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Review

Trends and Challenges of Technology-Enhanced Learning in Geotechnical Engineering Education

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Abstract: The integration of technology and new tools in engineering education has created opportunities for the advancement of geotechnical engineering education (GEE). Technology-enhanced learning (TEL) has been implemented in GEE by many educators, and its impacts have been studied by different researchers. This review paper presents a comprehensive analysis of the state-of-the-art implementation of TEL in GEE based on published journal articles. This study adopts a systematic approach in examining the literature on TEL in GEE, identifies emerging trends and challenges, presents potential solutions, and outlines research gaps and recommendations. The literature indicates that, over the past couple of decades, the major trends of TEL in GEE have included computer-based simulations and computations, physical and centrifuge modeling, virtual laboratory and field experimentation, internet-based online resources, and virtual and augmented reality. The implementation of TEL in GEE can support students in effectively comprehending complex engineering concepts and augment their preparedness for the demands of professional practice. Furthermore, the integration of TEL with instructional design strategies involving problem-based learning, experiential learning, collaborative learning, and critical thinking cultivation is recognized as a favorable strategy. However, challenges such as a lack of resources and experience, optimization of pedagogies, alignment with course content, and quantification of TEL's impact on GEE and student learning experiences remain to be addressed by continuing research and development in this field. In addition, an outcome-based education (OBE) theory-inspired quadruple framework is proposed in this study for the efficient implementation of TEL in GEE.

Keywords: technology-enhanced learning; geotechnical engineering education; teaching pedagogy; computer-based learning; virtual/augmented reality; internet-based learning

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1. Introduction

Geotechnical engineering is a key field of study in the higher education sector across the world, particularly in civil, mining, and geological engineering programs. Geotechnical engineering education (GEE) typically involves the principles of soil and rock mechanics and the design and construction of foundations, retaining structures, and underground structures [1]. GEE involves classroom instruction, as well as laboratory work and fieldwork, to provide students with hands-on knowledge in testing and analyzing soil and rock samples. Graduates having foundation knowledge in geotechnical engineering can pursue careers in a variety of fields, including infrastructure development, construction, environmental consulting, drilling, and mining. The literature manifests that academicians have implemented diverse educational strategies to enhance the teaching and learning process in GEE, and several studies have evaluated the efficacy of these methods. Among these strategies, technology-enhanced learning (TEL) has gained widespread adoption, which involves the use of technology to augment the teaching and learning experience [2]. It is important to mention that TEL is not a teaching pedagogy in and of itself but rather a set of analytical or digital tools and strategies that can be used to enhance existing teaching pedagogies and improve the teaching and learning experience. Moreover, TEL can encompass technology-enhanced classrooms and learning approaches that are facilitated by technology rather than being limited to learning that occurs solely through technology. The sphere of TEL is a dynamic and ever-evolving area that attracts noteworthy attention across all strata of the educational landscape. Specifically, the field of engineering education has witnessed a high adoption of TEL, specifically in the context of learning product design, manufacturing, and performance-related concepts. These topics are often presented abstractly to students through deductive teaching methods, making TEL an increasingly valuable tool in this area. Consequently, TEL carries noteworthy implications for GEE to enhance the learning experience of students. TEL offers geotechnical engineering students access to diverse learning resources, i.e., computer-aided design tools, virtual reality simulations, and online resources that can help them visualize and analyze geotechnical problems in a more interactive and intuitive manner. Additionally, TEL can provide geotechnical engineering students with real-life scenarios that they can use to apply their knowledge and skills, which can help them establish critical thinking and problem-solving skills that are the core requirement for learning [3]. By means of TEL, geotechnical engineering students can learn more proficiently, engage more vigorously with the course content, and gain a deeper understanding of geotechnical engineering problems, which can eventually prepare them for success in their careers as geotechnical or civil engineers.

Further, the literature demonstrates that TEL encompasses a wide range of technologies, including both basic and complex tools, such as presentation and simulation tools. The literature also highlights that the effectiveness of TEL on learning outcomes is multifaceted and influenced by a range of factors, including student motivation, prior knowledge, and the quality of the instructional design [1,4]. Moreover, the successful application of TEL in various educational settings is also significantly influenced by cultural and contextual factors. Researchers and educators must consider a variety of aspects to determine the efficacy of TEL, such as the effectiveness of various technologies and tools, the effectiveness of the instructional design, and cultural and contextual factors that may affect their adoption and use [4]. By taking a comprehensive approach to TEL research, educators and instructional designers can better understand how these technologies can be used to enhance the teaching and learning experience in GEE and other domains.

Within GEE, TEL primarily employs presentation, simulation, e-learning, and computational tools to engage students in active learning. Additionally, new and emerging technologies such as augmented reality and artificial intelligence offer exciting opportunities for enhancing learning outcomes within GEE [5]. Nowadays, many educators who deliver GEE are leveraging TEL to facilitate and augment effective teaching and learning. TEL has opened up opportunities for the advancement of GEE, enabling learners to engage with complex concepts and practical experiences in new and innovative ways. However, despite the growing popularity of TEL in GEE, a comprehensive review of the trends and benefits of TEL in GEE, as well as the challenges that educators and learners face, is still needed. Through a comprehensive review of the state-of-the-art implementation of TEL in GEE, educators and researchers can gain a better understanding of the existing practices and research gaps in this domain. This knowledge can also enable them to make informed decisions concerning the effective integration of technology in their teaching practice. Additionally, students can benefit from an enhanced and engaging learning experience through the application of these insights. However, to the best of the author's knowledge, there is currently no existing study in the literature discussing the aforementioned aspects, highlighting a notable research gap. Therefore, the aim of the current paper is to present a literature review in order to address the following research questions: (i) What is the extent of the published journal article-based literature on the usage of TEL in GEE? (ii) What are the trends of TEL in GEE? (iii) What are the challenges of TEL in GEE and their solutions? Thus, this manuscript is aimed at presenting a detailed evaluation of the integration of TEL in GEE. As such, it represents a significant and valuable resource for educators and researchers seeking to explore this topic in depth.

2. Methods and Framework

In this paper, the implementation of TEL in GEE is reviewed in order to identify the trends and challenges of TEL in GEE based on the published data. To avoid complexity, the major categories of TEL tools selected for review are the most pertinent to GEE, namely the presentation tools, simulation tools, computational tools, online resources, and modern tools. This study commences by identifying a database that is closely related to GEE education and TEL implementation. The objective of this study is to analyze the state-of-the-art literature in the chosen database to comprehend the trends, advantages, and challenges of TEL in GEE. The search for research records is conducted in the world's largest abstract and citation databases of peer-reviewed literature, namely Web of Science (WoS), Google Scholar, and Scopus.

To carry out this study, the pertinent literature was searched in the aforementioned databases based on relevant keywords associated with the aim of the current study. A database was generated based on the research questions of the current study, and scrutiny schemes were established to shortlist the most relevant literature for analysis discussions. Figure 1 presents the study selection criteria. Around 1101 papers were selected based on specific keywords such as "geotechnical engineering", "geotechnical engineering education", "technology-enhanced learning", "presentation tools", "simulation tools", "computational tool", "online resources tool", "student experience", "student learning outcomes", "education", "learning", "teaching", "soil mechanics", "rock mechanics", "e-learning", "blended learning", "classroom learning", "virtual reality", "augmented reality", "artificial intelligence", "machine learning", "gamification", "curriculum design", "learning management systems", "instructional design", "challenges", "trends", and "student/teacher training". The number of research records was substantially reduced to 119 by removing duplicates and non-journal/magazine articles. An additional title and abstract screening were carried out to remove non-GEE articles, which reduced the list to 39. The eligibility of the screened research records was further analyzed by full-text screening, and the final list included 31 articles that were mainly used for literature reviews and identifying the trends, challenges, and solutions of TEL in GEE. The comprehensive framework of this study is presented in Figure 2. In addition, it is pertinent to mention that this review explored the use of technology in instructional design and delivery for all forms of learning and teaching in GEE. This includes classroom teaching, blended learning, fully online learning, and any other forms of learning and teaching that incorporate technology.

This study mainly undertakes a scoping review to comprehensively explore the trends, advantages, challenges, and solutions of TEL implementation in the domain of GEE. Meanwhile, to further examine the landscape of the existing literature, a bibliometric review is also conducted, enabling the identification of some additional trends within the field. Moreover, for a scoping review, data were extracted from a screened article based on relevant variables such as the study objective, methodology, tools and technologies used, results, key findings, recommendations, and limitations. The extracted data were analyzed using thematic, content, and frequency analysis approaches to identify key themes and patterns in the data. These techniques enabled the identification and categorization of bibliographic information, keywords, key concepts, tools, themes, limitations, and patterns in the data, which were then used to identify the trends and challenges. The content analysis focused on examining the textual content of the included studies, while the thematic analysis focused on identifying the key themes and concepts that emerged from the data. Meanwhile, the content, themes, and subthemes were organized into a framework that provided an overview of the current state-of-the-art implementation of TEL in GEE to synthesize the findings across studies (Figure 2). Finally, based on the synthesized data from the selected studies, the findings were presented in a narrative format that provided a comprehensive overview of the trends, benefits, challenges, and solutions of TEL in GEE. Further, a frequency analysis was used to quantify the frequency of the identified trends and themes. For the frequency analysis, the data encompass quantifiable information in the bibliography and content such as the publication year, journal name, first author affiliation, cooccurrence of keywords, and nature and type of technological tools under consideration. The quantified trends were presented in visualization form to provide objective and meaningful interpretations. Moreover, the quality and rigor were assessed based on publication type, i.e., peer-reviewed publications, and also by self-analyzing the studies based on sample size adequation, description sufficiency, clarity, and appropriateness of the data collection and analysis methods and the handling of confounding factors as defined by the Joanna Briggs Institute Critical Appraisal System. Furthermore, the alignment of the findings of this study with Science, Technology, Engineering, and Mathematics education was examined by reviewing pertinent review or perspective articles covering TEL in STEM, resulting in a final list of 33 references.

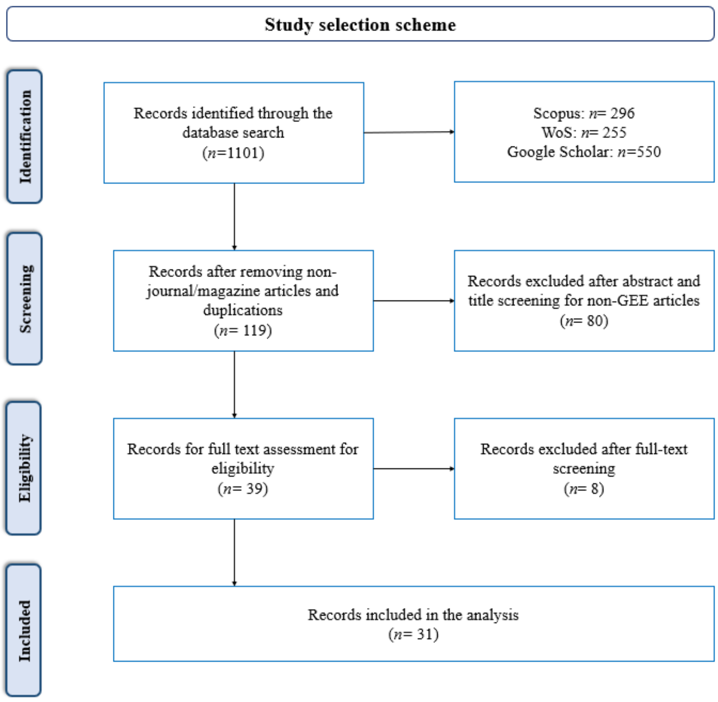

Figure 1. Flow diagram of the study selection scheme.

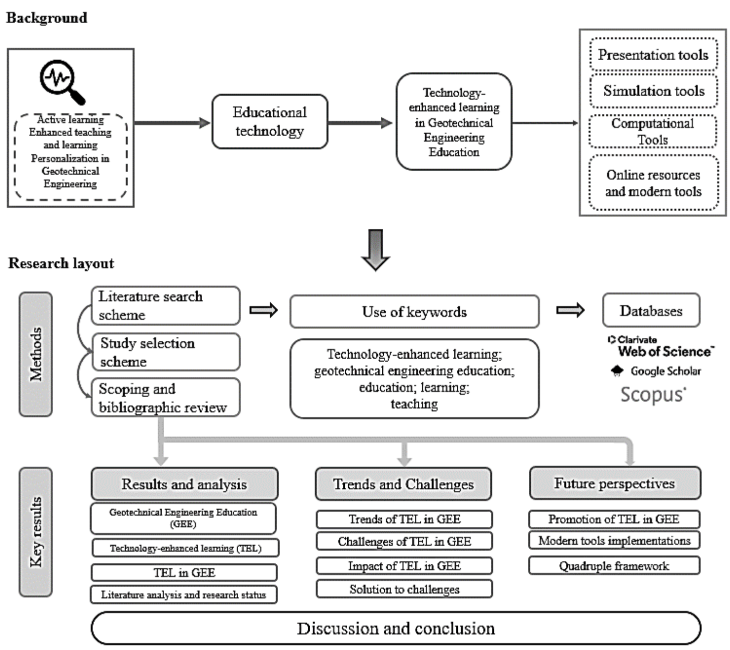

Figure 2. The framework of the current study.

3. Results and Analysis

3.1. Overview of Geotechnical Engineering Education

Geotechnical engineering deals with the behavior of soil and rock, geohazards, and their interactions with structures and is regarded as a subdiscipline of civil engineering, engineering geology, and mining engineering. GEE involves a combination of theoretical knowledge and practical skills in the design and construction of structures, as well as the analysis of geohazards, with a focus on ensuring the safety and stability of structures interacting with soil and rocks. GEE is commonly initiated at the undergraduate level, where it is primarily integrated into civil engineering programs. Within these programs, GEE is integrated with fundamental engineering principles, such as mechanics, materials science, and structural design, among others. Furthermore, GEE is also integrated into other major programs at the undergraduate level, such as mining engineering and geological engineering. Core courses in geotechnical engineering cover topics such as soil mechanics, rock mechanics, foundation design, and earth retention systems. At the graduate level, students can pursue specialized geotechnical engineering degrees. These degree programs prepare students for careers in academia or industry by giving them advanced knowledge and research skills. Advanced subjects such as soil dynamics, constitutive behavior and modeling of soils and rocks, and advanced foundation design are frequently covered at the graduate level. Additionally, original research projects and the presentation of the results in a thesis or dissertation are frequent requirements for graduate students.

GEE includes theoretical and practical knowledge through lectures, laboratory demonstrations, internships, and field visits. In addition to traditional classroom learning, GEE also incorporates laboratory work and field testing/visits. These schemes provide students with the opportunity to gain theoretical knowledge of major geotechnical engineering content, experiments in the laboratory to have enhanced learning of theoretical knowledge, and work in the field and gain hands-on experience in geotechnical engineering design and construction. Overall, GEE provides students with a strong foundation in civil engineering principles and specialized knowledge of the behavior of soil and rocks. Through a combination of classroom learning, laboratory work, field testing, and practical experience, students are prepared for careers in geotechnical engineering design, construction, and research. Thus, the implementation of TEL is essential in conventional classroom learning, laboratory and field testing, and internships for active learning in GEE.

Different researchers have identified different challenges and modern trends for improvement in GEE. For instance, the literature emphasizes the need for geotechnical engineers to have a strong foundation in both theory and practical skills and to be able to adapt to new technologies and methods, emphasizing the need for GEE to evolve in response to changing demands and trends in the field. Pierce et al. (2013) highlighted the importance of creating environments with modern strategies that promote critical thinking and provide examples of instructional strategies that can facilitate this process in GEE through different tools [6]. Further, this study also highlighted the importance of incorporating practical experience and real-world applications into coursework in GEE for active learning. Wirth et al. (2016) discussed the need for interdisciplinary education and the incorporation of new technologies and methods, as well as the importance of practical experience and hands-on learning opportunities in GEE [7]. Jiang et al. (2021) highlighted the need for continued innovation in GEE to ensure that students receive a high-quality education in the face of COVID-19 disruptions [1]. Further, Dewoolkar et al. (2009) provided valuable insights into the use of hands-on learning in GEE [8]. Townsend (2005) highlighted the challenges faced by GEE in the United States and emphasized the need for graduate education programs to keep up with modern developments [9]. Table 1 summarizes the literature highlighting the current challenges and pertinent solutions for GEE in promoting active learning. Overall, the literature emphasizes the use of modern tools and technologies to deal with the looming challenges of GEE posed by the modern era in teaching and learning in order to promote flexible learning.

Table 1. Overview of the literature on GEE.

Year	Challenges	Solutions	References
1991	Inadequate coverage of geotechnical engineering in undergraduate civil engineering programs.	Collaboration between academia and industry and the implementation of modern tools	[10]
2007	Insufficient incorporation of digital image analysis in GEE.	Incorporation of digital image analysis in the geotechnical engineering curriculum.	[2]
2009	Limited opportunities for hands-on learning in GEE.	Implementation of modern tools and strategies and ABET outcomes.	[8]
2013	Difficulty in fostering critical thinking in GEE.	Creation of environments that foster critical thinking with a modern approach such as Geo-EFFECTs.	[6]
2017	Inadequate preparation of undergraduate geotechnical engineering students for 21st-century challenges.	Incorporation of modern technologies, field experience, and problem-based learning.	[7]
2019	Underutilization of unsaturated soil mechanics in geotechnical engineering practice.	Increased education and awareness of unsaturated soil mechanics among geotechnical students by using animations.	[11]
2021	Disruptions to geotechnical and geo-environmental engineering education caused by the COVID-19 pandemic.	Implementation of remote learning technologies, such as online lectures and virtual laboratories.	[1]
2021	Inadequate development of teamwork and project management skills in GEE.	Integration of project-based learning and cooperative learning strategies using modern tools.	[3]
2023	Difficulty in promoting engagement and understanding	Development of instructional modules to promote "aha" moments in geotechnical engineering courses by using modern technologies.	[4]

3.2. Overview of Technology-Enhanced Learning in GEE

Technology has a significant impact on the field of education, including GEE, and TEL has become an increasingly adopted practice in GEE [12]. TEL has become popular, since it provides an opportunity to improve the quality of education and make it more engaging for students through the support it provides to active learning designs. This article identified different types of TEL increasingly used in GEE, including presentation tools, simulation tools, computational tools, augmented reality, virtual reality, and online resources.

Presentation tools are an essential component of TEL in GEE, the most frequent tools utilized across disciplines. Lectures, presentations, and other educational materials can be delivered using these tools. In GEE, creating and delivering engaging presentations using presentation software such as PowerPoint, Prezi, and Google Slides is typical. In order to make the learning process in GEE more interactive, these tools enable instructors to include multimedia components such as videos, images, and audio. A different class of TEL tools that are frequently used in GEE is simulation software resources. These resources enable students to simulate real-world scenarios and use their knowledge to address engineering issues. Technology for geotechnical-specific simulations has been revolutionized by the use of finite element modeling and the establishment of constitutive models for soils. A common practice in GEE is to simulate the behavior of soils and structures under various conditions using simulation tools such as Plaxis, Abaqus, GeoStudio, discrete element modeling tools, and other finite modeling tools [13,14]. These tools offer students a practical learning experience that aids in their comprehension of the applications of geotechnical engineering concepts in real-world situations. They also prompt mistake-induced feedback, allowing students to learn more effectively [15]. The use of physical simulation tools such as centrifuge modeling and other physical modeling techniques that are not used in conventional soil testing has also proven to be effective in providing students with first-hand experience with geotechnical engineering-related real-world problems [4,16–19]. A significant portion of TEL in GEE also includes computational tools. These tools support students in performing intricate calculations and data analysis [20]. The use of computational tools such as MATLAB, computer languages, Excel, and ANSYS to handle numerical problems and perform finite element analyses is well documented in the literature [21,22]. These resources aid students in developing a deeper comprehension of the mathematical ideas underlying geotechnical engineering. Additionally, emerging technologies such as augmented reality (AR) and virtual reality (VR) are being used more frequently in GEE [23]. Students can experience virtual worlds that replicate real-world scenarios using AR and VR tools. AR tools such as GeoAR and CivilView allow students to view and manipulate 3D models of structures and geological formations in real-time, which are critical topics in GEE [24,25]. VR tools such as GeoExplorers and GeoSimVR provide students with immersive learning experiences that allow them to explore geotechnical engineering concepts in a virtual environment. Other modern tools such as digital image analyses and artificial intelligence-based tools have also proven to be effective in enhancing active learning in GEE [21,26]. In addition, the implementation of virtual experiments to give an overview of the laboratory tests to the students is in practice in GEE, and many researchers have worked to establish different virtual experimentation tools [5,27,28]. Online resources are another important aspect of TEL in GEE [9]. These resources include online textbooks, lecture videos, online courses, and interactive tutorials [1]. Table 2 presents a list of useful online resources that provide students with access to high-quality geotechnical engineering learning forums from top universities around the world. Online resources, including information and communication technologies, streaming platforms, social media, and websites owned by different universities, provide students with access to free instructional videos that cover a wide range of geotechnical engineering topics [29,30]. Overall, TEL has become an essential part of GEE. Tools for presentations, simulations, computation, augmented reality, virtual reality, and online resources all have a part to play in raising the standards of education and making them more interesting for students. New tools and technologies are likely to emerge as technology develops, improving the learning experience of students for geotechnical engineering.

Table 2. Important online resource information for GEE.

Platform	University/Institution	Learning Forums	Web Link
Continuing and Professional Education	University of California, Berkeley	Construction Materials, Soil Mechanics	https://extension.berkeley.edu/ (accessed on 1 February 2023)
Coursera	Various universities/institutions	Earthquakes, Mechanics of Materials, Soil Mechanics,	https://www.coursera.org/ (accessed on 1 February 2023)
edX	Various universities/institutions	Geology and Engineering Geology, Soil Mechanics Fundamentals,	https://www.edx.org/ (accessed on 1 February 2023)
Engineering Online	North Carolina State University	Geotechnical Engineering, Soil Mechanics and Foundation Design	https://engineeringonline.ncsu.edu/ (accessed on 1 February 2023)

Table 2. *Cont.*

Platform	University/Institution	Learning Forums	Web Link
Future Learn	The Open University, the University of Southampton, University of Leeds and others	Soil Science, Thawing Permafrost	https://www.futurelearn.com/ (accessed on 1 February 2023)
Geo-Institute	American Society of Civil Engineers	Geotechnical Engineering, Foundation Design, Earthquake Engineering	https://www.geoinstitute.org/ (accessed on 1 February 2023)
Geotechpedia	Misc. institutions	Geotechnical Engineering, Earthquake Engineering, Soil Mechanics	https://www.geotechpedia.com/ (accessed on 1 February 2023)
ISSMGE	Misc. institutions	Geotechnical Engineering, Advanced Soil Mechanics, Earth Retaining Structures, Soil Dynamics, and other related topics	https://www.issmge.org/ (accessed on 3 May 2023)
LinkedIn Learning	Misc. institutions	Foundations of Structural Geology, Civil Engineering Foundations, Expansive soils, Stabilized Earth, Roads, and Railways Construction Earthworks	https://www.linkedin.com/learning/ (accessed on 1 February 2023)
MIT Open Course Ware	Massachusetts Institute of Technology (MIT)	Soil Behavior, Geotechnical Site Characterization, Earthquake Engineering, Elasticity, and Plasticity	https://ocw.mit.edu/index.htm (accessed on 1 February 2023)
NPTEL	Indian Institute of Technology (IIT)	Geotechnical Earthquake Engineering, Soil Mechanics, Foundation Engineering, etc.	https://nptel.ac.in/ (accessed on 1 February 2023)
Open Learning	University of New South Wales, London Metropolitan University	Highway Engineering	https://www.openlearning.com/ (accessed on 1 February 2023)
Skillshare	Misc. institutions	Engineering Mechanics	https://www.skillshare.com/ (accessed on 1 February 2023)
SoilModels	Alert Geomaterials research group	Constitutive Modeling	https://soilmodels.com/ (accessed on 1 February 2023)
Teachable	Misc. institutions	Earthquake Engineering	https://teachable.com/ (accessed on 1 February 2023)
Udacity	Private for-profit organization	Engineering Mechanics	https://www.udacity.com/ (accessed on 1 February 2023)
Udemy	Misc. institutions	Geotechnical Engineering Fundamentals, Advanced Soil Mechanics, Earth-Retaining Structures	https://www.udemy.com/ (accessed on 1 February 2023)
YouTube	Misc. Channels	Geotechnical Engineering, Soil Mechanics, Theory, and Testing	https://www.youtube.com/ (accessed on 3 May 2023)

The student-centered approach has been proposed in numerous studies as a way to increase student engagement and learning outcomes through TEL in GEE. In combination with conventional teaching techniques, the approach makes use of a number of tools, including case studies, videos, e-learning, and demonstration models. The literature demonstrates that TEL can offer students more interactive, interesting, and productive learning experiences. For instance, the use of a digital image analysis can help students visualize and analyze soil samples and geological features, which may not be possible with traditional methods [2,31]. Similarly, students can explore various scenarios and simulate complex geotechnical phenomena using centrifuge modeling and DEM simulations, which may not be possible in conventional experiments [19]. Additionally, computer-aided learning systems offer students individualized comments and directions on the designs of foundations and other geotechnical structures [1]. Furthermore, the literature emphasizes the significance of active learning teaching techniques in GEE through TEL, such as peer instruction, problem-based learning, and flipped classrooms [4]. These techniques can motivate students to actively participate in their education, collaborate with their peers, and use their knowledge to address current issues. Additionally, the literature contends that cutting-edge technologies such as data-driven site characterization techniques, augmented reality, and digital learning platforms have the potential to revolutionize GEE [24]. Augmented reality can provide students with immersive and interactive learning experiences by overlaying virtual models in real-world environments. Digital learning platforms can facilitate self-paced learning, collaboration, and assessments [12], while data-driven site characterization methods can provide more accurate and efficient ways to assess soil properties and site conditions [31]. Overall, the literature underscores the need to embrace TEL in GEE to produce well-rounded, skilled, and innovative professionals who can tackle the challenges of the field [15]. Table 3 presents an overview of the published literature in journals on the implementation of different TEL tools in GEE and their impacts on teaching and learning.

Table 3. Research status of TEL implementation in GEE based on pertinent published journal articles.

Year	TEL Tools	Impact on Teaching/Learning in GEE	Reference
1998	Computer-aided learning system for foundation design	Improved understanding and visualization of foundation design	[21]
1999	Computer-aided teaching for effective stress	The mistake-induced dialogue was generated by a computer-aided program to provide progressive and instant feedback to students	[16]
2003	Centrifuge modeling	Enhanced understanding of soil behavior and geotechnical engineering principles	[17]
2003	Geotechnical Virtual Laboratory (Permeability)	Improved student engagement and understanding of permeability	[27]
2005	Geotechnical Virtual Laboratory (Consolidation)	Improved student engagement and understanding of the consolidation	[28]
2005	Online resource for virtual geotechnical earthquake testing	The online resource is determined to be beneficial and effective based on a created education assessment framework and compiled student feedback.	[29]
2006	Geotechnical physical modeling	Enhanced understanding of soil behavior and geotechnical engineering principles	[18]
2007	Digital image analysis	Improved visualization and understanding of soil behavior	[2]
2007	Microsoft Excel for pile foundation design	Improved understanding of foundation design and data analysis	[22]
2010	DEM simulations	Improved visualization and understanding of soil behavior	[13]
2013	Integration of centrifuge testing in undergraduate education	Enhanced understanding of soil behavior and geotechnical engineering principles	[19]
2014	Finite element simulation for computer-aided simulation	An efficient simulation tool was developed for teaching Mohr's circle concept to students	[14]
2015	Information and communication technologies	Highly satisfactory for students in terms of active learning; good feedback was received	[30]
2019	Augmented reality	Improved visualization and understanding of geotechnical engineering principles	[24]
2020	Online resources, virtual field trips and simulations	Well-rounded GEE incorporating both theoretical and practical knowledge	[15]
2021	Educational interactive LabVIEW simulations	Improved visualization and understanding of hydraulic conductivity tests	[5]
2021	Online resources and virtual labs	Identified challenges and solutions in geotechnical and geo-environmental engineering education	[1]

Table 3. *Cont.*

Year	TEL Tools	Impact on Teaching/Learning in GEE	Reference
2022	Educational modules demonstrating soil moisture measurement and regulation	Improved understanding of soil behavior and practical applications	[23]
2023	Instructional modules to create “aha moments”	Enhanced student engagement and understanding of geotechnical engineering principles through physical model simulations and online resources	[4]
2023	Digital teaching in geotechnics	Improved accessibility and flexibility in GEE	[12]
2023	Data-driven site characterization methods	Improved understanding and analysis of site characterization methods	[31]

3.3. Analysis of Published Literature

In this study, a frequency analysis of published journal articles pertaining to TEL in GEE was conducted by developing a coding scheme. This analysis was based on several essential aspects such as publication information, adopted tools, and trends based on the cooccurrence of keywords in the existing database. These analyses were conducted to analyze the trends in the literature on TEL in GEE. In this regard, the analysis of publications by year revealed that the significance of TEL in GEE was recognized in the literature during the early 1990s (Figure 3). However, the majority of research conducted on various trends and techniques of TEL and their impact on teaching and learning in GEE has been carried out in the last two decades. The upsurge in research in the last few years could be related to the post-COVID scenario, which urged the implementation of TEL in the education sector. Further, the analysis of journal-wise publication records showed that publications on TEL in GEE could mainly be found in Education-related journals. There is an urge for more publications in geotechnical engineering or technology-based journals to reach out to the pertinent readership in the geotechnical engineering domain and provide them more insight into this topic (Figure 4). In addition, publishing in geotechnical engineering or technology-based journals can help to establish TEL in geotechnical engineering as a legitimate area of research and practice and encourage further investment and development in this field. This can ultimately lead to the development of new tools, techniques, and technologies that can improve GEE. The analysis of the country-wise distribution of the first authors in journal publications on TEL in GEE revealed that the United States is the leading country in the research and implementation of TEL in GEE (Figure 5). Meanwhile, as per the affiliated distribution of the first academic author, the University of Alberta, Southern Methodist University, and the Gaziantep University have published more frequent research publications in the domain of TEL implementation in GEE (Figure 6).

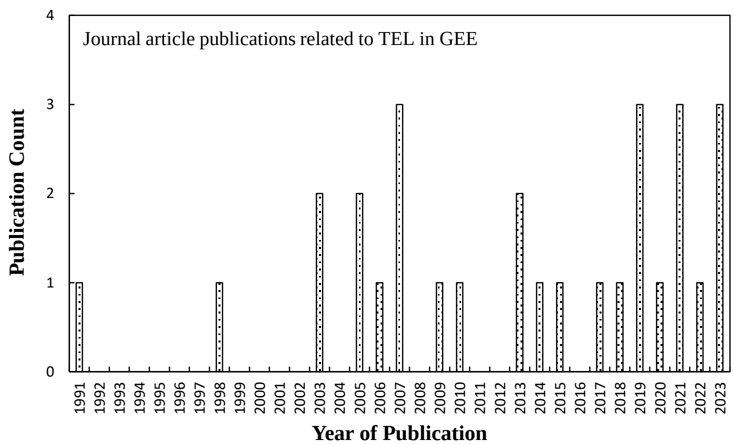

Figure 3. Year-wise journal publication analysis of TEL in GEE.

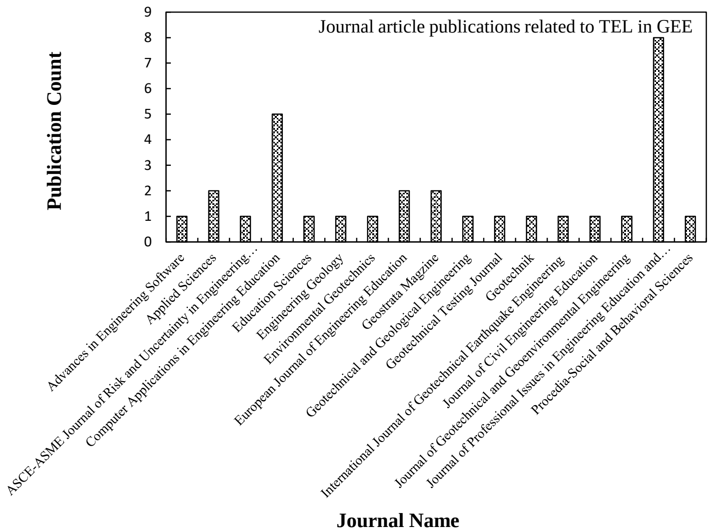

Figure 4. Journal-wise journal publication analysis of TEL in GEE.

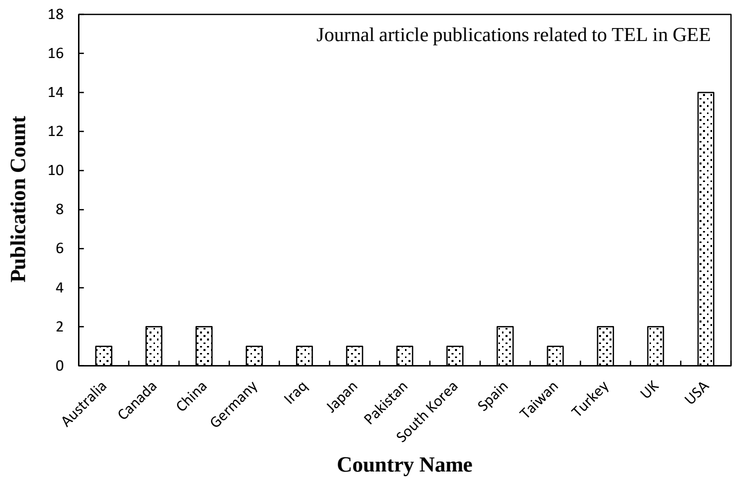

Figure 5. Country-wise journal publication analysis of TEL in GEE.

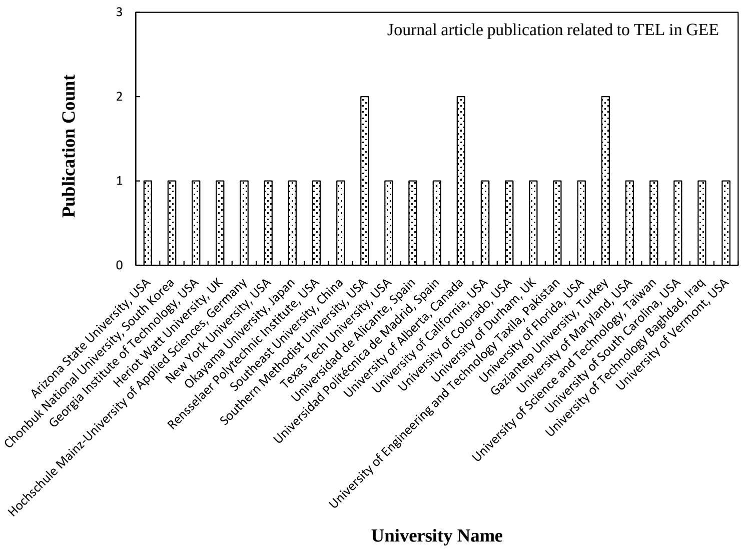

Figure 6. University-wise journal publication analysis of TEL in GEE.

The analysis of the journal publication database further indicates the trends of TEL in GEE. It is observed that simulations, collectively including computer-aided simulations, gaming and interactive simulations (25%), are the leading TEL tools, followed by virtual laboratory and field experimentations using simulation and computation technologies (20%), online resources and information communication technologies (15%), centrifuge modeling (15%), physical simulation (10%), augmented/virtual reality (10%), and efficient computational tools (5%) (Figure 7). Based on these data, it can be further analyzed that computer-based TEL tools are the most implemented and researched in terms of publishable data (50%), followed by physical (25%), internet-based (20%), and mobile-based (5%) TEL tools in GEE (Figure 8). Moreover, to conduct a thorough analysis of the database utilized for this study, the cooccurrence of the keywords and fields of study was taken into consideration, as indicated by various research studies. To achieve this, VOSviewer software was employed to visualize the cooccurrence analysis of the keywords pertaining to publication. Through an analysis of all articles cited in the current review, approximately 178 keywords were examined by establishing a low cooccurrence level (Figure 9). The results of the analysis indicated that GEE, instructional software, physical modeling, computer-aided learning, digital technique, remote laboratories, mobile applications, curriculum, and soil mechanics were the primary keywords found in the published literature. Furthermore, a year-wise examination of a TEL investigation in the GEE field disclosed a shift from physical modeling and computer-based software to virtual laboratories, and currently, the emphasis is more on online resources and mobile-based virtual reality tools.

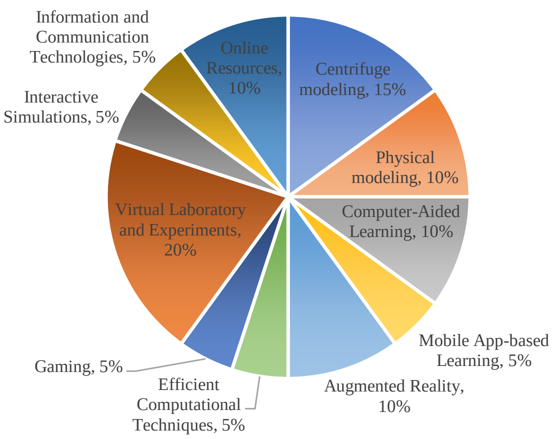

Figure 7. TEL-related teaching and learning tools in the published literature.

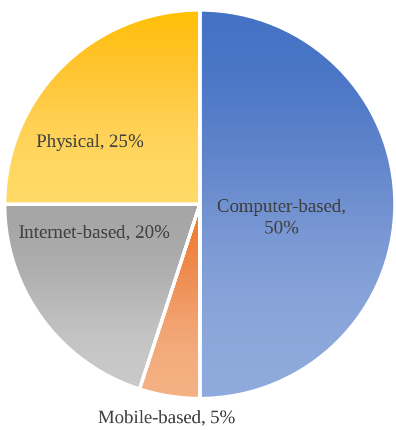

Figure 8. Classification of the nature of TEL-related tools in the published literature.

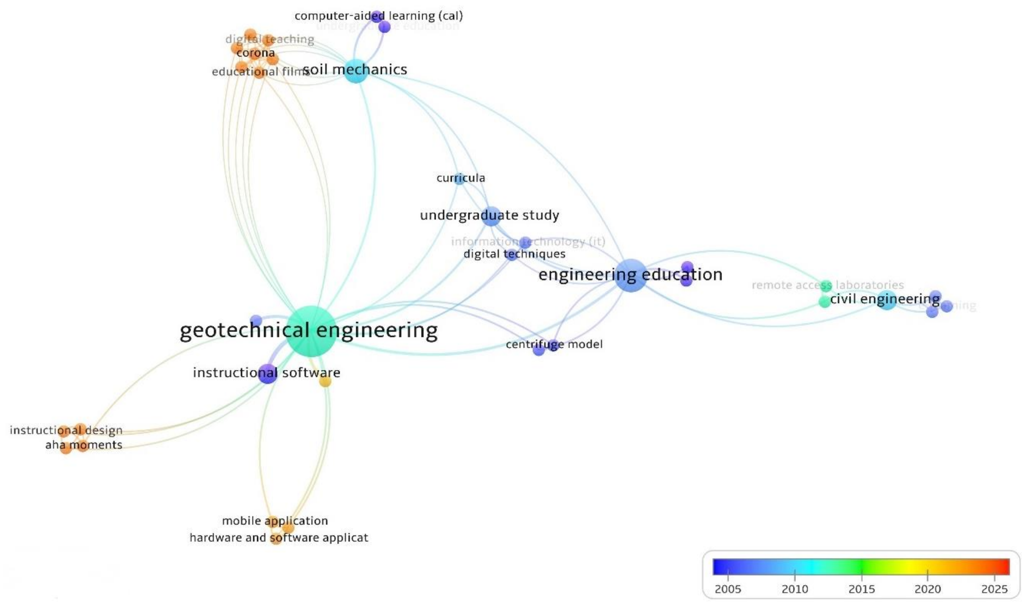

Figure 9. Overlay visualization of a network of keywords that cooccur within the finalized literature database.

4. Discussion

4.1. Trends of Technology-Enhanced Learning in Geotechnical Engineering

Geotechnical Engineering is undergoing significant technological advancements similar to other engineering disciplines, and the application of TEL is becoming increasingly popular in GEE. The use of digital image analyses, physical model simulations, finite element implementation, the usage and development of online resources, and computer-aided learning programs are some of the emerging technologies that are being utilized to improve the teaching and learning experience in GEE, along with conventional technologies used for enhanced learning. The use of instructional modules and project-based learning strategies in combination with TEL is also gaining momentum in GEE. The pandemic has accelerated the shift towards online learning and has led to the development of new TEL-based approaches to teaching geotechnical engineering.

One of the most significant trends of TEL in GEE is the use of digital tools and platforms. These include virtual and augmented reality, computer simulations, and geotechnical software. Ref. [6] contended that TEL can facilitate critical thinking and problem-solving skills by creating engaging and interactive learning environments in GEE. For instance, virtual and augmented reality tools can help students visualize complex concepts such as soil mechanics and groundwater flow. Virtual and augmented reality tools are used to simulate real-world scenarios and enhance the learning experience. With the aid of these resources, students can investigate intricate geotechnical and structural systems such as tunnels, dams, and rock and soil formations in a secure and engaging setting. Additionally, GEE has adopted virtual laboratory experiments and fieldwork simulation tools, giving students the experience of experiments without the associated expenses and logistical difficulties. Specifically, virtual experiments and field trips can help students better understand how soil properties and mechanics affect the design and construction of geotechnical structures in a more convenient way. In this regard, to give students a more interesting and interactive learning experience, ref. [7] suggested using virtual field trips. Further, to help students apply their theoretical knowledge to real-world geotechnical engineering problems, computer software, finite element, and discrete element modeling techniques can be used to generate digital simulations that simulate real-world situations. Furthermore, geotechnical software can support data analysis and modeling, improving the caliber and accuracy of outcomes. A variety of geotechnical engineering subjects such as soil mechanics, foundation design, and slope stability can be taught using digital or computer simulations. Additionally, they can aid students in developing a more thorough understanding of how various factors, such as soil characteristics and loading conditions, affect the behavior of geotechnical structures. Gamification is another critical trend that involves the use of game-like components, points, and leaderboards to engage and motivate learners in GEE. In the context of TEL, gamification can be integrated with simulation tools and can be used to simulate real-world engineering problems and give students a fun and safe environment to practice their problem-solving abilities. This method can enhance learning by making it more engaging and interactive and aid in students' understanding of complex ideas in a fun environment. For example, students can be engaged to design a hypothetical geotechnical structure using any pertinent technological tool by awarding them points for meeting certain criteria and establishing the leaderboard and deductions for mistakes.

The application of virtual and augmented reality is one of the key themes of TEL in GEE. Ref. [6] proposed an immersive learning platform that uses virtual reality to recreate various field conditions for students of geotechnical engineering directed towards critical thinking development. The usage of virtual field trips was also recommended by [7] as a way to give students a more interesting and participatory learning experience. Students can learn complex ideas more effectively by using virtual and augmented reality, which can also aid in the development of critical thinking abilities. Another piece of technology that is frequently utilized to improve teaching and learning in GEE is virtual laboratory testing [27,28] to minimize the overdependence on physical laboratories without compromising learning standards.

The use of physical modeling and digital image analyses to comprehend diverse fundamental theoretical and experimental principles in geotechnical engineering is a significant and newly emerging trend in TEL in GEE. Particularly in soil mechanics, foundation engineering, and seismic engineering, digital image analysis is utilized to supplement conventional laboratory investigations. A digital image analysis makes it easier and less invasive to observe and examine soil samples and eliminates the need for physical experimentation and soil sampling. Students can perceive changes in soil behavior over time by using a digital image analysis through real-time examination. It has been demonstrated that this technique is useful for teaching the fundamental principles of geotechnical engineering [2]. Further, in the teaching of GEE, physical modeling—primarily centrifuge modeling—has also been utilized to deliver complex and crucial concepts such as slope stability, foundation stability, and geohazards such as landslides and rainfall-induced geotechnical failures.

The usage of online learning tools and materials is another TEL trend in GEE. Nowadays, online learning is more crucial than ever owing to the COVID-19 epidemic. In this regard, ref. [1] recommended adjusting to the changing conditions by employing online tools and platforms in GEE. Online platforms offer students a flexible and practical way to access course materials and engage with instructors and peers, regardless of their location and time zone. Additionally, they can encourage personalized learning by letting students learn at their own pace and concentrate on the areas where they require more help. Moreover, online learning platforms can give teachers data and analytics on student performances, allowing them to spot problem areas and modify their teaching strategies accordingly. Additionally, the beneficial use of social media platforms in GEE has also been shown in a few studies, and this is because it encourages students to engage in active learning [30]. In general, online learning materials increase the affordability and accessibility of education while allowing students to learn at their own pace and on their own schedule, which is very crucial for GEE, since it involves a lot of theoretical and practical assignments, simultaneously making it non-flexible in terms of the schedule in a physical classroom setting.

A few educators and researchers have also combined TEL with project-based learning, problem-based learning, and cooperative learning in GEE. In this regard, the application of TEL with project-based learning, which involves students working on design projects that require them to apply the knowledge and skills they have learned in class, is growing in popularity in GEE [3]. With the help of this method, students gain real-world experience, develop problem-solving abilities, and become better-equipped to handle the demands of the workplace. Meanwhile, project-based learning in geotechnical engineering can be facilitated by digital resources and technologies such as collaboration software, project management platforms, and data analysis tools, allowing students to work on projects remotely and engage with peers and mentors virtually.

4.2. Benefits of Technology-Enhanced Learning in Geotechnical Engineering

This literature review also identified several advantages that TEL imparts to GEE. The facilitation of learning activities that enhance critical thinking among students is one of the key advantages. Ref. [6] underlined the value of developing critical thinking abilities among students undertaking GEE and emphasized the effectiveness of TEL as a means of support during this process. TEL also has the potential to assist students in improving their analytical and problem-solving skills by giving them access to digital resources and interactive learning materials. Giving students practical learning experiences in a flexible manner is another advantage of TEL in GEE. Ref. [8] investigated the usage of TEL in GEE hands-on modules and discovered that this strategy was successful in facilitating student engagement and content comprehension. For students to learn geotechnical engineering ideas realistically, TEL can offer virtual simulations, interactive lab assignments, and other digital tools. TEL may make it easier to communicate theoretical ideas in GEE. For instance, ref. [2] looked into the application of digital image analyses in GEE and discovered that this method was successful in assisting students in comprehending theoretical ideas concerning soil mechanics. In a similar way, ref. [13] investigated the use of DEM simulations in geotechnical earthquake engineering teaching and discovered that this method was successful in aiding students in visualizing and comprehending difficult ideas connected to earthquake engineering. There are numerous potential advantages for TEL in GEE, but there are also certain limitations to consider for optimization. For instance, ref. [7] pointed out the necessity for geotechnical engineering instructors to create efficient TEL campaigns that enthuse and inspire students. Moreover, ref. [11] pointed out that, in order to successfully integrate TEL into teaching, geotechnical engineering instructors must keep up with the developing technology. The COVID-19 pandemic has also highlighted the importance of TEL in GEE. Ref. [7] discussed the challenges faced by geotechnical engineering educators during the pandemic, including the need to rapidly adapt to online teaching methods. They emphasized the importance of using TEL to facilitate remote learning and maintain student engagement during this difficult time.

Overall, TEL has the potential to revolutionize GEE by facilitating learners in designated learning activities that promote critical thinking, provide hands-on learning opportunities, and enhance the delivery of theoretical concepts. Meanwhile, there are challenges associated with TEL in GEE, and these can be overcome through effective TEL strategies and a commitment to staying up to date on emerging technologies. As geotechnical engineering continues to evolve, it will be important for educators to embrace TEL. The reported advantages of TEL employment in GEE possess broader applicability in STEM education and related disciplines, since GEE encompasses the essence of all of these fields [32]. TEL has the potential to dynamically support learners in designated learning activities that support critical thinking development, augment analytical and problem-solving proficiencies, furnish experiential learning opportunities, and facilitate the dissemination of theoretical constructs in STEM, analogous to its utility in GEE. Additionally, TEL can engage and motivate students and help educators stay up to date on emerging technologies and trends. These benefits are not exclusive to GEE and can be applied to other disciplines as well.

4.3. Challenges and Solutions of Technology-Enhanced Learning in Geotechnical Engineering

TEL is increasingly being adopted in the field of GEE; however, the adoption of TEL also brings with it a number of challenges. The literature indicates that one of the main challenges is support in creating an environment that fosters effective critical thinking through TEL. One of the major challenges is the difficulty in integrating TEL into the traditional geotechnical engineering curriculum. Geotechnical engineering courses often involve hands-on laboratory experiments and fieldwork, which can be difficult to replicate in an online or virtual environment. Thus, instructors may struggle to design TEL activities that supplement traditional teaching methods and align with the course objectives. Ref. [8] argued that hands-on laboratory experience is necessary for students to develop a comprehensive understanding of geotechnical engineering concepts, and TEL should be used to enhance the hands-on experience rather than restrict it. A blended approach must be adopted where students get the experience of virtual laboratories, as well as hands-on experience in physical laboratories. Ref. [4] proposed the development of instructional modules based on a blended approach of TEL and hands-on experience that can create "aha moments" in geotechnical engineering courses, thereby enhancing student engagement. Meanwhile, many geotechnical engineering programs lack sufficient laboratory resources to provide such practical experiences. Therefore, TEL methods that can simulate real-world scenarios for such geotechnical engineering courses must be developed to offer students the opportunity for practical learning. Ref. [2] proposed digital image analysis as a TEL method that can be used in GEE to analyze soil samples and rock textures, thereby giving students practical experience in analyzing geological structures.

Another challenge of TEL in GEE is the limited availability of experienced instructors. Instructors may lack the necessary skills and knowledge to develop and deliver TEL activities, while students may struggle to navigate the online platforms and tools used in TEL activities; thus, there is a need for specialized training for both instructors and students [1]. Ref. [9] argued that the shortage of experienced geotechnical engineers in academia that can promote the usage of TEL in GEE is a major challenge. The requirement for specific expertise in several geotechnical engineering subdisciplines to apply TEL in GEE successfully exacerbates this issue. The utilization of digital learning systems that may offer virtual classes and enable instructors and students to communicate with geotechnical engineering specialists from across the world was suggested by [12] as a solution to this problem. According to the literature, things are rapidly improving in terms of applying TEL in GEE because of the needs of the present day and COVID-19 imperatives [1]. On the other hand, the pandemic has brought forth modern challenges for TEL in GEE, including the requirements for distant learning and the absence of on-campus lab resources. Consequently, alternative teaching strategies and the usage of simulation software to provide students with virtual laboratory experiences are now required.

The requirements for continuous course content updates and the linking of TEL with course contents present another issue for TEL in GEE. Ref. [7] contended that, in order to guarantee that students have the necessary abilities, educators must constantly update the course content due to the rapid pace of technological advancements in geotechnical engineering. For instructors, especially those without prior academic or industry experience, the requirements for constant updates can be intimidating. To overcome this difficulty, ref. [11] advocated the necessity of industry and academic cooperation, which can result in the creation of curricula that are pertinent to business requirements.

Moreover, the pedagogical challenges associated with integrating TEL in GEE go beyond technological challenges. For instance, all technology supported learning activities may not be as effective at promoting critical thinking, collaboration, and problem-solving skills as traditional classroom instruction. On the other hand, the optimization of teaching pedagogies with TEL is another critical aspect in GEE that involves the intentional selection, design, and implementation of pedagogies that are best suited to meet the specific needs and goals of learners. Moreover, the lack of social interaction and face-to-face communication in TEL activities may hinder students' ability to develop relationships with their peers and instructors. Finally, TEL activities may not be equally accessible to all students due to factors such as socioeconomic status, language barriers, and disabilities. Instructors must ensure that TEL activities are inclusive and accessible to all students to prevent the marginalization of certain groups. Further, the word "enhanced" in TEL needs to be well quantified in GEE; thus, more research needs to be done on the effectiveness of TEL in GEE, since limited literature is currently available. Moreover, more research needs to be done on the effectiveness of less-focused modern technologies such as artificial intelligence, cloud computing, and virtual and augmented reality in teaching and learning GEE to promote these technologies. In addition, despite the potential benefits of TEL in GEE, there is a dearth of research exploring the impact of TEL on student experiences and learning outcomes in this field. This is a significant gap in the literature, as understanding student experiences and the impact of TEL on learning outcomes is essential for developing effective teaching strategies and improving the quality of GEE. To address this gap, more research needs to be conducted centered around student experiences and learning outcomes. This entails scrutinizing the advantages of incorporating TEL in GEE and making comparisons between students' experiences in GEE with and without TEL integration.

Moreover, most of the challenges identified in the adoption of TEL in GEE are not unique to this field but are common in other education fields, particularly STEM [32,33]. The challenges of integrating TEL into the curriculum that are taught by conventional teaching methods and providing a blended approach that combines virtual and physical experiences are prevalent in STEM fields, where laboratory experiments and hands-on experiences are often required. Similar to GEE, the lack of resources, experienced instructors, and continuous updating of course contents are also major challenges in STEM [32,33]. Additionally, the need to ensure that TEL activities are inclusive and accessible to all students and the lack of research on the effectiveness of TEL based on student experiences and learning outcomes are challenges across all educational fields.

In general, the optimization of teaching pedagogies, linkage with course contents, and augmentation of student learning experiences have been identified as the key factors for the successful implementation of TEL in GEE. In this regard, to effectively implement TEL in GEE or STEM education, this study proposes an intuitive quadruple framework as a potential solution inspired by the outcome-based education (OBE) theory (as presented in Figure 10). Implementing TEL in a STEM or geotechnical engineering course requires careful planning and the consideration of various factors. The proposed process starts with identifying the learning outcome of the course and target levels of the cognitive, affective, and psychomotor domains. This helps in determining the potential technology tools or resources and level of implementation of TEL in teaching and learning. The subsequent phase encompasses the design of the course content and, accordingly, selection of the appropriate technology tools to achieve the learning outcome and target cognitive, affective, or psychomotor levels. The next phase is the determination of the level of integration of TEL in a course based on the optimization of critical thinking fostering, affective learning, active learning, blended learning, flipped classrooms, personalized learning, hands-on experience, and collaborative learning. This could range from simple integration, such as using online quizzes, simulations, computer-aided computations, and videos to supplement classroom teaching, to full integration, such as a completely online course, depending on the learning outcome and teaching pedagogies. Subsequently, TEL is implemented in a course on a real-world scale, and the necessary training and support are provided to the students to effectively use the technology. Finally, the effectiveness of the TEL is evaluated in the particular course. This could involve collecting feedback from students on their experiences with the technology tools and assessing whether the learning objectives were achieved. Based on evaluations and assessments, corrective measures could be designed for continuous improvement of the course and the implementation of TEL for the next cycle. Further, with continuous research, more effective and appropriate tools can be designed that can be implemented in GEE in particular and STEM education in general.

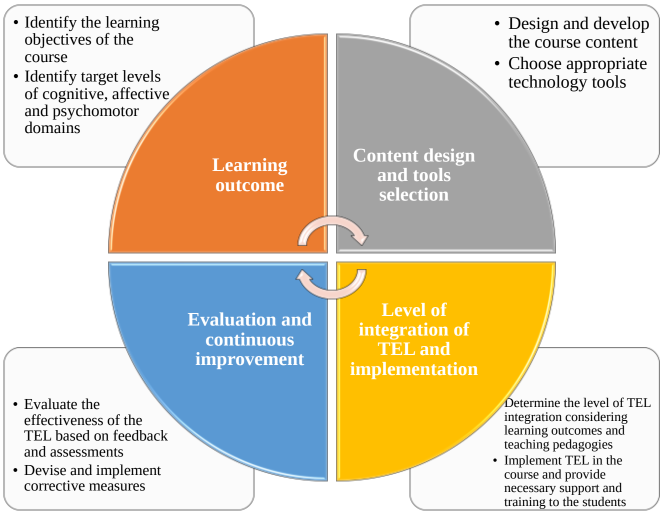

Figure 10. OBE-inspired quadruple framework of the efficient implementation of TEL in GEE.

5. Summary and Conclusions

This review paper provides an analysis of the implementation of technology-enhanced learning (TEL) in geotechnical engineering education (GEE) based on published journal/magazine articles. This paper presents a state-of-the-art review of TEL implementation in GEE, identifying major trends such as computer-based simulations, physical and centrifuge modeling, virtual laboratory and field experimentation, internet-based online resources, and virtual and augmented reality. This study highlights the benefits of TEL implementation in GEE, including the improved comprehension of complex concepts and enhanced readiness for professional practice. The analysis of the literature indicates a significant transformation of TEL in GEE over the past few decades. This evolution has resulted in a shift from physical modeling and computational software to more advanced TEL methods, such as virtual laboratory and computer-based simulations, augmented reality, and online resources. Furthermore, this paper suggests integrating TEL with instructional design strategies that involve project-based learning, hands-on experience, curriculum alignment, critical thinking development, and teacher and student experience augmentation as a promising approach to improve GEE. Meanwhile, this paper recognizes several challenges in TEL implementation in GEE, such as a lack of resources and difficulties in quantifying TEL's impact on GEE. To address these challenges, this paper proposes future perspectives, including continued research and development in this field. Finally, an outcome-based education (OBE) theory-inspired quadruple framework is proposed in this study for the effective implementation of TEL in GEE involving the identification of learning outcomes, selection of appropriate course contents and technology tools, the decision on the level of integration and subsequent implementation of TEL in the course, and the evaluation and continuous improvement. Overall, this paper provides valuable insights for researchers and educators interested in TEL implementation in GEE. Meanwhile, this paper has certain limitations—specifically, the scope of the study is restricted to an examination of TEL implementation in GEE based solely on a review of the published journal/magazine articles. Additionally, there exists a paucity of empirical evidence concerning the impact of TEL on students' learning outcomes in GEE, which could attribute to the limited pertinent published data. It is therefore suggested that further research be conducted to address these limitations while considering this study a foundational benchmark for future investigations and enhancements in this area.

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