International Journal of Current Educational Studies

2025, Vol. 4, No. 1, 47-76 ISSN 2822-4914

Artificial Intelligence in Geography Teaching: Potentialities, Applications, and Challenges

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Article Info

Article Type

Review Article

Article History

Received:

22 March 2025

Accepted:

19 June 2025

Abstract

This study aims to comprehensively examine the potential of artificial intelligence (AI) technologies in geography education in terms of their application domains, pedagogical contributions, and key challenges. Using a descriptive method based on a literature review, the findings reveal that natural language processing, learning analytics, location-based systems, and intelligent tutoring systems effectively support student-centered learning. AI applications contribute significantly to physical and human geography instruction mapping, classification, analysis, and prediction tasks. However, limitations such as inadequate infrastructure, disparities in teacher competencies, and ethical/privacy concerns hinder effective classroom integration. Therefore, the study recommends developing in-service teacher training programs, implementing AI-supported instructional scenarios, creating culturally responsive and localized content, and promoting ethical data use awareness. It also emphasizes the need for experimental research using quantitative and qualitative methods to evaluate AI's pedagogical value in enhancing students' mapping skills, spatial thinking, and conceptual understanding. Overall, AI technologies are not merely technical tools but transformative mechanisms capable of reshaping geography learning environments.

Keywords: Geography, Geography teaching, Artificial intelligence, Digital learning, Pedagogical transformation.

Citation:

Şanlı, C., (2025). Artificial intelligence in geography teaching: Potentialities, applications, and challenges. *International Journal of Current Education Studies (IJCES), 4*(1), 47-76. https://doi.org/10.5281/zenodo.15703194

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Introduction

Geography teaching aims to help students understand the environment and global context, develop spatial reasoning skills, comprehend human-nature interaction, and gain environmental awareness. It also aims to provide students with versatile perspectives on both local and global scales and instill democratic values (Chang & Wi, 2018; Çifçi & Dikmenli, 2019; Dixit & Dixit, 2024; Lambert et al., 2015; Solem & Weiguo, 2018; Syamsunardi et al., 2024). In addition, geography teaching contributes to the development of tolerance and intercultural understanding by providing students with opportunities to interact with different cultures and geographical regions (Bustin, 2019; Dörfel et al., 2023; Honrubia-Montesinos & Otero, 2025; Kırkeser, 2021; Lambert, 2018; Miao et al., 2022; Şahin & İnce, 2021). The effective realization of these multidimensional teaching objectives in classroom environments is closely linked to the integration of technological innovations (Yılmaz, et al., 2022). Technologies such as digital cartography, remote sensing, and geographic information systems (GIS) play a critical role in enhancing students' spatial thinking skills (Arıkan, 2023; Bikar et al., 2022; Bondarenko, 2025; Hickman, 2023; Kerski, 2023; Pınar, 2017). In recent years, the inclusion of AI applications within this technological infrastructure has emerged as a promising development with the potential to significantly enhance both the effectiveness of geography teaching and student engagement.

The teaching process empowered by AI technologies, including adaptive content aligned with student performance, automated feedback mechanisms, natural language processing-oriented query-response systems, and learning analytics, has been transforming the roles of educators and students in education (Knox, 2020; Rakuasa, 2023; Ou & Chen, 2024; Zhai et al., 2021; Zhao et al., 2021). However, the integration of AI technologies into pedagogical environments has introduced several challenges, such as inadequate infrastructure, disparities in educators' technological pedagogical competences, and ethical concerns about the confidentiality of student information (Patra et al., 2024; Rakuasa, 2023; Rosenstrauch et al., 2023). Although these issues are frequently emphasised in the educational technology literature, studies specifically addressing the use of AI in teaching geography remain relatively limited. This study aims to explore the potential of using AI technologies in geography teaching, identify applicable tools and methods for use in the teaching process, determine the areas of physical and human geography where these tools may be functional, and evaluate both the opportunities these technologies offer and the limitations and risks they may present. Thus, the study seeks to contribute to the widespread and effective use of AI technologies in instructional practices by focusing specifically on their application in geography education. In this respect, the findings are considered significant for enabling teachers to develop technology-based pedagogical approaches, supporting policymakers in shaping digital education policies, and guiding researchers in producing further studies.

Artificial Intelligence in Geography: Historical Development and Its Use in Teaching

The use of AI in geography has historically evolved in parallel with the advancement of computer technologies. GIS and remote sensing technologies began to develop in the 1960s, and AI applications within these systems emerged with the development of decision support systems and expert systems in the 1980s (Couclelis, 1986). During this period, Dobson (1983) emphasized the role of computers in processing geographical data by introducing the concept of "Automated Geography." Marble and Peuquet (1983) stated that technical limitations hindered the progress of this process. Smith (1984) increased interest in AI in geography by proposing that AI can be effectively used in spatial decision-making processes. In the late 1980s and 1990s, AI technologies such as artificial neural networks (ANNs) and expert systems were experimentally applied in geographical analyses (Hewitson & Crane, 1994; Openshaw & Openshaw, 1997). Notably, Openshaw developed the "GeoComputation" approach and advocated for the more active integration of AI in geography. In the 2000s, models supported by big data, spatial statistics, and high-resolution remote sensing data came to the fore; thus, AI began to be widely applied in areas such as image processing, classification, and feature extraction. Since the 2010s, with the development of technologies such as deep learning, object recognition, route optimization, and the Internet of Things (IoT), the concept of Geographic Artificial Intelligence (GeoAI) has emerged as a significant advancement in geography (W. Li et al., 2024; Song et al., 2023). This tool has been integrated into software such as ArcGIS to support tasks such as object recognition, land cover classification, disaster management, and urban planning (Bennett, 2018; Hu et al., 2019). GeoAI has introduced new epistemological possibilities for representing and interpreting complex systems in geography.

This increasing use of AI in geographical research has been increasingly reflected in the field of education in recent years. Especially the integration of applications such as satellite image classification, spatial pattern analysis, and natural disaster modeling into teaching processes has played a crucial role in developing students' geographical skills. AI-supported software working with GIS and satellite imagery has made it possible for students to analyze phenomena such as population density, transportation routes, and urban growth on a spatial plane (Abdimanapov et al., 2025). In geographical fieldwork, deep learning algorithms and convolutional neural networks (CNNs) are widely used to visualize urbanization trends. In line with the geoscience tradition, artificial neural networks (ANNs) are used to analyze climate data, and tools such as TensorFlow support the creation of predictive water flow models based on historical climate data (Zhou, 2023). The use of these algorithms in remote sensing, water pollution modelling, soil and land classification, disaster management (e.g., earthquakes and floods), agricultural production, smart city planning, weather forecasting, and tourism geography is quite remarkable. It is also known that these applications are used in geography teaching to produce landslide susceptibility maps or to evaluate agricultural suitability based on soil classification (Rakuasa, 2023). Moreover, AI-based technologies are employed in studies that extract cultural and linguistic geographical patterns from social media data using natural language processing (NLP) tools (Wilby & Esson, 2024), as well as in geopolitical geography to identify border conflicts and energy corridors (Huang et al., 2021). This widespread use of AI technologies for pedagogical purposes in geography education, especially when combined with contemporary teaching approaches such as problem-based, project-based, and scenario-based learning, deepens the learning process and promotes an interdisciplinary perspective (Kim, 2022; Matkovič, 2024). AI transcends its role as a mere technical tool by supporting students' ability to analyze complex geographical problems and generate and communicate solutions (Rakuasa, 2023). Therefore, the integration of AI into geography education not only improves the quality of education but also prepares students for the data-driven world of the future (Zhao et al., 2021).

Literature Review

In recent years, the integration of artificial intelligence (AI) technologies into geography education has garnered increasing scholarly attention, reflecting a broader shift toward digital transformation in teaching and learning practices. Kim (2022) examined the use of AI-based tools in geography teaching. Using tools such as Teachable Machine, AutoDraw, and Deep Dream Generator, he evaluated their integration into the teaching of various geographical topics, including the classification of dune plants, the visualization of landforms, urban icon design, and the artistic interpretation of city landscapes. Almelweth (2022) investigated the effect of a teaching strategy based on AI applications on higher-order thinking skills and academic achievement in geography classes. The findings of this quasi-experimental study revealed significant improvements in favor of the experimental group, indicating that AI-supported teaching enhances both academic performance and thinking skills.

In a similar vein, Rakuasa (2023) investigated the potential of AI in geography learning and the difficulties encountered during implementation, noting that AI contributes to teaching through interactive visualization and personalized learning; however, limited access to technology, insufficient teacher training, and infrastructure inadequacies are significant barriers. Building on this technological perspective, Lee (2023) emphasized the potential of new data sources such as open data, big data, and AI in education, discussing their application in geography teaching under four main categories: geographical web services, open/big data, GIS-based fieldwork, and AI-assisted coding. Spatial inquiry activities developed within this framework are valuable tools for equipping students with 21st-century skills. Expanding the application domain to cultural and symbolic contexts, Sabato and De Pascale (2023) examined how AI influences spatial experiences, particularly in the context of video games. They emphasized the role of AI in creating virtual and symbolic spaces and its potential to offer personalised content based on individuals' geographical location. Their study provides valuable insights into how AI can offer more interactive, localized, and real-digital space-integrated gaming experiences within cultural geography.

Shifting the focus to the role of large language models, Wilby and Esson (2024) evaluated the opportunities and limitations of tools such as ChatGPT in geographical knowledge production, critical thinking, and curriculum development. They noted that the model contributes to areas such as writing support, content generation, and research evaluation; however, they also raised concerns about issues such as fabricated sources, model bias, and ethical implications. Focusing on teachers' instructional practices, Pashkova and Demianenko (2024) examined how AI technologies in geography teaching have become effective tools, especially for educators. They analyzed how neural network-based platforms such as ChatGPT, Suno, and D-ID Studio can be integrated into the production of teaching materials. These tools facilitate lesson planning, promote visual literacy and creativity, and support individualized instruction. The study also emphasized variability in teacher usage patterns and underlined the importance of training and technical support for wider adoption.

In relation to immersive learning technologies, Matkovič (2024) explored how advanced tools such as AI, virtual reality (VR), and augmented reality (AR) contribute to more engaging geography learning environments. These technologies allow students to interact with complex geographical content in sophisticated ways. Similarly, Nawaz and Sattar (2024) demonstrated that combining Geo-AI and AR in interdisciplinary earth science education leads to innovative and immersive learning experiences. Their findings highlight the role of real-world simulations in helping students understand complex spatial concepts in contextualized 3D environments.

Considering the perceptions of practitioners, Castro et al. (2025) explored elementary teachers' attitudes toward AI integration. Their findings suggest that teachers perceive AI as a tool to personalize instruction, reduce workload, and manage diverse classrooms. Importantly, they emphasize the necessity of offline-compatible tools and context-specific curricula, and advocate for robust infrastructure and professional development support. While many studies focus on opportunities, some highlight limitations. Ioanid and Andrei (2025) evaluated ChatGPT's ability to handle Romania-specific geography and history assignments. They reported frequent factual errors and geographic inaccuracies, particularly in topics with low digital representation. The study underscores the need for human oversight and the integration of localized knowledge in AI-driven instruction.

Attempting to unify these insights, Lane (2025) proposed a theoretical framework for the integration of Generative AI (GenAI) in geography education. Drawing from a wide range of literature, the framework outlines applications such as retrieval-augmented generation (RAG), environmental simulation, and spatial data visualization. Lane also critically examines implementation challenges such as hallucinations, algorithmic bias, and spatial reasoning limitations, offering a foundation for future empirical work. In a complementary study, Lee et al. (2025) adopted the SAMR model to explore GenAI's transformative potential across four dimensions of geography education: curriculum, pedagogy, assessment, and fieldwork. They not only present practical recommendations but also highlight implementation challenges that must be addressed in future research. From a regional policy perspective, Nurgazina et al. (2025) compared AI integration efforts in Kazakhstan and Uzbekistan. Based on survey data from 966 geography teachers and national documents, they found Kazakhstan more proactive in embedding AI into curricula, while Uzbekistan emphasized AI research and platform development. Both countries face shared barriers, including low digital literacy, limited access to advanced technologies, and a shortage of trained professionals. Turning to questions of equity and representation, Day and Esson (2025) provided a compelling case of how GenAI may replicate cultural bias. When asked to generate an image of students conducting fieldwork, ChatGPT produced only East Asian faces, despite no such instruction. This incident highlights the importance of critical AI literacy, particularly regarding representation and user intention in educational content.

In a practical field-based example, Liu et al. (2025) implemented an AI-enhanced course on bird habitats in China using ERNIE Bot. The tool supported students through personalized learning paths, real-time data analysis, and feedback mechanisms. Their findings suggest that AI technologies can effectively bridge theory and practice in geography education. Lastly, Alaeddinoğlu and Alaeddinoğlu (2020) explored the implications of AI for behavioral geography. They argued that processing human behavior and environmental data through appropriate AI tools could generate valuable insights, thereby providing a foundational base for future empirical investigations in this domain.

Given the literature review, it appears that AI is widely used in areas such as data analysis, mapping, and spatial modeling in the field of geography. However, the number of studies on its use in teaching processes is quite limited, and the body of knowledge in this field is still in its formative stage. In today's world, the increasing importance of geographical knowledge at both individual and social levels raises critical questions of how this knowledge is taught in a more meaningful way. In this context, this study sought answers to the following questions:

1. What is the potential of using AI technologies in geography teaching?
2. What AI tools and applications can be used in geography teaching?
3. What pedagogical opportunities do AI tools offer for geography teaching?
4. What are the limitations and possible risks associated with the use of AI tools in geography teaching?

The increasing use of AI technologies in education necessitates the redesign of teaching processes across many disciplines. However, in geography education, there is a lack of holistic and systematic research on how, to what extent, and with which pedagogical approaches AI applications can be integrated. This study aims to fill this gap by addressing the potential of using AI in geography teaching, its areas of application, as well as opportunities and limitations. The study emphasizes that AI technologies are not only digital tools but also pedagogical instruments that transform the production and transfer of geographical knowledge. Through examples presented in the context of physical and human geography, the study demonstrates how skills such as spatial thinking, data literacy, and field-based learning can be reconstructed and enhanced through AI. The study also addresses key considerations for the sustainable integration of technology by analyzing limiting factors, such as teacher competences, data security, ethical concerns, and content misalignment in the use of AI. In this regard, the study holds the potential to offer practical, critical, and forward-looking recommendations for educators, policymakers, and researchers.

Research Model

This study was structured using a descriptive research design. This approach aims to reveal the functional aspects of AI in geography teaching, offering a holistic perspective on the use of these technologies in educational settings (Rakuasa, 2023). To this end, several academic databases were utilized, including ERIC, Scopus, Web of Science, ULAKBİM, and the YÖK Thesis Database. The key terms of ‘geography education and artificial intelligence’, ‘AI in geography teaching’, and ‘AI-supported instructional methods’ were used during the search, with a particular emphasis on AI tools and applications.

The selection of studies included in the review was guided by specific inclusion criteria: (1) addressing the use of artificial intelligence technologies in geography or geography education; (2) focusing on the functionality of AI-based tools and applications within an educational context; (3) being accessible through the aforementioned academic databases; and (4) contributing to pedagogical practices, methodological innovations, or the existing body of literature. In this context, studies that merely provided general evaluations of technology without direct relevance to educational applications and those addressing artificial intelligence only indirectly were excluded from the analysis. Considering the scope and content density of the literature, a total of 76 original and recent studies were examined in detail. The findings were synthesized and reported under four thematic categories: (1) potential for use, (2) tools and areas of application, (3) pedagogical contributions, and (4) limitations and risks.

Findings

Potential of Using AI in Geography Teaching

Considering the existing literature, it can be stated that the use of AI technologies is gradually increasing; these technologies are effectively utilized in areas such as NLP, learning analytics, intelligent tutoring systems (ITS), image recognition, and location-based applications. In geography teaching, NLP technologies, intelligent chatbots, and automatic assessment systems can contribute to students' knowledge construction, written expression, and critical thinking skills (Wilby & Esson, 2024). These tools provide instant feedback by linguistically analyzing and making sense of students' written answers or questions (Bulut et al., 2024; Deeva et al., 2021; Ioanid & Andrei, 2025; Jansen et al., 2023; Parker et al., 2024). For instance, a chatbot used in geography education (e.g., ChatGPT or Socratic developed by Google) can pose open-ended questions to students, analyze their responses, and provide corrective feedback when necessary. Through the use of such AI-supported tools, pedagogical processes such as identifying conceptual misunderstandings, structuring knowledge, and promoting meaningful learning can be effectively facilitated. For example, when a student responds with a statement like, "The temperature in a region depends only on its distance from the equator" while studying the factors that influence temperature distribution, the system may recognize this as a one-dimensional line of reasoning and offer the following corrective feedback: "Temperature distribution cannot be explained solely by latitude (distance from the equator). Various geographical factors-such as landforms, continentality and proximity to the sea, elevation, air masses, and the distribution of land and sea-also play a decisive role in determining temperature."

Learning analytics is an area of AI application that guides the teaching process by analyzing large datasets derived from student interactions in digital education environments. The aim is to provide supportive, individualized learning environments for each student by identifying trends and learning needs from the data collected. Indeed, learning analytics can use online activity data to identify which subjects a student is struggling with or which types of geographical knowledge are lacking (Liu et al., 2024; Matkovič, 2024). Teachers can thus adapt the geography course content and instructional methods to better align with student needs. Prominent tools used for this purpose include KNIME, Knewton, ALEKS, Power BI (Microsoft), Moodle + Learning Analytics Plugin: Moodle LMS, ClassDojo, and Edmodo. For example, a KNIME application integrated into geography teaching can identify the stages that need revision by reporting student errors in map-reading activities. In this respect, learning analytics also provides the opportunity to design personalized learning experiences.

ITS are applications that can provide teaching materials and learning activities by adapting them to the individual needs of each student. Seterra Geography, GeoGuessr, Google Earth, Brainscape-Learn World Geography, StudyGe-World Geography Quiz, Stack the Countries, Smart Sparrow, Knewton Alta, and Century Tech are among the prominent ITS that can be used in geography teaching (Figure 1). For example, in a geography lesson unit designed to familiarise students with countries and capitals, a teacher may use different applications according to the level of each student. For beginner students, Seterra Geography can be used for country-location matching, while more advanced students can use GeoGuessr to guess random locations around the world based on visual clues. Thus, each student enhances their geographical knowledge by following a learning path tailored to their own learning pace and level. In addition, the teacher can enable students to review the capitals with flashcards through applications such as Brainscape, or have them observe the borders of continents and countries using authentic satellite images in Google Earth. Through this kind of ITS, geography lessons become both visual and interactive, and the learning process progresses in a personalised way. Research indicates that these applications enhance student motivation and have a positive impact on achievement (Ayas et al., 2015; Bahçeci & Gürol, 2010; Holmes & Tuomi, 2022).

Figure 1. ITS Examples

The most significant potential use of AI in geography teaching is image recognition and location-based applications. Image recognition applications enable land cover classification and change analysis, especially through satellite images and aerial photographs. The most common applications are Google Earth Engine and YOLO (Figure 2). For example, Google Earth Engine provides users with analysis-ready, processed data obtained from a wide range of satellites and sensors (Cao et al., 2021; Gomes et al., 2020; Gorelick et al., 2017). Similarly, object recognition algorithms such as YOLO (You Only Look Once) and Mask R-CNN are used for automatic identification of urbanization patterns, road networks, and agricultural areas, as well as real-time detection of plant species (He et al., 2020; Qiu et al., 2022; Redmon et al., 2016; Yasak, 2021).

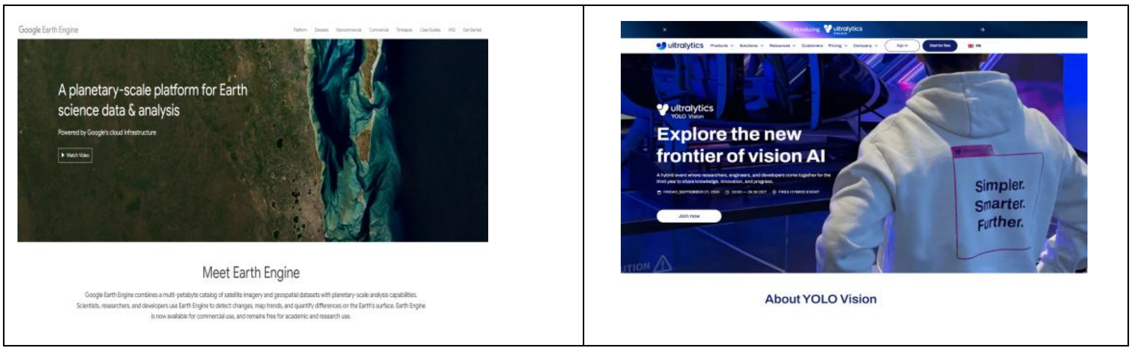

Figure 2. Examples of Image Recognition and Location-based Applications

Location-based applications allow students to collect field data directly from the environment and perform spatial analyses. In particular, GIS software such as ArcGIS and QGIS (Figure 3) enables students to analyze spatial data, create thematic maps, and engage in decision-support processes (Yıldırım & Ünlü, 2021). Applications such as Collector for ArcGIS and Survey123, which can be used on mobile devices, allow students to collect location data quickly during fieldwork; the collected data are visualised on ArcGIS Online, where density analyses are performed (Sinjari Xhafa & Kosovrasti, 2023). Additionally, digital mapping platforms such as Google Maps, OpenStreetMap, and Mapillary are utilized in classroom activities to analyze local spatial patterns and facilitate route planning (Toprak, 2023).

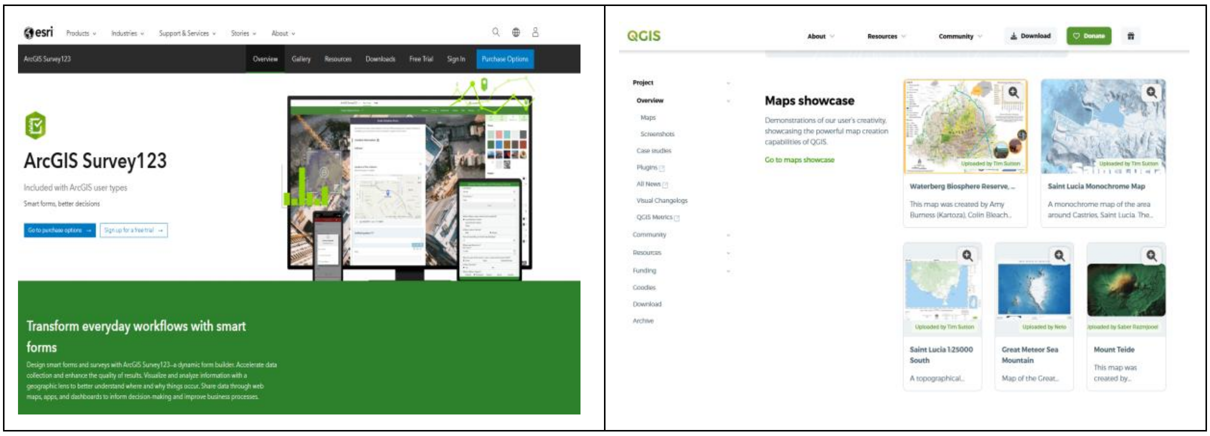

Figure 3. Examples of Location-based Applications

AR-based location applications also allow students to visualise three-dimensional landforms and compare historical maps with current data (Tuncer & Pınar, 2023; Yıldırım, 2021). With AR technology, layered information about a specific location is displayed on the student's mobile device screen by overlaying it onto the real-world image. Thus, students can access enriched information about the geological structure, climate characteristics, or cultural elements of their environment on-site. For example, with Zappar and Metaverse Studio, a student can learn about tree species in the schoolyard through predefined content, either by seeing them on the screen in real-time or by comparing the old and new appearances of a historical place. VR and AR applications improve students' perception of space by creating interactive and immersive learning experiences in geography education (Huang & Hu, 2025; Jantanukul, 2024; Roelofsen & Carter-White, 2022). In geography lessons, students can have the opportunity to examine real-life geographical datasets by working with AI tools that analyze drone or satellite images (Ergün, 2023). Additionally, ChatGPT-4 Geography stands out as an innovative digital assistant in geography education. This application, developed with ChatGPT infrastructure, supports students and teachers in explaining geographical concepts, developing spatial thinking, and making data-driven interpretations. GeoGebra AR and Metaverse Studio, both location-based and AR-based technologies, allow for interactive and three-dimensional exploration of topics such as landforms, climate zones, and natural disasters. For example, field-based tasks prepared with Actionbound allow students to navigate and collect data on-site, while using GeoAR.it increases spatial awareness by enabling environmental data to be presented in an AR environment.

Usage Areas and Applications of AI Tools in Geography Teaching

With the rapid advancement of digital technologies, artificial intelligence (AI) has emerged as a transformative tool in geography education, particularly in enhancing the teaching of physical geography topics. Although Pattison's (1964) concept of four fundamental geographical traditions has long been accepted among geographers, two main subfields stand out within the discipline of geography: physical geography and human geography. In the field of physical geography, it is possible to benefit from AI-based platforms in teaching topics such as landform classification, climate element analysis, river system modeling, and vegetation cover identification. Examples include studies that classify landforms using digital elevation models through Google Earth Engine (Cao et al., 2021; Safanelli et al., 2020), studies that predict temperature patterns based on climate data (Chen et al., 2023; Lewis et al., 2024; Taylor & Feng, 2022), and simulation-based models of disaster scenarios (Behravan et al., 2024; Kuratle et al., 2024; Li et al., 2024).

Moreover, AI-supported tools have become increasingly prominent in modeling and analyzing natural disaster risks within geographic contexts. The use of AI-based algorithms is growing in spatial risk analysis of natural disasters such as floods and landslides. For example, El-Haddad et al. (2021) employed AI-supported methods in spatial modeling to assess disaster susceptibility. In addition, recent studies have produced maps using algorithms such as SVM and random forest, which are among the machine learning (ML) modules of GIS. Bicák (2023) used the random forest algorithm to design an improved model for assessing agricultural drought, while Lemenkova (2024) used it to distinguish landscape patterns along the east coast of Mozambique. Additionally, Hu et al. (2019) used the same algorithm to relate the presence or absence of seagrasses to various ocean conditions.

Beyond disaster-related contexts, it is evident that AI technologies are also effectively applied in fields such as plant species classification (Adeline et al., 2021; Çulha & Ünaldı, 2025; Yasak, 2021) and the creation of fire susceptibility maps (Bayram, 2024; Iban & Aksu, 2024). It has been reported that the Diluvium Digital Elevation Model (DEM) was used to model changes in sensitive ecosystems, such as coastal areas, and environmental issues, such as sea level changes, were analyzed in detail with this model (Dusseau et al., 2023). Taken together, these studies illustrate the diverse potential of AI-based tools in supporting the teaching and learning of key topics across sub-disciplines of physical geography. Table 1 presents examples of tools and applications that can be used in various disciplinary areas of physical geography.

Table 1. Using AI in Physical Geography

Disciplinary Field	Purpose	Example Tools	Application Example
Geomorphology	Classification of Landforms	Google Earth Engine + Machine Learning (Random Forest, k-means clustering) Faster-RCNN	Students can automatically classify landforms in an area using digital elevation models. With the random forest algorithm or Faster-RCNN, forms such as mountains, valleys, and plateaus can be distinguished.

Climatology	Temperature and Precipitation Prediction	Python + Scikit-learn / Keras (Artificial Neural Network model)	Students can create an ANN model using 40 years of temperature data from a meteorological station.
Hydrography	River Flow Prediction	TensorFlow + ArcGIS Pro (Hydrology Toolbox + Python Notebook)	Students can build a model to predict river discharge based on past flow and precipitation data. Results can be analyzed with flood risk maps.
Disaster Geography	Landslide Susceptibility Analysis	ArcGIS, QGIS + SAGA GIS + SVM	Landslide risk analysis is performed in areas with steep slopes. Students can build a susceptibility model using layers such as land use, slope, lithology, and drainage density with SVM.
Soil Geography	Agricultural Suitability and Soil Classification	QGIS + SVM	Students classify suitable agricultural areas based on data such as soil type, permeability, temperature, and humidity; they identify ideal soil types for productivity using the SVM algorithm.
Biogeography	Plant Species Identification and Distribution Analysis	YOLOv5 + Drone Images + Convolutional Neural Networks + TreeSatAI	Students can classify plant species, forest cover, and endemic areas using object detection algorithms; they can perform real-time species detection.

In recent years, artificial intelligence (AI) technologies have also been increasingly utilized in the teaching of human geography, offering educators innovative ways to explore complex socio-spatial phenomena. In this context, AI-based platforms can be effectively used to analyze a wide range of topics such as urbanization processes, population mobility, migration, tourism, language, culture, education, the distribution of economic activities, and the interpretation of geopolitical risks. Convolutional Neural Network (CNN) algorithms are used in the detection and prediction of urbanization patterns (Amer et al., 2017; Fawzy, et al., 2024). Particularly, advanced deep learning models such as YOLOv5 provide effective results in the rapid analysis of targets such as building density, urban sprawl, and infrastructure monitoring using satellite and aerial imagery (Qiu et al., 2022). In population and settlement geography analyses, themes such as population distribution, urban growth, and income inequality can be interactively processed and visualized using platforms such as ArcGIS and Esri's Location Intelligence API (Chen, 2024). Furthermore, big data tools such as Google BigQuery, AutoML Tables, and Power BI allow for the large-scale analysis of migration patterns, demographic transitions, and the spatial distribution of economic activities (Huang et al., 2021).

In addition to visual and spatial data analysis, the integration of AI into human geography also includes natural language processing (NLP) technologies, which enable the interpretation of textual and cultural data. Open-source NLP tools, such as NLTK and SpaCy, can be used to analyze cultural trends and language use in a geographical context through social media data. A report prepared by the Asian Development Bank (2022) highlights the use of NLP technologies to analyze public sentiment, particularly in relation to social media discussions on COVID-19 and climate change. Such content can be visualised using tools such as GeoPandas and Tableau Public and transformed into teaching materials that can be integrated into instructional processes (Latue & Rakuasa, 2023).

Equally important, AI-based methods have been applied in tourism geography using SVM, random forest, gradient boosting trees, and GeoAI-based platforms for demand analysis, forecasting, and recommendation systems (Kırtıl & Aşkun, 2021; Kim et al., 2024). These approaches offer practical examples for planning and managing tourist destinations and help create scenario-based learning environments for geography education. In spatial network analyses—such as those focusing on accessibility and transport links—tools like ArcGIS Network Analyst, Python with NetworkX, Google OR-Tools, PGrouting, and PostGIS with PostgreSQL are frequently utilized (Geethika et al., 2025; He et al., 2024; Kostecki, 2024; Raza et al., 2024).

Finally, the use of AI-supported GIS is becoming increasingly widespread in the geographical analysis of geopolitical risks. Tools such as GeoAI Risk and Mapping ArcGIS are used to analyze the spatial distribution of hot conflict areas and geopolitical pressure zones (Baklykov, 2024). Taken together, these studies provide valuable findings on the applicability of AI-based tools in teaching subjects related to sub-disciplines of human geography. Table 2 presents examples of tools and applications that can be used in various disciplinary areas of human geography.

Table 2. Using AI in Human Geography

Disciplinary Field	Purpose	Example Tools	Application Example
Population Geography	Population Density and Migration Analysis	ArcGIS Insights, Location Intelligence API (Esri)	Students generate population density maps using location data collected from mobile devices. Supervised learning algorithms are used to classify migration patterns.
Urban Geography	Urban Development Prediction	Google Earth Engine, Convolutional Neural Networks (CNN)	Students analyze spatial urban growth using satellite imagery over time and apply CNN models to predict areas of urban expansion within the next five years.
Agricultural Geography	Land Use Identification	Drone Imagery, YOLOv5 (object detection via deep learning)	Students conduct plant health assessments based on drone imagery, identifying and classifying healthy versus unhealthy vegetation.
Tourism Geography	Destination Suitability Analysis	Weka, ArcGIS ModelBuilder	Students assess natural and cultural tourist sites based on climate, infrastructure, and accessibility, generating a suitability map for potential tourism development.
Transport Geography	Route Optimization	ArcGIS Network Analyst, Python + NetworkX, Google OR-Tools PGrouting ve PostGIS ile PostgreSQL	Students analyze public transportation systems to determine optimal routes based on traffic congestion data.

Social Geography	Spatial Analysis of Social Structures	NLTK, SpaCy GeoPandas / Shapely QGIS + Plugin'ler (ör. Orfeo Toolbox)	Students use NLP tools to analyze social media content and map the spatial distribution of variables such as language, education, and cultural practices.
Political Geography	Geopolitical Boundary and Risk Assessment	GeoAI Risk Mapping Toolkit, ArcGIS Pro, GeoPandas, Sentinel Hub	Students map geopolitical risk areas such as conflict zones and border disputes while analyzing the location of strategic energy corridors.
Economic Geography	Spatial Distribution of Economic Activities	Power BI, Google BigQuery, AutoML Tables, Orange Data Mining	Students analyze spatial data on industrial, trade, and service sectors to uncover economic patterns and regional development disparities.

Opportunities Offered by AI Technologies in Geography Teaching

The use of AI technologies in geography education not only digitizes the teaching process but also transforms the nature of learning. In this context, considering the opportunities provided by AI at pedagogical, conceptual, and practical levels, these can be listed as follows: personalised learning experiences, detection and correction of misconceptions, development of spatial thinking, data literacy and critical thinking, digitalisation of field-based learning, adaptive feedback mechanisms, and real-time interaction. To date, the use of AI in geography has been primarily concentrated in integration with GIS (Yasak, 2021). In areas such as land use classification, disaster risk analyses, spatial modelling, and image recognition, AI makes significant contributions, especially through machine learning and deep learning techniques. However, most of these applications are not directly oriented toward educational processes but are developed for geographical field research. In the context of geography education, the pedagogical potential of AI, such as personalised learning experiences, detection of misconceptions, and development of critical thinking skills, is underexplored.

AI offers adaptive learning pathways by analyzing students' individual learning needs (Baskara, 2023; Nugraheni et al., 2024; Meylani, 2024; Mulally, 2024; Pashkova & Demianenko, 2024). These platforms address students' needs by using AI to customize educational content (Mishra et al., 2024; Rakuasa, 2023; Ou & Chen, 2024). This makes it possible to create learning environments that are meaningful to the level of learning in geography courses, especially in teaching abstract concepts (e.g., landforms, climate types, and disaster susceptibility). Thanks to NLP technologies, students' open-ended responses can be analyzed semantically, and misconceptions can be detected. Systems integrated with this technology (e.g., Q-Assign and ChatGPT API) provide teachers with insights into students' meaning-making processes, allowing them to develop cognitive awareness by offering meaningful feedback to students (Balcı, 2024; Birenbaum, 2023; Ioanid & Andrei, 2025; Roldán-Álvarez, 2023).

The discipline of geography, which treats space as its central object of study, inherently involves visual, spatial, and analytical thinking. In this context, map reading and interpretation activities integrated with AI technologies such as image processing, computer vision, and machine learning significantly improve students' spatial perception and interpretation skills. In particular, tools such as Google Earth Engine, ArcGIS Image Analyst, and YOLO enable students to perform operations such as terrain classification, soil type distinction, and vegetation analysis using real satellite images, thereby directly promoting data-driven learning (Almelweth, 2022; Rana & Bhambri, 2025; Rakuasa, 2023). Thus, students' ability to analyze and interpret complex spatial problems improves. The big data processing capacity offered by AI also supports geography students in developing high-level skills, such as data literacy, pattern recognition, causal analysis, and scenario generation. AI-supported AR and location-based applications provide the opportunity to integrate with field data, regardless of physical space, in geography teaching (Shaikh, 2024). Students can collect and analyze data instantly in field studies and integrate it into digital environments. Finally, the use of AI-based applications as measurement and evaluation tools in the teaching process is also becoming increasingly widespread. These applications enable both students and teachers to monitor and evaluate their academic progress instantly. In traditional teaching approaches, measurement and evaluation processes often consume a considerable amount of time, leading to delays and a loss of motivation (Mishra et al., 2024; Ou & Chen, 2024). In this sense, AI-based assessment and evaluation tools make the learning process more interactive, motivating, and effective.

Limitations and Possible Risks of Using AI Technologies in Geography Teaching

Despite the opportunities provided by AI in teaching, there are some structural, pedagogical, and ethical limitations encountered in classroom applications. These limitations include teacher competences and pedagogical integration, inequities in infrastructure and access, ethical, security, and privacy concerns, content appropriateness and interdisciplinary constraints, a lack of empirical research, concerns about the accuracy of AI-generated information, and the risk of information pollution. In particular, teacher competences and the level of pedagogical integration appear as important limitations. Many teachers struggle to integrate AI-based tools pedagogically into classroom content, resulting in a superficial use of technology (Alasgarova & Rzayev, 2024; Meylani, 2024; Yadav, 2025). Comprehensive training programs are required for teachers to make effective use of AI tools (Arya & Verma, 2024; Tang, 2024). Research on geography teachers has revealed low levels of technology integration (Castro, et al., 2025; Lee, 2023; Matkovič, 2024; Pashkova & Demianenko, 2024; Rakuasa, 2023; Sezer et al., 2022). Notably, the lack of knowledge and methodological uncertainties about how to use AI-based applications for pedagogical purposes is also noteworthy. As a result, teachers may resort to using AI tools merely as visual aids or content delivery platforms. In this context, it is of great importance to develop applied, content-specific, and AI-oriented in-service training programs for geography teachers, as well as to design pedagogical training that is tailored to the disciplinary structure of geography.

Another fundamental limitation is inequities in infrastructure and access. Structural limitations such as inadequate infrastructure and insufficient training for educators hinder the effective integration of AI into classrooms (Zhang, 2024). This issue is particularly pronounced in rural and socioeconomically disadvantaged areas, where infrastructure deficiencies are known to exacerbate existing educational inequalities rather than promote equitable access to technology (Sasipriya & Reddy, 2024). As a result, students in these regions may face significant barriers to accessing AI-supported tools such as GIS-based map creation and analysis, online fieldwork applications, and spatial data visualization platforms. This, in turn, makes it more difficult for them to develop basic skills in geography teaching. Ethical, security, and privacy issues represent some of the most significant barriers to integrating AI in education. Particularly in AI-supported processes such as learning analytics and student behavior monitoring, the continuous collection of personal data raises various ethical concerns (Porayska-Pomsta et al., 2023; Santos, 2024; Takona, 2024). These include risks related to data security, compromised user autonomy, and a lack of transparency (Damasevicius, & Sidekerskiene, 2024; Meylani, 2024). Invasion of privacy is a serious concern, especially in student profiling systems or feedback mechanisms based on personal learning history, and can lead students to develop mistrust towards these systems (Hermansyah et al., 2023; Mustofa et al., 2025). In geography teaching, monitoring students' spatial movements, especially in applications such as location data sharing, online mapping activities, and field observations, makes these ethical risks even more visible. In addition, it is of great importance to observe ethical principles such as the protection of personal data, obtaining explicit consent, and clearly defining the purpose of data use in image recordings made during drone-assisted fieldwork and interview processes with local communities.

The direct relevance of AI applications to the teaching content also stands out as an important limitation. Wilby and Esson (2024) emphasize that ChatGPT's definition of geography does not include the basic concepts of the discipline (place, scale, space, and time), the definition put forward in the context of physical and human geography is insufficient and superficial, and AI-based applications need instructor guidance and critical thinking in terms of both content and conceptual depth. The accuracy of AI-generated information and the risk of information pollution are significant limitations, particularly in the context of chatbots (Elstad, 2024; Liu, 2024; Sidhu, 2025; Tang et al., 2023). These findings suggest that integrating AI tools directly into the educational process without critical filtering has pedagogical drawbacks. These deficiencies weaken students' ability to evaluate geographical events in a multidimensional way. Therefore, the meaningful integration of AI tools into geography education necessitates the embedding of discipline-specific conceptual frameworks within the technology. In addition, since most of these tools are English-based, language barriers and cultural context differences can also pose challenges in the teaching process (Elifas & Simuja, 2024; Kour et al., 2025; Zhang, 2024). This can result in the misrepresentation of geographical concepts, content, and cultural diversity, potentially leading to inaccurate or misleading perceptions. Therefore, the localization of AI-supported applications, provision of multilingual support, and enrichment of content with a culturally inclusive perspective are critical for meaningful, equitable, and inclusive learning experiences in geography teaching.

Although AI is increasingly becoming a topic of interest in educational research, empirical findings on its effects in teaching contexts remain limited. Chiu et al. (2023), in their systematic review of the opportunities and challenges of AI in education, state that the existing literature remains largely at the conceptual level, while empirical research on pedagogical effects is insufficient. Similarly, Zhai et al. (2021) emphasize in their systematic review of machine learning applications in education that most studies in this field are short-term and conducted with limited samples, while long-term measures of effectiveness have not yet been sufficiently developed. This situation makes it difficult to scientifically demonstrate the concrete contributions of AI to teaching processes. When considered in the context of geography education, the number of qualitative and quantitative studies that examine the effects of AI on students' geographical knowledge, map literacy, and fieldwork practices remains quite limited (Kim, 2022; Liu et al., 2025; Pashkova & Demianenko, 2024; Rakuasa, 2023). The lack of robust empirical evidence in this field presents a challenge in grounding the integration of AI into geography education on sound scientific foundations.

Discussion

This study examines the integration of AI technologies into geography teaching from a multidimensional perspective, highlighting both their potential contributions and the limitations that hinder the realization of this potential. The findings show that AI technologies have the capacity not only to digitize geography teaching but also to transform it pedagogically. However, the extent to which this transformation can be achieved depends largely on how these technologies are implemented and for what pedagogical purposes they are employed. In this sense, it is clear that AI-supported geography teaching offers not only opportunities but also structural, pedagogical, and ethical challenges that need to be addressed.

To begin with, in line with the first research question, the potential of using AI technologies in geography teaching was evaluated. The findings revealed that NLP, learning analytics, intelligent tutoring systems (ITS), and location-based applications function as tools that support student-centered learning. These technologies enable students to identify their conceptual gaps, receive instant feedback, and individualize their learning processes (Agostini & Picasso, 2024; Chang & Kidman, 2023; Wilby & Esson, 2024; Zhao et al., 2021). Thus, the learner is transformed from a passive recipient of information into an active subject who directs their own learning process. Nevertheless, for this potential to turn into genuine educational value, it is directly related to geography teachers' competences in integrating AI tools with teaching goals and their digital pedagogical formation. Considering that geography teachers' technological competencies remain limited (Nurgazina, et al., 2025; Pashkova & Demianenko, 2024; Sezer et al., 2022), it can be inferred that teachers will play a decisive role in the successful integration of AI into geography education.

In addition, within the scope of the second research question, the use of AI technologies in both physical and human geography was assessed. The findings indicated that in physical geography, AI-based classification algorithms (e.g., CNN, SVM, and random forest) can be effectively integrated into topics such as land use, soil structure, climate data analysis, and disaster risk assessment (Kim, 2022; Rakuasa, 2023; Zhou, 2023). On the other hand, in human geography, big data is transformed into valuable teaching material through location-based systems and GeoAI applications, particularly in themes like migration, urbanization, cultural geography, tourism, and geopolitical analysis (Alaeddinoğlu & Alaeddinoğlu, 2020; Castro, et al., 2025; Huang et al., 2021; Lane, 2025; Nawaz & Sattar, 2024; Sabato & De Pascale, 2023).

Despite these advancements, several challenges continue to hinder the integration of AI in real classroom contexts. These include language barriers, misalignment with curriculum content, and limited AI literacy among educators (Matkovič, 2024; Pashkova & Demianenko, 2024; Rakuasa, 2023). Nonetheless, the potential of AI technologies in geography teaching remains highly promising. Given that geography is inherently a discipline that requires multidimensional analysis to understand both natural environments and human systems, AI-based tools play a crucial role in enhancing students' ability to grasp these complex relationships.

The versatility of AI tools—such as the dual use of the YOLO algorithm in monitoring urbanization dynamics and identifying plant species—demonstrates their flexibility and applicability across diverse geography subfields.

Importantly, AI should not be viewed merely as an information delivery tool; it also serves as a dynamic learning environment that cultivates students' higher-order thinking skills such as scenario building, pattern recognition, and causal reasoning. Looking ahead, the application of AI in interdisciplinary and pressing topics—such as environmental sustainability, disaster risk management, and spatial planning—has the potential to fundamentally transform geography education, fostering more creative and holistic pedagogical approaches.

Moving forward, the third research question examined the pedagogical opportunities offered by AI technologies. The findings underscore that these technologies facilitate the implementation of contemporary instructional methods such as problem-based learning, project-based teaching, and field-based studies (Almelweth, 2022; Lee, et al.,2025; Matkovič, 2024; Nawaz & Sattar, 2024). In particular, AR applications and big data-driven visualization tools (Liu et al., 2025; Matkovič, 2024) are highly effective in enhancing students' spatial literacy and fostering meaningful interaction with their environment.

Moreover, AI-supported applications—such as image processing, computer vision, and machine learning tools (e.g., Google Earth Engine, ArcGIS Image Analyst, YOLO)—provide students with opportunities to conduct terrain classification, vegetation analysis, and soil type differentiation in a data-driven and interactive manner. This contributes directly to the development of spatial analysis and geographic interpretation skills (Almelweth, 2022; Rana & Bhambri, 2025; Rakuasa, 2023). At the same time, the big data processing capabilities of AI further nurture students' higher-order thinking skills, including pattern recognition, causal reasoning, and scenario generation.

Furthermore, in the realm of assessment and evaluation, AI-supported platforms make the learning process more flexible and measurable. Teachers can monitor student performance in real time and tailor instructional strategies based on individual differences (Lee, 2023). However, for AI technologies to produce meaningful and pedagogically sound outcomes, it is crucial that their integration aligns with geography education goals, is appropriate to student levels, and is grounded in sound instructional design. Otherwise, AI risks being reduced to a superficial trend, failing to provide real added value to learning processes.

Finally, the fourth research question explored the limitations and potential risks associated with AI technologies in geography teaching. The findings revealed several critical threats to the sustainable use of AI in education, including teachers' inadequate competencies, lack of technological infrastructure, data privacy concerns, and ethical issues (Almelweth, 2022; Hu et al., 2019; Sasipriya & Reddy, 2024). Of particular concern is the tendency of LLMs (e.g., ChatGPT) to sometimes generate inaccurate or decontextualized information, which can result in conceptual misunderstandings (Wilby & Esson, 2024).

Moreover, the lack of proper protection of student data during collection and use introduces serious ethical dilemmas and legal obligations. In addition to these concerns, language and cultural limitations of current AI tools must be acknowledged (Day & Esson, 2025; Rakuasa, 2023). The dominance of English in AI-generated content, coupled with limited representation of local cultural and geographical contexts, may cause shifts in meaning and misunderstanding—especially when teaching conceptually dense or culturally specific content (Tao et al., 2024).

Therefore, the integration of AI into educational programs should occur not only at the technological level but also at the cultural and pedagogical levels. To ensure conceptual clarity, contextual relevance, and student-centered learning, it is essential to develop localized and geography-specific AI applications. This is particularly critical in student projects involving field data—such as drone imagery or community interviews—where ethical data collection practices, including privacy protection, informed consent, and transparent use policies, are indispensable responsibilities shared by both teachers and students.

In conclusion, the lack of long-term, empirical, and discipline-specific research on the pedagogical impacts of AI in geography education (Chiu et al., 2023; Zhai et al., 2021) represents a major gap. This makes it challenging to assess AI-supported teaching practices on a strong scientific basis. The absence of such evidence hampers our understanding of how key educational goals—such as spatial reasoning, environmental awareness, and field-based inquiry—can be fostered through AI integration in geography teaching.

Conclusion

This research provides a holistic assessment of the field by examining how AI technologies can be integrated into geography teaching from pedagogical, contextual, and practical perspectives. The results show that AI applications are not only tools that digitize the teaching process, but can also create a learning ecosystem that redefines the production, transfer, and structuring of geographical knowledge. In particular, technologies such as NLP, learning analytics, location-based systems, and ITS enhance students' conceptual understanding while supporting feedback mechanisms, individualized learning pathways, and the development of higher-order thinking skills. Furthermore, the study illustrates how AI-supported tools can be applied in the context of both physical and human geography, the two major sub-disciplines of geography education. Content such as remote sensing, land use classification, and disaster modeling algorithms in physical geography, as well as urbanization patterns, migration dynamics, and spatial analysis of social media data in human geography, can be effectively integrated into the teaching process through AI-supported applications. Such applications not only facilitate the understanding of complex geographical phenomena but also promote interdisciplinary thinking and problem-solving skills among students. From this perspective, AI technologies have the potential to build a learning environment that strengthens not only students' access to knowledge but also their ability to construct, evaluate, and transfer this knowledge. This aligns with contemporary educational paradigms that emphasize active learning, student agency, and data-informed inquiry.

However, despite these promising potentials, limitations identified in the existing literature are also likely to affect geography teaching similarly. These limitations include misalignment between content and curricula, inadequate technological infrastructure, inequitable access, variations in teachers' digital pedagogical competencies, the predominantly English-based nature of AI applications, and ongoing ethical and privacy concerns. Given these challenges, this situation necessitates careful planning and implementation at pedagogical, technical, and ethical levels to ensure AI technologies' practical, inclusive, and responsible integration into geography education. Only through such a comprehensive approach can the transformative potential of AI be fully realized in supporting meaningful, context-sensitive, and equitable geography learning experiences.

Recommendations

For the successful integration of AI technologies into geography teaching, a holistic approach to using these technologies for pedagogical purposes should be adopted. This process should begin with strengthening the professional competences of geography teachers. In particular, in-service training programs should be designed to equip teachers with the skills to use AI components such as NLP, location-based analysis, and learning analytics in geography instruction in alignment with course objectives. These programs should not only focus on the technical operation of AI tools, but also emphasize pedagogical strategies for integrating them effectively into curriculum-based teaching practices.

Moreover, another important need highlighted by the findings is the development of content that supports the integration of AI-based applications into geography subjects. To address this, sample teaching scenarios involving AI use in topics such as disaster management, soil classification, urban growth, migration, and geopolitical analysis should be created. These scenarios should be tested through pilot applications at different educational levels. In this regard, collaboration between academics, curriculum developers, and practicing teachers is particularly valuable for ensuring the relevance and feasibility of AI-integrated instructional designs.

In parallel with these developments, it is essential to conduct experimental studies using both quantitative and qualitative research methods to evaluate whether AI technologies contribute pedagogically to geography education. These studies could examine the impact of AI applications on students' map-reading abilities, spatial thinking, and conceptual understanding, thus providing evidence-based insights into the effectiveness of such technologies in real classroom settings.

In addition to pedagogical considerations, preventive measures should be taken to address the limitations of AI technologies. Challenges such as the predominance of English-language content, the underrepresentation of local contexts, and cultural mismatches may cause misconceptions or alienation in geography lessons. Therefore, it is imperative to develop localized, multilingual, and culturally responsive content that can be meaningfully integrated into national curricula.

Equally important is the need to ensure that the use of AI-based applications in educational environments is conducted in a safe, transparent, and ethical manner, with particular attention to the protection of personal data. This is especially crucial in learning analytics, location-based services, and profiling-based feedback systems that involve student data processing. Policies must be developed based on transparent data usage, informed consent, and respect for user autonomy. Additionally, students should be trained in ethical data collection practices—such as securing legal permissions and protecting privacy—particularly when engaging with tools like digital mapping, field observations, or drone technologies.

Finally, structural barriers such as inadequate technological infrastructure and digital inequality must be addressed. Limited access to hardware, software, and internet connectivity—particularly in rural or socioeconomically disadvantaged areas—can prevent equitable participation in AI-enhanced geography education. Therefore, educational policies should prioritize expanding access to technological resources to ensure that all students benefit equally from the pedagogical opportunities AI can offer.

Author(s)' Statements on Ethics and Conflict of Interest

***Ethics Statement*:** We hereby declare that research/publication ethics and citing principles have been considered in all the stages of the study. We take full responsibility for the content of the paper in case of dispute. This study does not involve qualitative or quantitative data collection methods that require ethics committee approval, such as surveys, interviews, focus groups, observations, experiments, or similar techniques. Therefore, obtaining approval from an ethics committee does not apply to this research.

***Statement of Interest*:** We have no conflict of interest to declare.

Data Availability Statement: Data available on request from the authors.

***Funding*:** None

***Acknowledgements*:** None

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