

# Sustainable Geotechnics: A Review of the Integration of Technology, Material Innovation, and Socio-Economic Evaluation for Resilient Infrastructure

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## ARTICLE INFO

*Keywords:* Sustainable Geotechnics, IOT, Life Cycle Assessment, Bioremediation, Carbon Sequestration, Eco-Friendly Materials, Green Economy, Sustainable Development, Resilient Infrastructure

*Received :* 3 May

*Revised :* 20 June

*Accepted:* 20 July

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## ABSTRACT

Rapid urbanization and climate change pose significant challenges to conventional geotechnical practices, prompting the adoption of a sustainable geotechnical paradigm that integrates technical, environmental, social, and economic aspects into infrastructure planning. This article aims to examine the implementation, technological innovations, and socio-economic impacts of sustainable geotechnics amidst global demands. By using a qualitative literature review approach, approximately 60 selected scientific articles from publications between 2015 and 2025 are analyzed in depth to gain critical insights into related trends, techniques, and policies. The study results indicate that the integration of digital technology such as the Internet of Things (IoT) and artificial intelligence (AI) has improved project monitoring efficiency and supported data-driven decision making. Material innovations, such as the use of geopolymer from industrial waste, and the application of the reduce, reuse, recycle (3R) principles, have proven to significantly reduce carbon emissions and construction waste. Bioengineering and bioremediation approaches have also shown effectiveness in soil recovery and erosion control. The implementation of Life Cycle Assessment (LCA) and geological carbon sequestration technology further strengthens the contribution of geotechnics to sustainable development targets and climate change mitigation. Sustainable geotechnics has opened up opportunities for the creation of quality jobs and promoted a green economy

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## INTRODUCTION

Sustainable geotechnics has become an important pillar of modern development that pays attention to the balance of environmental, social, and economic factors. This approach not only involves traditional techniques in land and foundation management but also incorporates sustainability aspects to preserve the environment and meet the needs of future generations (Jonkman & Jansen, 2019). By considering sustainability principles, geotechnics offers more efficient and environmentally friendly solutions in addressing development challenges.

The global construction sector faces increasingly complex, ongoing challenges in the modern era, particularly in the context of climate change and rapid urbanization. The construction industry contributes to about 39% of global carbon emissions and consumes nearly 40% of the world's resources, creating a significant environmental footprint (Nyame & Adesanmi, 2024). In this context, sustainable geotechnics emerges as a discipline that integrates sustainability principles with conventional geotechnical engineering practices to create environmentally friendly, resource-efficient infrastructure solutions that support social well-being (Eze et al., 2024; Gooding, 2023).

The rapid global urbanization, with projections that 70% of the world's population will live in urban areas by 2050, puts immense pressure on urban land management and its supporting infrastructure (Harrison, 2025). This challenge is exacerbated by the impacts of climate change on geotechnical infrastructure, soil erosion, changes in rainfall patterns, and the threat of rising sea levels that affect the stability of geotechnical structures (Goldman, 2024). This condition demands innovative approaches in geotechnics that not only consider technical aspects but also environmental and socio-economic sustainability (Kandalai et al., 2023). The development of digital technology has opened up new opportunities for the application of sustainable geotechnics. The integration of technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analysis has been shown to improve project monitoring efficiency by up to 30% compared to conventional methods (Bassi, 2025; Firoozi & Firoozi, 2024; Oktavia & Nurkholis, 2022; Peiyuan et al., 2024). These technologies enable real-time monitoring of soil conditions, early prediction of potential structural failures, and optimization of resource use in geotechnical projects (Hendryarto & Suwandi, 2025; Y. Li et al., 2025).

This research aims to provide a comprehensive review of the implementation of sustainable geotechnics in the context of current global challenges. Specifically, this study will: (1) analyze the integration of sustainability principles in modern geotechnical practices, (2) evaluate the role of digital technology in supporting sustainable geotechnics (Y. Li et al., 2025), (3) identify material and environmentally friendly technique innovations in geotechnical applications, and (4) examine the socio-economic impacts of implementing sustainable geotechnics on infrastructure development (Song et al., 2025).

The novelty of this research lies in a holistic approach that integrates three dimensions of sustainability—environmental, economic, and social—in the

context of modern geotechnics. Unlike previous reviews that tend to focus solely on technical aspects, this study emphasizes: (1) the role of cutting-edge digital technologies such as IoT and AI in the transformation of sustainable geotechnical practices (Bassi, 2025; Lu et al., 2024), (2) a comprehensive analysis of bioengineering innovations and eco-friendly materials for soil stabilization (Mickovski, 2021), and (3) a systematic evaluation of the socio-economic impacts of sustainable geotechnical implementation, including the creation of quality jobs and the development of a green economy.

Another aspect of novelty is the emphasis on the importance of Life Cycle Assessment (LCA) in geotechnical projects as a tool to measure the comprehensive environmental impact from material extraction to final disposal (Dossche et al., 2017; Ebeh et al., 2024; Speranza et al., 2022). This research also presents a new perspective on carbon sequestration in the context of geotechnics, where geological CO<sub>2</sub> sequestration techniques can be an innovative solution for climate change mitigation through carbon storage in geological formations (Fentaw et al., 2024; Gooding, 2023; Jorat et al., 2017; Khalid, 2024; Massarweh & Abushaikha, 2024; A. Smith, 2023).

In addition, this research provides a unique contribution through an in-depth analysis of waste management in geotechnical projects by applying the principles of reduce, reuse, and recycle (3R), which has been shown to reduce waste production by up to 40% in large projects (Redford, 2025). The integration of this approach with IoT-based sensor monitoring technology creates a new framework for more efficient and sustainable geotechnical project management (Bassi, 2025).

## LITERATURE REVIEW

### 1 Scope of Sustainable Geotechnics

Sustainable geotechnics is a field of science that integrates geotechnical engineering with sustainability principles to create environmentally friendly infrastructure solutions that are resource-efficient and support social well-being. Unlike conventional geotechnical approaches, the sustainable approach focuses on responsible resource management and design that minimizes negative impacts on the environment. The primary goal of sustainable geotechnics is to create development that not only meets present needs but also does not compromise the capability of future generations to meet their needs. This approach is increasingly relevant in the modern era characterized by rapid urbanization and climate change (J. Smith & Brown, 2022).

Sustainable geotechnics encompasses various applications such as slope stabilization, environmentally friendly foundation design, and management of soil waste from construction projects (Przewłócki, 2021). Its scope also includes the use of recycled materials, energy sustainability analysis, and the application of technology for real-time soil condition monitoring. Innovations in geotechnical engineering not only mitigate environmental damage risks but also enhance the economic efficiency of large construction projects (Dossche et al., 2017). The use of geopolymer-based materials sourced from industrial waste is widely used as

a more environmentally friendly alternative to conventional concrete (Bekkouche et al., 2022).

The development of sustainable geotechnical methodology requires a deep understanding of the interaction between soil properties, water behavior, and the impact of human activities on it. In the context of infrastructure development, this approach ensures that technical design not only considers physical resilience but also long-term sustainability. This integrated approach also utilizes modern technologies such as geophysical scanning and big data analysis to more accurately predict the impact of projects on the environment. Data-driven technology plays a crucial role in supporting the concept of sustainable geotechnics (Samuelsson et al., 2024).

With the increasing complexity of environmental issues and pressures on natural resources, the scope of sustainable geotechnics is now expanding to various sectors, including transportation infrastructure, energy, and coastal protection. This not only demonstrates the flexibility of this method but also its relevance to various development contexts that require efficient, safe, and sustainable solutions. The integration of technical innovation and sustainability principles emphasizes the importance of this approach in ensuring that development is not only directly beneficial but also remains relevant and responsible in the long term (Song et al., 2025).

## **2. Principles of Sustainability in Geotechnics**

The application of sustainable geotechnics is based on principles that make efficiency, environmental protection, and social impact the main focus. Resource efficiency involves strategies to utilize renewable materials, energy-saving practices, and eco-friendly solutions. Environmental protection demands responsible construction waste management and the use of technology to reduce the carbon footprint of projects (Fentaw et al., 2024; A. Smith, 2023). In the context of social impact, these principles aim to ensure that infrastructure development considers the needs of the surrounding community and does not harm the socio-economic balance. The implementation of sustainability principles can reduce project waste by up to 30% through the use of recycled materials (Davis et al., 2021; Ogunseye et al., 2023).

The principle of efficiency in geotechnics involves optimizing designs to reduce the need for additional expensive resources or those that could harm the environment. Soil stabilization techniques using environmentally friendly chemicals have become a popular alternative to support sustainability (Bekkouche et al., 2022). Innovations in excavation and soil compaction techniques ensure that disruptions to the surrounding ecosystem can be minimized without compromising the technical performance of the constructed geotechnical structures (Jonkman & Jansen, 2019).

The aspect of environmental protection demands a holistic approach in geotechnical project management. This includes mapping erosion and landslide risks, controlling water flow to prevent ecosystem damage, and rehabilitation techniques for degraded land. These efforts are also reinforced by international policies that promote sustainability practices in the construction sector (Dossche et al., 2017; Song et al., 2020). Various engineering organizations have developed

guidelines that integrate these principles into design and implementation standards, making sustainability an integral part of the planning process (Samuelsson et al., 2024).

Sustainability is also closely related to technological innovation. The application of simulation software can model the environmental impacts of projects in detail, allowing for design improvements before field implementation (Harahap et al., 2024). Technologies such as smart sensors and drones assist in monitoring project conditions in real-time so that corrective measures can be taken earlier to minimize negative impacts (Y. Wang & Tian, 2024). This principle not only ensures safe and responsible outcomes but also provides efficiency in project implementation that supports long-term sustainability goals.

### **3. The Relevance of Geotechnics in Sustainable Development**

The relevance of geotechnics in sustainable development is becoming increasingly irreplaceable amid the rising demand for efficient and environmentally-friendly infrastructure. Geotechnics directly contributes to the management of soil and foundations needed to support various types of infrastructure, such as highways, dams, and skyscrapers (Sanei et al., 2025; Song et al., 2025). In every aspect, geotechnical engineering plays a key role in reducing the risk of structural failure, enhancing construction efficiency, and ensuring that the impact on the environment remains minimal (Dossche et al., 2017). Sustainable geotechnical engineering is capable of reducing carbon emissions from construction projects by up to 25% compared to conventional methods (Fentaw et al., 2024; Y. Wang et al., 2020; Zhu et al., 2025).

In the context of rapid urbanization, the relevance of geotechnics becomes increasingly evident in managing complex and dense urban land. The limited space in large cities requires innovative approaches to ensure that development is not only safe but also does not compromise the surrounding environment. Foundation techniques using porous materials help address drainage issues without causing local flooding (Song et al., 2025). This approach also supports green infrastructure, which is increasingly being applied in modern urban areas (Sanei et al., 2025). Geotechnics also contributes to sustainability through improved operational efficiency in infrastructure projects. This includes design optimization that reduces material needs, the use of soil compaction techniques to maximize stability, and construction waste management to support material recycling (Ogunseye et al., 2023). These sustainable approaches not only reduce project costs but also significantly mitigate negative environmental impacts. (Kara, 2025).

Relevansi geoteknik dalam pembangunan berkelanjutan mencakup penerapan prinsip ecology in the design and management of projects. Soil reclamation techniques with native vegetation restore disrupted ecosystem functions, while the utilization of renewable energy in this project reduces dependence on fossil resources. Geotechnics, besides being a tool to achieve technical goals, is also an instrument to promote broader global sustainability (D. Kumar, 2025).

## METHODOLOGY

The method in this article uses a qualitative literature review (QLR) approach (Susanto et al., 2024) to gain a deeper understanding of issues, findings, and current trends in sustainable geotechnics (Luft et al., 2022). This study refers to a non-systematic method that is interpretative and critically synthesizing (Gaborov et al., 2024). The entire process of searching, selecting, and analyzing articles is carried out with the aim of interpreting the diversity of discourse, approaches, and dynamics that have developed in the field over the past 10 years. The scientific articles reviewed were selected based on the relevance of the topic with a primary focus on practices, challenges, and innovations in sustainable geotechnics. The articles were obtained from various indexed publications and published within the last 10 years to ensure the novelty of the data and contextual relevance. A total of approximately 60 articles have been qualitatively analyzed to understand the approaches used, the strengths and limitations of the methods, and to formulate the contributions of this study to the development of sustainable geotechnical science. This qualitative analysis process includes the stages of identification, selection, relevance mapping, and synthesis of key findings in accordance with the practices recommended in qualitative research (W. M. Lim, 2024; Szajnfarber & Gralla, 2017).

The use of a qualitative literature review method offers advantages in obtaining a comprehensive and narrative picture related to the technical, social, and policy aspects emerging in this field of research, as well as allowing researchers to explore the relationships between variables and detect knowledge gaps for further studies (Carrera-Rivera et al., 2022; Susilawati et al., 2025). The validity of the results is enhanced by conducting a critical evaluation of the methodology, outcomes, and implications of each article, in accordance with the standards of credibility and dependability in qualitative research (W. M. Lim, 2024; Szajnfarber & Gralla, 2017). Thus, this approach not only reflects the latest research developments but also contributes theoretically and practically to enriching the discourse on sustainable geotechnics globally (Snyder, 2024).

## RESULTS

### 1. Environmental Challenges in Geotechnical Projects

Geotechnical projects face various environmental challenges that threaten the sustainability of development, including soil degradation due to intensive construction activities, such as excavation and compaction. This process often leads to soil erosion, loss of humus layers, and changes in soil structure that are important for the local ecosystem. Soil contamination from construction materials such as concrete and chemicals often becomes a major issue that requires sustainable mitigation strategies. About 40% of degraded soils due to construction projects in urban areas require intensive rehabilitation to restore their ecological functions (Dossche et al., 2017; Green et al., 2023).

Water pollution also poses a major challenge in geotechnical projects. Activities such as drilling and excavation result in chemical leaks into water bodies, negatively impacting aquatic life and drinking water quality. This issue is exacerbated by the lack of adequate wastewater management systems in many infrastructure projects. The construction of roads or dams often causes

sedimentation in rivers, reducing flow capacity and increasing the risk of flooding. These challenges require the implementation of technologies and designs that consider sustainability, such as the use of more environmentally safe soil barriers and natural filtration methods (Kara, 2025).

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In addition to technical and environmental challenges, there are regulatory barriers that limit the implementation of sustainable geotechnics. Many countries still lack specific guidelines for integrating sustainability principles into the design and execution of projects. This creates oversight gaps and ensures that every construction step aligns with sustainability goals (Song et al., 2020). Collaboration between the government, research institutions, and the private sector becomes crucial in facing these challenges. With strengthened regulations and increased awareness of the importance of sustainability, many environmental challenges in geotechnical projects can be managed more effectively (D. Kumar, 2025).

## **2. Socio-Economic Impacts of Sustainable Geotechnical Management**

Sustainable geotechnical management has a significant impact in both social and economic contexts, especially in creating a balance between development needs and sustainability (de Melo et al., 2023). From a social perspective, the implementation of sustainable geotechnics ensures that infrastructure projects do not harm surrounding communities but instead improve their quality of life. The use of recycled materials or minimally invasive techniques in construction can minimize disruption to local communities. Geotechnical projects with a sustainable approach increase community satisfaction by up to 35% compared to conventional methods (Ahmad et al., 2023; Song et al., 2020).

From a sustainable geotechnical economic perspective, it contributes to long-term construction cost reduction through the use of more efficient materials and designs (Song et al., 2020). Soil stabilization using natural materials such as coconut fibers or wood waste, which are not only cheaper but also available in large quantities in various developing countries (Bekkouche et al., 2022; Kara, 2025). The energy efficiency generated from the application of technologies such as smart sensors and planning software also helps reduce project operational costs. By minimizing environmental impact, projects can also avoid sanctions or fines that are often imposed due to violations of environmental regulations.

Sustainability in geotechnics helps create higher quality and innovative jobs. Sustainable projects involve cutting-edge technology and require special expertise, thereby encouraging the capacity building of the local workforce. The

development of environmentally friendly techniques opens new market opportunities for the sustainable materials sector and geotechnical technology. Companies offering bioengineering-based geotechnical solutions have seen a significant increase in demand over the past few years, indicating a great potential in the development of the green economy (Zhang et al., 2024).

The positive socio-economic impact further strengthens the urgency to widely adopt sustainable geotechnical approaches (Ahmad et al., 2023). In addition to helping reduce social gaps through fair infrastructure development, this approach also supports inclusive economic growth. These efforts reflect long-term benefits that are not only enjoyed by current generations but also by future generations. Strong collaboration between government, academia, and the private sector is needed to ensure that sustainable geotechnics can become the norm in every aspect of infrastructure development (J. Smith & Brown, 2022). The development of technology and innovation in geotechnics plays a crucial role in realizing sustainable construction practices (Dossche et al., 2017). The application of environmentally friendly materials, soil recovery techniques, digital technology, energy optimization, and innovations in waste management are the main focuses of these efforts (Y. Li et al., 2025; Y. Wang & Tian, 2024).

### **3. The Use of Environmentally Friendly Materials in Geotechnical Construction**

The development of technology in the construction field brings various innovations, one of which is the use of environmentally friendly materials (S. Wang et al., 2024). Materials such as natural fiber geotextiles, recycled concrete, and organic composites are the primary choices in supporting sustainability (de Melo et al., 2023). These materials are designed to reduce negative impacts on the environment while ensuring the strength and durability of the buildings. Recycled concrete has proven to have a high level of energy efficiency during the production process and is capable of significantly reducing construction waste (Ogunseye et al., 2023). The use of environmentally friendly materials also enhances project credibility as they meet global sustainability standards. Innovations in environmentally friendly construction materials are key to sustainable construction (Hendriansyah, 2020)..

The utilization of local materials also becomes an important focus in sustainable geotechnics. Materials such as bamboo, clay, or natural fibers that are easily found around the project site can reduce the carbon footprint from the transportation of materials. Local materials tend to be more compatible with the local environmental conditions, thus providing more optimal performance in the long run. The construction of roads using locally stabilized soil materials based on lime and cement has proven effective in enhancing soil stability while being environmentally friendly (Junata et al., 2024; M. Li et al., 2023; Zhu et al., 2025). These efforts not only support sustainability but also provide added economic value to the local community (de Melo et al., 2023).

Material processing also becomes an integral part of environmentally friendly geotechnical innovation. Advanced technology allows for the reduction of material waste through recycling and reuse processes (Rahgozar et al., 2018). The use of concrete aggregates from old building debris for new concrete mixtures. This process is capable of producing high-strength concrete with a

reduction in carbon emissions of about 50%. Innovative materials such as geopolymers are also becoming popular as they can provide strength similar to conventional concrete but using industrial waste materials like fly ash (Alaa Salim & Alaa H. J. Al-Rkaby, 2024; D. Kumar, 2025).

Regulations and rules become an important element that supports the use of environmentally friendly materials. Several countries including Indonesia have begun to implement sustainability certifications in the construction process. Certificates like Greenship and EDGE help ensure that the materials used in projects meet certain sustainability standards (J. Lim et al., 2025). This encourages manufacturers and contractors to innovate in creating materials that are not only strong but also environmentally friendly. This joint effort shows that the use of environmentally friendly materials is no longer an option but a necessity for sustainability (Alaa Salim & Alaa H. J. Al-Rkaby, 2024).

#### **4. Soil Recovery Techniques and Erosion Control**

Soil remediation is a vital aspect of sustainable geotechnics because soil degradation issues often arise due to uncontrolled construction activities. One commonly used technique is bioremediation, which is the recovery of soil using certain microorganisms to eliminate pollutants (Faruqi et al., 2023; Zhang et al., 2024). These microorganisms can break down hazardous chemicals into relatively simple compounds that are non-toxic. Phytoremediation, or the use of plants to absorb heavy metals in the soil, is also increasingly being applied. Phytoremediation techniques can reduce heavy metal concentrations by up to 70% within six months (Azarafza & Nyambayo, 2023; Mamat, 2020).

Erosion control is also a major challenge in geotechnical projects, especially in sloped areas or steep lands (Przewłócki, 2021). The use of geosynthetics such as geotextiles or geomats can enhance soil stability while preventing erosion. Geotextiles work by binding soil particles, while geomats help vegetation growth to create natural buffers. Terracing techniques in hilly areas have proven effective in controlling surface water flow, thus preventing landslides (Azarafza & Nyambayo, 2023; Iman et al., 2022).

The management of erosion based on modern technology has become an important innovation. Geographic Information Systems (GIS) are used to analyze erosion risk based on topographic and rainfall data in a certain area. With this data, engineers can create more precise designs to address potential soil damage before a project begins. An example is the use of GIS to determine which types of vegetation are most suitable for planting in a specific area to minimize erosion (Scharenbroch et al., 2022). Community approaches can also support soil recovery and erosion control programs. Involvement of local communities in land maintenance, tree planting, and building simple drainage systems can have a long-term impact on maintaining soil fertility. This approach not only restores environmental conditions but also raises community awareness of the importance of land preservation (Scharenbroch et al., 2022).

#### **5. Utilization of Digital Technology for Project Monitoring**

Digital technology brings significant changes to geotechnical project management, particularly in the sustainability monitoring of projects. IoT (Internet of Things) enables real-time field data collection through the use of

sensors installed in various construction elements (Bassi, 2025). These sensors continuously monitor soil pressure, humidity, and structural deformation. With this data, project teams can quickly identify potential issues and take corrective actions more rapidly (Y. Li et al., 2025). IoT-based technology improves efficiency by up to 30% compared to conventional methods in project monitoring (Mamat, 2020).

Drone is also one of the main tools in monitoring modern geotechnical projects. With aerial survey capabilities, drones can map topography and identify changes in land conditions that may occur during the construction process. This data is then processed using software such as CAD or BIM to produce accurate 3D models. These models not only assist in project visualization but also allow for environmental impact simulations of the chosen design (Y. Wang & Tian, 2024). The use of blockchain technology has begun to be introduced in project management to create transparency in the supply chain of materials and logistics. With blockchain, all data related to sourcing, delivery processes, and material installation is automatically recorded and immutable. This ensures that all materials used in the project meet sustainability standards (Y. Wang & Tian, 2024).

One of the latest implementations is the use of augmented reality (AR) for field inspections. AR technology allows field workers to visualize structures to be built virtually, making it easier to identify potential design errors. The integration of this technology makes project monitoring more efficient, accurate, and in line with sustainability principles (Rautmare et al., 2025).

## **6. Energy Optimization in Geotechnical Projects**

Energy optimization is an important part of sustainability in geotechnics aimed at reducing energy use without compromising project effectiveness (de Melo et al., 2023). One of the main approaches is the application of energy-efficient technology in excavation and earthmoving. Modern heavy equipment is now equipped with hybrid technology capable of reducing fuel consumption by up to 30%. Tools like electric excavators are becoming increasingly popular due to their low carbon emissions and greater efficiency in day-to-day operations. The adoption of energy-efficient heavy equipment can reduce emissions by up to 25% in large construction projects (Rizky, 2021).

Project designs that maximize the use of passive energy also make a significant contribution. Designs such as processing materials close to the construction site reduce the need for energy-intensive transportation of materials (Vieira, 2022). The implementation of energy storage systems, such as solar batteries to operate small equipment in the field, has become a strategic choice in reducing dependence on fossil fuels (Pijoh et al., 2024). Technological innovation also plays a crucial role in energy optimization. The use of analytical software allows engineers to simulate various scenarios of heavy equipment operation so that methods with the lowest energy consumption can be selected. For example, modeling tools like PLAXIS or ABAQUS not only assist in analyzing soil stability but also enable simulation of the energy consumption impact of equipment throughout the project (A. Kumar & Sharma, 2023; Siregar et al., 2024). With this approach, energy use is not only efficient but also sustainable.

Policies and regulations also encourage efforts to optimize energy in geotechnics. Several countries have established energy efficiency standards that must be met by every major project. In Indonesia, the Ministry of Public Works and Housing (PUPR) mandates an energy efficiency evaluation in the design and operation of infrastructure projects. This policy ensures that sustainability aspects, especially in energy use, become a top priority in development (Ali et al., 2018).

### **7. Geotechnical Innovations for Waste Management and Reclamation**

Waste management is one of the main challenges in geotechnical projects. Unmanaged construction waste results in significant environmental degradation. Innovations in waste management are beginning to focus on the application of the principles of reduce, reuse, and recycle (3R) (Junata et al., 2024; Ogunseye et al., 2023). Reusing excavated soil for soil stabilization ensures that no material is wasted. Stabilization technology using recycled excavation waste materials reduces waste production by up to 40% in large projects (A. Majid et al., 2025; Chmielewska & Gosk, 2022; Wayan, 2022).

Industrial waste-based materials such as fly ash and slag are now increasingly popular in geotechnical concrete mixtures. These materials not only reduce industrial waste but also enhance the strength and durability of concrete. In land reclamation projects, the utilization of leftover soil and sand from mining to strengthen reclamation areas is one of the sustainable solutions. (Chmielewska & Gosk, 2022; Hariyadi, 2018) This approach ensures that the waste generated by the project is maximally utilized. Modern technologies such as IoT sensors are also beginning to be applied in waste monitoring at project sites. These sensors can detect the level of waste pollution entering the management system, allowing for corrective actions to be taken more swiftly. The integration of big data technology enables in-depth analysis of the types and amounts of waste produced, providing guidance for more effective management. (Bassi, 2025) The reclamation process has also experienced breakthroughs through modern geotechnical technology innovations. One of these is the use of solidification/stabilization (S/S) technology to compact soil and liquid waste materials (A. Majid et al., 2025). This technology is capable of transforming hazardous waste into stable and safe materials for reuse as construction or land reclamation materials (Rahgozar et al., 2018). This effort not only supports reclamation but also expands the potential use of construction waste as a new resource (Ogunseye et al., 2023; Vieira, 2022).

## **DISCUSSION**

Sustainable geotechnics plays a strategic role in supporting infrastructure development that aligns with environmental preservation goals (Zakaria & Jihadi, 2016). The integration of geotechnical methods with sustainable approaches helps reduce negative impacts on ecosystems and communities. This approach facilitates the implementation of modern technology, efficient resource utilization, and the application of policies that support sustainability in development projects (Firoozi et al., 2025). Sustainable geotechnics has the potential to become a main pillar in creating environmentally friendly

infrastructure that can withstand global challenges, including climate change and population growth (Firoozi et al., 2025; Waal et al., 2022).

### ***1. Evaluation of the Impact of Geotechnics on Local Ecosystems***

Sustainable geotechnics, besides contributing to infrastructure development, must also consider its impact on local ecosystems. Every geotechnical project has the potential to disrupt the soil, water, and surrounding ecosystems, therefore impact evaluation is crucial to ensure that the project proceeds without damaging the balance of nature. The construction of a dam in Turkey not only focuses on water storage needs but also considers the impact on the biodiversity surrounding the site. In this project, geotechnical engineers work alongside environmental experts to conduct in-depth analyses of the potential environmental risks posed by dam construction (Aulia et al., 2021; Soetjiono, 2018). By utilizing methods such as computer modeling and simulations, the impacts can be predicted more accurately, and necessary mitigation actions can be taken. Modern geotechnics integrates scientific-based approaches to ensure. Based on this evaluation, it was found that dam construction can cause changes in animal migration patterns and damage to natural habitats if not well planned. By carefully selecting locations, using more environmentally friendly materials, and employing construction techniques that prioritize ecosystem safety, these negative impacts can be minimized (Zakaria & Jihadi, 2016). One example of a mitigation technique applied is the adjustment of river flows to ensure smooth fish migration, as well as the construction of buffer zones to protect vital vegetation along the river. The use of local plants for buffer vegetation also positively impacts water quality, which is important for the surrounding fauna (Baldauf, 2017). This approach minimizes ecological damage while still allowing for the achievement of development goals.

Systematic evaluation of the impact of geotechnics on ecosystems needs to be complemented by continuous monitoring. In the dam project, long-term monitoring is conducted using technologies such as remote sensing and sensors to observe changes in the ecosystem in real-time. This step is crucial for early identification and rapid response to long-term impacts on soil quality, biodiversity, and water. One issue noted is the problem of erosion and sedimentation that increases after construction. The geotechnical team employs technology to detect and address these issues, ensuring the sustainability of the ecosystem around the dam (Harahap et al., 2024; Jorat et al., 2017).

The evaluation of the impact on this ecosystem also emphasizes the importance of further research that takes into account ecological sustainability aspects at all stages of the project. This dam project demonstrates that with a deep understanding of the long-term effects on the ecosystem, and by applying various mitigation methods, infrastructure development can be carried out more carefully. Long-term impact evaluation becomes a crucial element in ensuring the sustainability of geotechnical projects to the local ecosystem. The application of these techniques is expected to become the new standard for infrastructure projects in the future (Firoozi et al., 2025).

## ***2. Mitigation Strategies to Enhance Sustainability***

The evaluation of the impact on this ecosystem also emphasizes the importance of further research that takes into account ecological sustainability aspects at all stages of the project. This dam project demonstrates that with a deep understanding of the long-term effects on the ecosystem, and by applying various mitigation methods, infrastructure development can be carried out more carefully. Long-term impact evaluation becomes a crucial element in ensuring the sustainability of geotechnical projects to the local ecosystem. The application of these techniques is expected to become the new standard for infrastructure projects in the future (Firoozi et al., 2025). 5.2 Mitigation Strategies to Enhance Sustainability ...

Other mitigation strategies involve the selection of environmentally friendly material techniques (Zakaria & Jihadi, 2016). In this toll road project, geopolymers were used, which are lighter and more environmentally friendly than conventional concrete. This geopolymer concrete not only saves energy in the production process but also reduces carbon emissions from the production of ordinary concrete (M. Li et al., 2023; A. Smith, 2023). Additionally, this material is also more durable, thus reducing the need for maintenance or repairs over a shorter period. The use of this material also minimizes long-term impacts on the consumption of natural resources, which is a key principle in the sustainability of the project. This approach provides evidence that more efficient and sustainable construction techniques can be implemented without compromising quality (Vieira, 2022).

The use of local plants as part of the greening and vegetation protection program also serves as a mitigation technique applied in this road project (Baldauf, 2017). These plants function to maintain soil stability around the project and improve the existing air quality. Planting vegetation that is compatible with the soil conditions and local climate also strengthens the resilience of the local ecosystem, while simultaneously creating green zones along the highway. The use of technology-based monitoring systems, including sensors to evaluate soil and vegetation quality, has become an effective method for maintaining long-term project quality (Ula et al., 2025).

One of the important aspects of implementing mitigation strategies is the regular evaluation of the effectiveness of each method applied. In Malaysia, this evaluation is conducted every six months using remote sensing technology to analyze changes in land conditions and water quality around the project. With consistent monitoring and the use of advanced technology, this toll road project can serve as an example for other projects in applying effective mitigation strategies to preserve the environment. Effective mitigation requires a systematic strategy and the use of advanced technology to achieve sustainability goals (Harahap et al., 2024).

## ***3. Regulations and Policies in Sustainable Geotechnics***

Regulations and policies play a crucial role in ensuring that sustainable geotechnical practices are effectively implemented in infrastructure projects (Firoozi et al., 2025). In many countries, the success of implementing sustainable geotechnology greatly depends on the establishment of regulations that support

environmental preservation goals without sacrificing development aspects. The European Union has strict regulations regarding carbon emissions and natural resource management in every major project, including geotechnology (Albertz et al., 2023; M. Li et al., 2023). In applying sustainability principles, the EU requires planners and developers to identify potential environmental impacts from the planning phase, and projects must incorporate mitigation technologies that reduce damage to local land, water, and vegetation. Policies that support ensuring that infrastructure development is not only efficient but also environmentally friendly (Firoozi et al., 2025). Regulations like this are essential as reminders that sustainability goals should be met not only in technical aspects but also in social and economic contexts (Martins & Andrade, 2020).

Proper supervision is a crucial element in ensuring that this policy is implemented consistently. Sustainable geotechnical policies are effective not only by involving the creation of regulations that require developers to identify and mitigate impacts, but also by requiring supervision mechanisms that ensure the continuity of these strategies' implementation (Berry et al., 2023). Supervision in the form of independent environmental audits is conducted to assess long-term impacts and the suitability of the techniques used in the field. Regulations requiring an annual environmental evaluation could be an effective instrument to assess the long-term sustainability of a geotechnical project (Firoozi et al., 2025). With clear policies and good supervision, firmness against environmentally unfriendly development can be reinforced.

#### 5.4 Future Perspectives on Sustainable Geotechnics

Looking ahead, the future of sustainable geotechnics is increasingly influenced by advances in technology and demands for environmentally friendly development (S. Wang et al., 2024). Geotechnical projects in the future will increasingly integrate technological innovations focused on energy efficiency and reducing environmental impact. Technologies that are highlighted include the use of more energy-efficient building materials and soils, such as synthetic materials made from industrial waste. The use of geopolymers made from fly ash has great potential to reduce the carbon footprint of infrastructure projects (Albertz et al., 2023). This is because the process of making geopolymers consumes less energy than the conventional concrete production process. The use of geopolymers has become the main choice in sustainable geotechnics as a solution to reduce the carbon footprint from construction activities (Fentaw et al., 2024; M. Li et al., 2023). By using this technology, construction projects not only produce strong structures but are also more environmentally friendly and have a lesser impact on the surrounding environment (Hao et al., 2024; Sanei et al., 2025).

Developments in real-time monitoring and artificial intelligence (AI) can bring significant changes in how geotechnical projects are monitored and managed (Oktavia & Nurkholis, 2022). In the future, more advanced sensor devices will be seen installed on infrastructure projects to collect data directly regarding soil conditions, water quality, and the presence of flora and fauna around the project. This technology, besides being beneficial for maintaining ecosystem sustainability (Firoozi et al., 2025), can also enhance the operational

efficiency of projects by providing real-time data to engineers and builders. The use of AI helps analyze this data to provide early warnings of potential damage or the need for changes in the construction techniques used. AI and advanced sensors help elevate the management of sustainable geotechnics with more efficient monitoring systems (Firoozi & Firoozi, 2024).

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## CONCLUSIONS

Sustainable geotechnics has evolved as a new paradigm that integrates sustainability principles with conventional geotechnical engineering practices to create environmentally friendly, resource-efficient infrastructure solutions that support social well-being. This article has presented a comprehensive review covering various substantial aspects of sustainable geotechnics, ranging from basic concepts to practical implementation in the context of current global challenges.

In the realm of technology and innovation, this article reveals that the integration of digital technology has become a major catalyst for sustainable geotechnical transformation. The application of the Internet of Things (IoT) and artificial intelligence (AI) has proven to enhance project monitoring efficiency by up to 30% compared to conventional methods. IoT-based sensor technology enables real-time field data collection to continuously monitor soil pressure, moisture, and structural deformation, while AI helps in analyzing data to provide early warnings of potential damage. Innovations in augmented reality have also allowed workers to visualize structures virtually, improving efficiency and accuracy in project monitoring. These developments in digital technology align with global trends that indicate the integration of AI and IoT in geotechnics will continue to advance rapidly, with predictions of broader implementation in infrastructure monitoring systems.

Material aspects and soil recovery techniques are important focuses in sustainable geotechnics. Bioremediation using microorganisms to remove pollutants has shown promising results, while phytoremediation or the use of plants to absorb heavy metals can reduce concentrations by up to 70% within six months. Soil stabilization techniques using environmentally friendly chemicals have become a popular alternative, with the application of the principles of reduce, reuse, and recycle (3R) capable of reducing waste production by up to

40% in large projects (Rahgozar et al., 2018). Recent research shows that biogeotechnics or the application of living organisms for modifying soil properties is gaining attention as a sustainable solution, especially through Microbially Induced Calcite Precipitation (MICP) which combines the disciplines of geophysics, microbiology, and chemistry.

In the context of socio-economic impact, sustainable geotechnics has proven to create higher quality and more innovative jobs. Sustainable projects involving cutting-edge technology require specialized expertise, thereby encouraging the enhancement of local workforce capacity. The development of environmentally friendly techniques opens up new market opportunities for the sustainable materials sector and geotechnical technology, with companies offering bioengineering-based solutions recording a significant increase in demand, indicating substantial potential in green economic development (Zhang et al., 2024). This aligns with the sustainable development goals (SDGs), particularly SDG 9 which promotes innovation and resilient infrastructure, and SDG 13 which addresses the impacts of climate change.

Waste management and energy optimization have become crucial components in the implementation of sustainable geotechnics. Modern technologies such as IoT sensors have been applied in waste monitoring at project sites, allowing for early detection of pollution levels and quicker corrective actions. The integration of big data technology enables in-depth analysis of the types and quantities of waste generated, providing guidance for more effective management. Geographic Information Systems (GIS) have been used to analyze erosion risks based on topographic and rainfall data, allowing for more precise designs to address potential soil damage before the project begins.

The aspect of environmental sustainability has become a primary consideration in modern geotechnical design. Life Cycle Assessment (LCA) has emerged as an important methodology for comprehensively evaluating the environmental impact of geotechnical projects from material extraction to final disposal. Research shows that LCA in geotechnics still faces challenges in standardizing methodologies and the availability of transparent data. Carbon sequestration through geological CO<sub>2</sub> sequestration has developed as an innovative solution for mitigating climate change, with the potential for storing carbon in geological formations such as deep saline aquifers and depleted oil and gas reservoirs.

Regulatory and implementation challenges remain significant obstacles in the application of sustainable geotechnics. Many countries still lack specific guidelines for integrating sustainability principles into the design and execution of geotechnical projects. Collaboration between government, research institutions, and the private sector is key to addressing these challenges, with strengthened regulations and increased awareness of the importance of sustainability being crucial factors.

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## RECOMMENDATIONS

Based on a comprehensive analysis of sustainable geotechnical development, several relevant and urgent future research directions to be developed include the development of an integrated framework for smart geotechnics that combines AI, IoT, and machine learning in real-time infrastructure monitoring systems. This research should focus on developing predictive algorithms that can continuously analyze sensor data for early prediction of structural failures and optimization of preventive maintenance. The integration of digital twin technology in geotechnics also requires in-depth research to develop accurate virtual models of physical geotechnical systems, enabling simulation and optimization without risk to actual assets.

Further research in biogeotechnics and MICP (Microbially Induced Calcite Precipitation) is a high priority, particularly in developing more efficient microorganism strains and large-scale applications for various types of soil. Research should explore the combination of bioengineering with conventional geotechnical techniques to create more effective hybrid solutions. The development of biopolymers as an environmentally friendly alternative for soil stabilization also requires further research, especially in aspects of long-term durability and cost-effectiveness.

The standardization of Life Cycle Assessment (LCA) methodologies specifically for geotechnical projects has become an urgent need that requires international collaborative research. The research must develop a comprehensive LCA framework covering the entire life cycle of geotechnical projects, including the use and end-of-life stages that are often overlooked in current studies. The development of a materials and process-specific inventory database for geotechnics in various geographical regions is also a priority to improve the accuracy of LCA assessments.

Research in geological carbon sequestration requires a focus on geotechnical aspects to ensure the safety and long-term effectiveness of CO<sub>2</sub> storage in geological formations. The research should develop advanced geotechnical monitoring techniques to monitor the integrity of cap rock, detect leaks, and analyze induced seismic risks. The application of carbonation technology in soil treatment also requires further research to optimize the carbonation process and its application under various geotechnical conditions.

The development of smart infrastructure for sustainable urban development requires interdisciplinary research that integrates geotechnics with urban planning, environmental engineering, and information technology. Research should focus on the development of adaptive infrastructure systems that can respond to climate change and dynamic urban growth. The concepts of green infrastructure and nature-based solutions in geotechnics also require in-depth research to optimize the integration between natural solutions and engineering in the design of sustainable infrastructure.

Research in resilient infrastructure design for climate change adaptation has become a strategic priority, especially in developing geotechnical design methodologies that can adapt to changing rainfall patterns, rising sea levels, and increasing frequency of extreme natural disasters. The research must develop a comprehensive risk assessment framework and cost-effective mitigation strategies for various climate change scenarios.

Economic aspects and policies in the implementation of sustainable geotechnics require in-depth research to develop an economic valuation model that can quantify the co-benefits of sustainable geotechnical investments. Research should explore economic incentive mechanisms and regulatory frameworks that can encourage broader adoption of sustainable geotechnical practices. The development of circular economy principles in geotechnics, including strategies for reusing and recycling construction materials, also requires further research to optimize economic and environmental value.

Research in educational frameworks and capacity building for sustainable geotechnics is an important aspect that is often overlooked. Research should develop curricula and teaching methodologies that can prepare generations of geotechnical engineers with competencies in sustainability principles and digital technologies. The development of professional certification and standard practices for sustainable geotechnics also requires collaborative research among academics, industry, and regulators.

Ultimately, research within the international collaboration framework for sustainable geotechnics has become a strategic necessity given the global nature of sustainability challenges. Research must explore mechanisms for knowledge sharing, technology transfer, and collaborative research that can accelerate the adoption of sustainable geotechnical practices in various countries with diverse geographical and economic conditions. The development of global standards and best practices for sustainable geotechnics through international organizations such as ISSMGE is also an important area of research for the future.

## **FURTHER STUDY**

This research still has limitations so that further research is needed on the topic of Sustainable Geotechnics: A Review of the Integration of Technology, Material Innovation, and Socio-Economic Evaluation for Resilient Infrastructure to perfect this research and increase insight for readers and authors.

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