainable development will help teachers to confidently integrate AI technologies into the educational process.
- The creation of a bank of adapted tasks and lesson scenarios with AI will facilitate the introduction of ChatGPT and similar tools into mainstream practice by providing a centralized database of age-appropriate materials.
- Monitoring and researching the long-term effects of applying AI in an educational environment will enable us to regularly evaluate results, adjust methods, and identify the most effective strategies.
- Implementing these recommendations will improve the quality of environmental education and help students develop sustainable critical thinking, interdisciplinary analysis, and digital literacy skills. This is essential for preparing responsible citizens in the context of global challenges.

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