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Sustainable Foundations: Integration of Recycled Materials and Geosynthetics in Intelligent Design

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Abstract: The demand for innovative, sustainable foundation engineering solutions has increased due to the rising pressure to lessen the environmental impact of major developments. The integration of geosynthetics and recycled materials into intelligent foundation design is critically examined in this work as a means of achieving robust, low-carbon, and resource-efficient infrastructure systems. This paper's thematic analysis and structured literature review demonstrate how waste-derived materials, including fly ash, recycled concrete aggregates, waste plastics, and industrial by-products, can successfully replace conventional building materials in ground improvement and foundation applications. Furthermore, geosynthetics—such as geotextiles and geogrids—provide lightweight, long-lasting, and eco-friendly reinforcement substitutes that improve soil performance while using less material. The study also looks at how real-time monitoring, sensor technologies, and artificial intelligence (AI) might improve structural performance, maximise material selection, and prolong the life of foundation systems. The results of life cycle assessment (LCA) and life cycle cost analysis (LCCA) show significant economic and environmental advantages, such as lower energy use, greenhouse gas emissions, and overall project costs. However, the main obstacles to broad adoption are found to be issues like material heterogeneity, a lack of standardisation, and a limited degree of digital integration. To promote sustainable foundation practices through material innovation, digital transformation, and the concepts of the circular economy, the study ends by offering practical suggestions for researchers, industry practitioners, and legislators. The results provide insightful information on how smart, sustainable foundation design may support the global shift to more resilient and environmentally friendly built environments.

Keywords: Sustainable construction, Recycled materials, Geosynthetics, Foundation engineering, Intelligent design.

1. INTRODUCTION

The global construction industry is at the forefront of addressing the pressing challenges of environmental. The interrelated problems of resource depletion, climate change, and environmental degradation are putting increasing pressure on the worldwide construction sector. Although they are very good at delivering the load-bearing capacity and structural stability required for infrastructure development, traditional foundation systems are usually linked to significant environmental costs. Among these expenses is the over-exploitation of virgin natural resources, such as cement, sand, and aggregates, which contributes to habitat loss and land degradation in addition to depleting limited supplies (Yang *et al*., 2023; Awewomom *et al*., 2024; John *et al*., 2024). The global carbon footprint of building operations is further increased by the high embodied energy and substantial greenhouse gas emissions associated with the manufacturing and shipping of these materials. The issue is made worse by the enormous amounts of garbage generated during building and demolition, much of which is dumped in landfills and contributes to pollution and unsustainable waste management techniques. A paradigm shift towards sustainable building approaches, which aim to reduce ecological harm while preserving the functional and financial sustainability of engineering projects, has occurred in response to these rising environmental concerns (Gursel *et al*., 2023; Passoni *et al*., 2022; John & Pu, 2023; John *et al*., 2023). The requirement to coordinate building operations with global sustainability frameworks—specifically, the Sustainable Development Goals (SDGs) of the UN, which demand climate action, resilient infrastructure, and responsible consumption and production—is driving this change increasingly. A key component of this new strategy is the use of recycled materials and cutting-edge technology to lessen the environmental effect of foundation and geotechnical systems. These practices provide chances for innovation, the integration of the circular economy, and improved material efficiency in addition to a way to lower resource use and carbon emissions (Scrucca *et al*., 2023; John *et al*., 2025b; Xiao *et al*., 2025).

The use of recycled materials as sustainable substitutes for traditional foundation materials is growing. These materials include crushed concrete, reclaimed asphalt pavement, waste plastics, scrap tires, and industrial by-products like fly ash, ground granulated blast furnace slag (GGBS), and silica fume (Singh & Chaudhary, 2023; Abera, 2024). The usage of these materials has several positive effects on the environment: It removes a significant quantity of trash from landfills, lessens the need to harvest virgin materials, and lowers greenhouse gas emissions from

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transportation and material processing. The mechanical viability of these recycled materials has been validated by several field and experimental investigations in a variety of geotechnical applications, such as subgrade stabilisation, road base layers, embankments, and even as aggregate substitutes in foundation systems (Algarni *et al.*, 2023; Yadav *et al.*, 2025). These studies show that recycled materials can have strength, stiffness, and durability that are equal to their conventional counterparts when treated and built appropriately, making them viable solutions for lowering the environmental impact of foundation engineering. However, several important information gaps and obstacles still exist that prevent the widespread use of recycled materials in foundation applications, even considering these encouraging discoveries (Neupane *et al.*, 2023; Cui *et al.*, 2024). The dearth of knowledge on these materials' long-term performance and durability under various loading and environmental circumstances is one of the main issues. Further research is necessary to guarantee structural integrity and environmental safety throughout the lifespan of foundation systems by addressing issues such material deterioration over time, moisture susceptibility, freeze-thaw cycles, and possible pollutant leaching. Furthermore, more thorough evaluations of the environmental consequences of recycled materials are required, such as full life cycle analyses (LCAs) that consider transportation emissions, end-of-life disposal or reuse possibilities, and cradle-to-grave effects. Building industry trust and promoting the shift to more robust and sustainable geotechnical infrastructure will require filling these gaps via thorough scientific research, standardised testing procedures, and practical demonstration projects (Kalali *et al.*, 2023; Harle, 2024; Marchiori *et al.*, 2025; Nyame & Adesanmi, 2024; Firoozi *et al.*, 2025a).

The rapid development and widespread application of geosynthetics in contemporary foundation design aligns with the growing emphasis on recycled materials in foundation engineering. Geosynthetics, a broad family of synthetic products that includes geotextiles, geogrids, geomembranes, geonets, and geocomposites, enable improving drainage, regulating deformations, strengthening soil reinforcement, and increasing the overall stability of geotechnical systems. Due of their unique mechanical, hydraulic, and chemical properties, engineers may tailor foundation solutions to site conditions, reducing the need for traditional, resource-intensive building methods (Figure **1**). By more uniformly distributing loads, reducing settlement, and providing effective separation and filtration, geosynthetics not only improve the structural performance of foundations but also extend the service life of infrastructure assets (Abedi *et al.*, 2023; Chatrabhuj & Meshram, 2024; Markiewicz *et al.*, 2025).

Pavement portions with and without geosynthetics are contrasted in Figure **1**. Reflective cracking spreads into the freshly laid asphalt overlay from the underlying damaged pavement on the left. Between the freshly laid asphalt and the pre-existing cracked layer on the right, a geosynthetic layer is added. This geosynthetic improves pavement performance and longevity by acting as a stress-absorbing interlayer and reinforcement, effectively slowing or stopping the spread of fractures. The incorporation of these may also drastically cut down on the use of natural resources like cement and aggregates, which are big contributors to the environmental effects of building. The combination of recyclable materials with geosynthetics offers a revolutionary chance to create intelligent, hybrid foundation systems that are both ecologically friendly and structurally sound. Due to this synergy, foundation systems may be designed to employ the least amount of material possible while yet

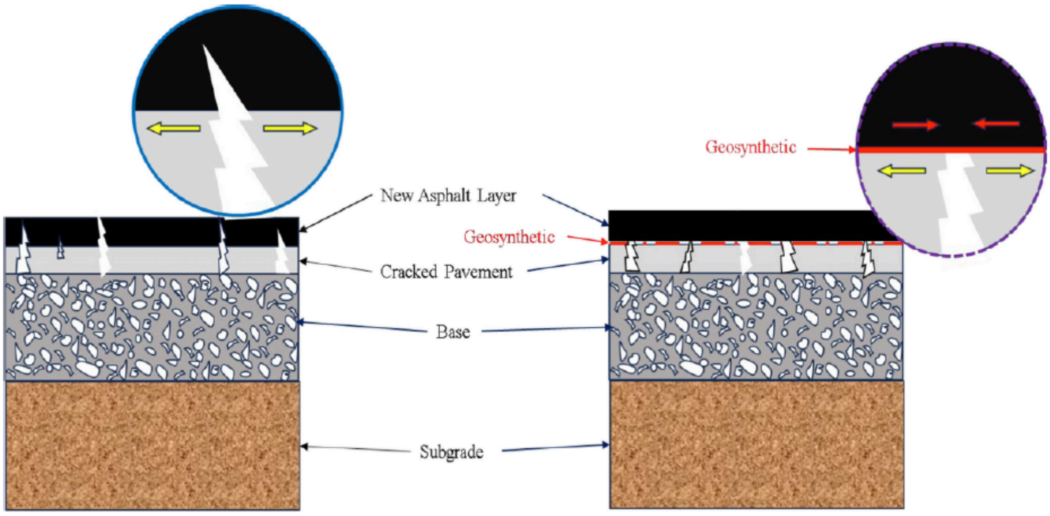

Figure 1: Geosynthetics' Function in Reducing Reflective Cracking in Asphalt pavement (Chatrabhuj and Meshram, 2024).

performing well under a variety of loading and environmental circumstances. To divert trash from landfills and conserve natural resources, geogrids and recycled aggregates, for instance, can be used to improve mechanical interlock, minimise differential settling, and increase bearing capacity. Engineers may design foundations with more flexibility and resilience when these integrated systems are further optimised to respond adaptively to site-specific geotechnical issues, such as poor soils, high groundwater tables, or seismic risk. These hybrid solutions closely connect with global environmental aims and sustainable development agendas by reducing energy consumption, carbon emissions, and the total ecological impact of infrastructure projects in addition to mechanical performance (Liu & Hung, 2023; Chatrabhuj & Meshram, 2024; Sheng *et al*., 2024; Rajczakowska *et al*., 2025).

To produce adaptable, robust, and resource-efficient systems, intelligent design in foundation engineering goes beyond this integration by utilising digital technology, sophisticated modelling approaches, real-time performance monitoring, and material optimisation strategies. The idea, design, and management of foundation systems have been completely transformed by the introduction of digital technologies like Building Information Modelling (BIM), Artificial Intelligence (AI), machine learning algorithms, and sophisticated geotechnical numerical modelling. With the use of these technologies, engineers may analyse various design scenarios, forecast performance results, and analyse environmental effects across a project's whole lifespan (Govers & Van Amelsvoort, 2023; Datta *et al*., 2024; Kantaros *et al*., 2025). A comprehensive sustainability viewpoint is provided from the very beginning of project development through the application of Life Cycle Assessment (LCA) tools, which enable a methodical assessment of the environmental, economic, and social effects of material and design decisions. The incorporation of recycled materials and geosynthetics into intelligent design frameworks has the potential to improve engineering performance while also meeting strict sustainability targets, reducing costs, and advancing the circular economy. However, several obstacles still prevent intelligent foundation systems from being widely used in practice, despite these encouraging developments. The intrinsic heterogeneity and diversity of recycled materials is one of the main obstacles, since it can cause uneven performance and make design standardisation more difficult. Furthermore, even though geosynthetics are becoming more widely used in practice, their wider implementation is still hampered by the absence of generally acknowledged design rules and performance standards, especially for complicated or hybrid applications. Practitioners' cautious adoption is further influenced by uncertainties around long-term durability, deterioration under environmental stresses, and interactions between recycled materials and geosynthetics (Sartori *et al*., 2022; Abedi *et al*., 2023; Marchiori *et al*., 2025; Wu *et al*., 2025). The integration of sustainability evaluations and cutting-edge digital technologies into everyday geotechnical design also calls for organisational change, multidisciplinary cooperation, and new skill sets—factors that might impede adoption in a historically conservative business. Coordination of research, policymaking, education, and industry participation will be necessary to overcome these obstacles and fully realise the promise of intelligent, sustainable foundation systems for the upcoming resilient infrastructure generation (Abbasnejad *et al*., 2024; Ajirotutu *et al*., 2024; Firoozi *et al*., 2025a). Despite new developments, there are still obstacles in the way of widely using geosynthetics and recycled materials in foundation systems. Concerns about mechanical performance consistency, a lack of standardised testing procedures, inadequate regulatory frameworks, and a lack of practitioner understanding are some of the main obstacles. It is also necessary to assess the trade-offs between structural reliability, cost, and environmental advantages. Developing thorough rules that can guide decision-making at the design and policy levels, multidisciplinary cooperation, and strong field validations are all necessary to close these gaps (Barker *et al*., 2022; Miller *et al*., 2023; Chatrabhuj & Meshram, 2024).

This paper aims to explore the sustainable integration of geosynthetics and recycled materials into intelligent foundation design to improve economic viability, structural efficiency, and environmental performance. The goals are (i) to evaluate the mechanical and environmental performance of specific recycled materials in foundation applications; (ii) to determine how well geosynthetics reinforce these materials; and (iii) to investigate how intelligent design tools can be used to optimise sustainable foundation systems. This study is prompted by the pressing need to minimise construction's negative environmental effects while preserving structural integrity and economic viability. Through a thorough assessment of material performance, design tactics, and sustainability measures, this study aims to further the development of environmentally friendly, robust, and future-ready foundation systems in the field of civil engineering.

2. METHODS

This study used an organised critical review technique to evaluate the present, new developments, and future of sustainable foundation systems that use geosynthetics and recycled materials. Technological developments in digital design intelligence, environmental sustainability, geotechnical engineering, and material science are all aspects of this naturally interdisciplinary area. The review was meticulously crafted to encompass this intricacy and offer a fair and thorough assessment of the literature and real-world applications. Four steps comprised the research process: topic synthesis, data extraction, selection and screening, and literature identification. Searches were carried out extensively throughout key academic databases, including as Scopus, Web of Science, ScienceDirect, ASCE Library, and Google Scholar, with a focus on articles from 2000 to 2025, to guarantee comprehensive and in-depth coverage. Boolean operators and targeted keywords were used to methodically find pertinent material. The most searched terms were: "sustainable foundations," "recycled construction materials," "geosynthetics in geotechnics," "reinforced soil structures," "eco-efficient foundations," "waste material utilisation in geotechnical design," "intelligent foundation systems," along with "life-cycle assessment in geotechnics." Grey literature, including government studies, technical recommendations, and conference proceedings, was also reviewed in order to document the latest advancements and applied techniques.

To guarantee the inclusion of excellent, pertinent material, a strict selection and screening procedure was used. Only credible conference papers, peer-reviewed journal articles, and technical reports that specifically addressed the incorporation of geosynthetics and/or recycled materials into foundation design were taken into consideration. Publications that only addressed non-geotechnical applications or other sustainability subjects were not included. A full-text review was conducted after an initial screening of abstracts and titles to ensure methodological soundness, technical relevance, and conformity with the review's goals. To ensure uniformity, only English-language materials were incorporated. In order to ensure systematic and reproducible gathering of important information throughout the chosen literature, a standardised extraction framework was created especially for this study and used to carry out data extraction. Critical parameters that were retrieved were as follows:

- The class and purpose of the geosynthetics used (such as geotextiles, geogrids, and geomembranes), as well as their mechanical and environmental performance,
- Bearing capacity, settlement reduction, robustness, and durability under different loads and environmental circumstances are examples of structural performance measures.
- Using life-cycle assessment, digital optimisation tools, and numerical modelling as part of intelligent design
- Field tests, documented case studies, and extensive applicability
- Sustainability metrics, cost consequences, regulatory issues, and adoption difficulties

Five major theme categories were created as a result of thematic analysis of the retrieved data:

1. New approaches to using recycled materials in geotechnical applications.
2. Developments in geosynthetic technologies for stabilising and reinforcing soil.
3. Intelligent design techniques for maximising sustainable foundation systems.
4. Environmental performance, life-cycle assessment, and resilience considerations; and
5. Difficulties, policy gaps, and future research directions

This theme synthesis made it possible to comprehend the state of knowledge on the sustainable design of foundation systems in its entirety. It identified shortcomings that prevent wider adoption while highlighting both cutting-edge innovations and well-established practices. Studies combining computerised decision-support systems, multi-criteria optimisation, and environmental impact assessments were given particular attention, as did literature examining the mix of recycled materials and geosynthetics in practical applications. The study provides a transparent, repeatable, and evidence-based evaluation of the contribution of recycled materials and geosynthetics to the development of more durable, intelligent, and sustainable foundation systems by using this rigorous and systematic review approach. It also emphasises the urgent need to fill important research gaps and overcome technology obstacles to promote widespread adoption and match foundation engineering practices with goals for climate resilience and global sustainability.

3. RESULTS AND DISCUSSION

3.1. Introduction to Sustainable Foundation Design

The idea of sustainable foundation design has become a crucial paradigm in the worldwide construction industry due to the pressing need to reduce greenhouse gas emissions, the depletion of natural resources, and growing environmental issues. Conventional foundation methods, which mainly use virgin materials like steel, cement, and quarried aggregates, have long been linked to serious ecological impacts, such as habitat loss, high embodied energy, and emissions from the extraction, production, and transportation of materials (Almusaed *et al*., 2024; Wang & Azam, 2024; de Haes & Lucas, 2024). This study, on the other hand, shows that attaining true sustainability in foundation design calls for a thorough, systems-based approach that prioritises long-term structural resilience, resource efficiency, and performance optimisation throughout the asset's life cycle. The use of low-carbon technology, recycling and material reuse, minimising waste from building and demolition, and improved durability to lower maintenance and reconstruction requirements are all important components of sustainable foundation initiatives. To compare and assess environmental trade-offs across time, performance-based design approaches and life cycle evaluations are also crucial tools. To ensure that sustainability is a primary driver of innovation rather than an afterthought, it is essential to include these concepts into the very early stages of planning and design (Yaro *et al*., 2023; Huang *et al*., 2024a; Mannucci, 2025). The creation of intelligent, eco-efficient infrastructure systems that can adjust to shifting environmental circumstances and social needs is encouraged by this progressive strategy, which also supports larger climate resilience aims

The critical review's main finding is the increasing use of recycled materials in sustainable foundation systems. Recycled aggregates, industrial by-products including fly ash and slag, shredded tyre chips and even plastic garbage may be effectively integrated into a variety of geotechnical applications without affecting structural performance, according to several research evaluated in this article (Keskin *et al*., 2024; Wu *et al*., 2025; Zabielska-Adamska, 2025). These substitute materials have a lot to offer the environment, such as lowering greenhouse gas emissions, conserving natural resources, and keeping trash out of landfills. It has also been demonstrated that the incorporation of geosynthetics, such as geotextiles, geogrids, and geomembranes, greatly improves the mechanical behaviour of foundation systems by offering filtration, separation, and reinforcement capabilities that increase bearing capacity, settlement control, and long-term durability. The combination of geosynthetics with recycled materials is a game-changing strategy that supports the ideas of green infrastructure and the circular economy. The review also emphasises that strict quality control, standardised testing protocols, and suitable design techniques catered to site circumstances are necessary for the effective use of these materials (Chatrabhuj & Meshram, 2024; Dąbrowska *et al*., 2023; Panagiotidou *et al*., 2025).

A noteworthy feature that has been observed is the rise of intelligent design methodologies as a driving force behind the development of sustainable foundation solutions. Building Information Modelling (BIM), finite element modelling, life-cycle assessment (LCA), and artificial intelligence (AI)-based optimisation are examples of digital technologies that are being used more to improve foundation design decision-making, according to the reviewed literature (Chen *et al*., 2024; Schneider *et al*., 2024; Zong & Guan, 2024). By simulating different material selections, loading scenarios, and environmental effects, engineers may create solutions that are sustainable, economical, and optimal. Predictive maintenance is made possible, and the chance of structural failures is reduced by the adaptive management of foundation systems throughout their service life made possible by the integration of smart sensing and real-time monitoring technology. Crucially, a new paradigm for foundation design is produced by the fusion of digital intelligence, geosynthetic technologies, and innovative materials. This paradigm not only satisfies technical performance requirements but also promotes more general sustainability objectives like socio-environmental equity, circularity, and climate resilience (Achouch *et al*., 2022; Shen *et al*., 2023; Firoozi *et al*., 2025a).

3.2. Recycled and Waste-Derived Materials in Ground Improvement

Ground improvement with recycled and waste-derived materials has become a sustainable and feasible substitute for conventional soil stabilisation techniques, providing advantages for the environment and geotechnical performance. Materials like fly ash, blast furnace slag, broken concrete, recovered asphalt pavement (RAP), shredded rubber tires and recycled plastics have all been shown in numerous research and experiments to be beneficial in improving the engineering qualities of troublesome soils. While shredded rubber tires have been used to improve shear strength and reduce soil density in embankment applications, studies have shown that the addition of fly ash may raise the unconfined compressive strength of soft soils by more than 200% (Bhagatkar & Lamba, 2024; Shah, 2024; Ali & Mohammed, 2025). Over 290 million waste tires are produced each year in the US alone, according to the US Environmental Protection Agency (EPA) (Kilani *et al*., 2024). By recycling them in geotechnical applications, large amounts of tires may be kept out of landfills. The use of RAP and crushed concrete to subgrade layers has also been shown to boost the California Bearing Ratio (CBR) by up to 30% while lowering the requirement for virgin materials. By completing material loops, these methods not only enhance the objectives of the circular economy but also reduce the embodied carbon linked to the extraction, processing, and shipping of conventional stabilising agents like cement and lime (Sandanayake *et al*., 20222; Martínez-Martínez *et al*., 2023; Roychand *et al*., 2023). Furthermore, life cycle assessments have shown that, in comparison to traditional approaches, the use of recycled materials in ground renovation can cut greenhouse gas emissions by as much as 50%. The use of these materials improves soils' stiffness, permeability, durability, and load-bearing capacity while also addressing waste management and climate action goals in civil infrastructure projects, which is in line with sustainable building principles (Lillian *et al*., 2025; Hoxha & Birgisdottir, 2025; Naskar *et al*., 2025). Recent hydrogeological and environmental engineering studies have started to estimate both migration fluxes and ecotoxicological thresholds, however there is still a dearth of study on tire-derived microplastics (TDMs) in geotechnical applications. Under moderate percolation rates (10–50 cm/day), reported fluxes range from <0.1 to ~3 mg/L-equivalent, with smaller particles (<50 μm) exhibiting greater mobility. Laboratory column tests and mesocosm trials (*e.g*., Mackay-Roberts *et al*., 2024; Porter & Cornwell, 2024) demonstrate that particle release rates are strongly dependent on tire size reduction method, surface weathering, leachate chemistry, and hydraulic gradients. In natural soils, biofilm formation and sorption onto fines can greatly slow migration, whereas clean, coarse sands promote faster transport rates. Acute/sub-lethal effects on aquatic invertebrates are noted above approximately 1–5 mg/L for chronic exposure (Wolmarans, 2021; Wang *et al*., 2023; Flemming *et al*., 2025), and zinc/organic additives in leachates frequently pose a higher risk than the polymer fragments themselves. However, ecotoxicological thresholds are still up for debate.

Industrial byproducts and recycled concrete aggregate (RCA) have become very promising substitutes for natural aggregates in base layer and subgrade stabilisation, providing advantages in terms of economy and ecology without sacrificing mechanical performance. According to studies, RCA may attain up to 90% of the load-bearing capability of natural aggregates in road base applications (Lu, 2024; Sahani *et al*., 2025). This makes it a dependable alternative in areas where the extraction of virgin materials is either prohibitively expensive or ecologically constrained. Additionally, it has been demonstrated that using industrial by-products like fly ash and ground granulated blast furnace slag (GGBS) as soil binders can improve the durability and compressive strength of stabilised soils while lowering dependency on Portland cement, which contributes about 8% of global CO_2 emissions. For instance, adding GGBS to soil-cement combinations in place of 50% cement has improved sulphate resistance and increased strength by up to 25% (Al-Khafaji *et al*., 2023; Gupta & Kumar, 2023; Ahmed *et al*., 2024). Laboratory tests have shown that rubber-amended soils have a 30–50% lower permanent deformation and a higher damping capacity under cyclic loading than untreated soils (Chu *et al*., 2024). The addition of shredded rubber from end-of-life tires also improves soil by increasing energy dissipation and flexibility. Due to the EU alone generates more than 50 million tonnes of building and demolition waste a year, using RCA and related materials in geotechnical applications might help divert large amounts of trash from landfills and promote circular economy initiatives. These results demonstrate that properly chosen and used recycled materials not only reduce environmental effects but also fulfil or surpass conventional technical requirements for pavement and foundation systems (Kazemi *et al*., 2023; Sharma *et al*., 2023; Mariyappan *et al*., 2023).

The analysis shows that waste plastics, especially high-density polyethylene (HDPE) and polypropylene, are increasingly being used as lightweight fillers and reinforcing agents in geotechnical engineering, with significant advantages in soil improvement and settlement management. The bulk density of soil can be reduced by up to 25% when these plastics are processed into shredded or pelletised forms. This improves workability and lowers overall loading on underlying strata, which are important benefits for backfill stabilisation, lightweight fill applications in soft soil regions, and embankment construction (Atienza *et al*., 2023; Smith *et al*., 2023). In experimental experiments, blending HDPE at 5–10% by weight with fine-grained soils resulted in considerable reductions in post-construction settlements and up to 30% improvements in compressibility control. In resource-constrained regions, bio-waste materials such as construction and demolition (C&D) debris, coconut shell ash, and rice husk ash (RHA) are becoming more popular as locally derived stabilisers. For example, at 10–15% inclusion rates, RHA has been shown to have pozzolanic qualities that raise the California Bearing Ratio (CBR) of clayey soils by as much as 50%, providing an affordable substitute for cement or lime treatments (Zafar *et al*., 2023; Abhishek *et al*., 2024; Ali & Atemimi, 2024). Additionally, by decreasing reliance on imported building materials and establishing circular value chains, the usage of such materials boosts rural economies. Notwithstanding these encouraging technical and socioeconomic results, the analysis also highlights the conspicuous absence of long-term performance statistics. Future research is necessary to guarantee the safe and sustainable adoption of these waste-derived materials in geotechnical applications. Concerns remain regarding the materials' durability, chemical leachability, and environmental interactions under extended exposure to fluctuating moisture, temperature, and loading conditions (Azmi *et al*., 2024; Keskin *et al*., 2024; Portan *et al*., 2025).

The synthesis emphasises that although recycled and waste-derived materials have a lot of potential for sustainable ground improvement, their effective integration necessitates a multifaceted strategy that incorporates intelligent design methodologies, geosynthetic reinforcement, and material innovation (Perera *et al*., 2025). Case studies have shown that the use of such materials in combination with geosynthetics greatly enhances the mechanical performance of soils. For instance, studies have demonstrated that, in comparison to unreinforced systems, the use of geogrids containing recycled aggregates in subbase layers can increase bearing capacity by as much as 60% and decrease surface rutting by more than 40% (Mazurowski *et al*., 2022; Hassan *et al*., 2023; Chatrabhuj & Meshram, 2024; Badiger *et al*., 2025). The use of fly ash mixes and shredded tyre chips in cellular confinement systems (CCS) has also demonstrated improved stiffness and load distribution efficiency, especially in soft soil conditions. Engineers may get predictive insights into performance, durability, and environmental trade-offs by optimising design parameters with the use of advanced modelling methods like life-cycle assessment (LCA) and finite element analysis (FEA) (Sharma *et al*., 2024; Yavan *et al*., 2024). Research using life cycle assessment (LCA) on recycled concrete aggregate in road subgrades suggests that, in comparison to virgin aggregate alternatives, there may be a 25–35% reduction in greenhouse gas emissions and a 20% reduction in life-cycle costs (Tang *et al*., 2022; Elahi *et al*., 2023). Despite these benefits, several enduring obstacles prevent such integrated systems from being widely used. Their adoption is constrained by material variability, the lack of widely recognised testing procedures and design standards, regulatory uncertainty, and stakeholder scepticism about long-term dependability. Cross-disciplinary cooperation, the creation of uniform standards, and pilot projects that demonstrate the practicality and economics of these sustainable solutions in practical settings are all necessary to overcome these obstacles.

Numerous studies have tackled the problem of "material variability" in recycled geomaterials like fly ash, RCA, and RAP by gathering statistical descriptors for important engineering properties that affect bearing-capacity performance and long-term settlement, such as mean, standard deviation, and coefficient of variation (COV). Significant between-source scatter is reported in grading, asphalt content, water absorption, modulus, and shear strength for RAP and RCA in meta-analyses and agency datasets (*e.g*., RAP φ ≈ 42–46°), with clearly defined variability envelopes appropriate for reliability modelling (Verbickas, 2024; Sahani *et al*., 2025). Two well-established probabilistic approaches are used to incorporate this quantified variability into design: (i) traditional Monte Carlo or First-Order Reliability Method (FORM) analyses that use bias and COV values for resistance parameters (Es, φ, c, and unit weight) in settlement and capacity equations; and (ii) random-field finite element modelling (RFEM) to capture scale effects and spatial variability for both serviceability and ultimate limit states. These methods have already produced calibrated LRFD resistance factors for bearing capacity and settlement; examples include probabilistic frameworks for improved fills that can easily incorporate recycled materials and random-field-based factors for shallow foundations (Najjar & El-Chiti, 2023; Primo *et al*., 2025; Yang *et al*., 2025c). Both AASHTO LRFD and Eurocode 7 offer reliability-calibrated formats at the code level (resistance factors for the former, partial factors for the latter). These formats can be locally recalibrated when project-specific data is available, or they can be adopted directly when recycled materials show statistical profiles similar to those of conventional fills. Therefore, the primary obstacle to widespread adoption is the availability of thorough, source-specific statistics (including spatial correlation) for recycled fills; in cases where such data are available, direct implementation or minimal local adjustment is already possible, even though the design methods and calibration procedures are already established and code-aligned (Shen *et al*., 2019; Melhem & Caprani, 2022).

3.3. Geosynthetics and Intelligent Soil Reinforcement

The integration of geosynthetics in soil reinforcement has markedly transformed sustainable foundation engineering by offering superior geotechnical performance while significantly reducing environmental impacts. Geosynthetics, including geotextiles, geogrids, geomembranes, geocells, and geocomposites, are essential for load distribution, soil stabilisation, filtration, drainage, separation, and reinforcing. Their ability to improve the structural integrity and resilience of foundation systems has been confirmed by several experimental and empirical investigations. It has been demonstrated that, in comparison to unreinforced structures, geogrid-reinforced foundations may minimise surface settlement by 30 to 40% and enhance load-bearing capacity by up to 50% (Chatrabhuj and Meshram, 2024; Hussain *et al*., 2024; Prakash *et al*., 2025). Through increased shear resistance and pore water pressure dissipation, the use of geocells and geotextiles has enhanced slope stability and decreased liquefaction potential in seismically active areas. Additionally, geosynthetics are particularly good at reducing differential settlement in expansive and soft soils, which helps to extend the life of infrastructure. From sustainability perspective, geosynthetics help to reduce the number of natural aggregates and imported fill; one study found that using geosynthetic-reinforced systems instead of traditional granular fills in retaining walls and embankments reduced CO_2 emissions by 20–35% (Dąbrowska *et al*., 2023; Deger & Guler, 2024; Malekmohammadi & Damians, 2024). Their lightweight design also lowers installation and transportation expenses and energy consumption. The long-term dependability of contemporary polymer-based geosynthetics is guaranteed by their resilience to mechanical, chemical, and biological deterioration. These benefits highlight the potential of geosynthetics as both performance enhancers and important facilitators of the shift to more robust and sustainable geotechnical design methods (Farghali *et al*., 2023; Abedi *et al*., 2023).

The expanding use of intelligent geosynthetic systems—where conventional geosynthetics are enhanced with embedded sensors and monitoring devices to enable real-time, in-situ performance assessment—is a significant achievement that this study highlights. To continuously monitor vital parameters like strain, deformation, moisture content, temperature, and porewater pressure, these smart geosystems incorporate technologies like wireless sensor networks, piezoelectric transducers, fibre optic Bragg grating sensors, and micro-electromechanical systems (MEMS). According to research, strain variations as tiny as 1 microstrain may be detected by fibre optic sensors placed in geotextiles, allowing for the early detection of structural abnormalities or stress redistribution (Sivasuriyan *et al*., 2024; Anjana *et al*., 2024; Hong *et al*., 2024). The efficiency of sensor-embedded geogrids in reinforced soil walls and embankments has been shown in case studies from major infrastructure projects in Europe and Asia, where real-time monitoring helped lower failure risks and optimise maintenance intervals. For instance, a sensor-integrated retaining wall in Japan allowed engineers to identify early settlement movements and carry out targeted repair, averting catastrophic failure, while a German highway embankment fitted with smart geotextiles demonstrated a 30% improvement in safety margin forecasts (Abedi *et al*., 2023; Acharya & Kogure, 2024). By enabling predictive maintenance and reducing the need for human inspections, these solutions not only increase safety but also save lifespan costs. Data interpretation is further improved by the combination of geosynthetics and digital technologies like artificial intelligence and the Internet of Things (IoT), which enables operational decision-making and adaptive design. Consequently, intelligent geosynthetic systems mark a revolutionary advancement in the development of intelligent, robust, and sustainable geotechnical infrastructure that meets the requirements of contemporary engineering (Rane *et al*., 2023; Abedi *et al*., 2023; Firoozi *et al*., 2025a).

The literature also emphasises how digital design optimisation, when combined with geosynthetic applications, is becoming increasingly important. To model intricate soil-structure interactions, optimise geosynthetic choices, and forecast long-term performance under various situations, tools like Finite Element Modelling (FEM), Building Information Modelling (BIM), and Artificial Intelligence (AI) algorithms are being used increasingly. With the use of these digital tools, engineers can optimise material amounts, save building costs, and create solutions that are particular to a certain site while maintaining environmental sustainability (Omrany *et al*., 2023; Mohammed *et al*., 2025). Furthermore, geosynthetic-based designs are using life-cycle assessment (LCA) approaches to examine the environmental effect throughout the structure's life cycle, from material manufacturing to building, operation, and decommissioning. The review of the literature shows that combining geosynthetics with intelligent design tools improves technical performance while also making it easier to comply with sustainability objectives including reducing emissions, conserving resources, and building resilience to the effects of climate change. Even Nevertheless, there are still several obstacles to the broad use of intelligent geosynthetics that must be overcome by further study and industrial cooperation (Abedi *et al*., 2023; Chatrabhuj & Meshram, 2024; Gupta *et al*., 2024). According to the assessment, the main obstacles are the high upfront costs of sensor-embedded systems, the absence of standardised rules for the design, installation, and monitoring of smart geosynthetics, and the limited field validation of these materials under various environmental circumstances. Furthermore, real-time monitoring system-related data management, interpretation, and cybersecurity challenges raise new difficulties that need to be methodically resolved. The findings highlight the necessity of interdisciplinary cooperation between data scientists, geotechnical engineers, material scientists, and policymakers to create intelligent reinforcement systems that are scalable, affordable, and easy to use. By overcoming these obstacles, geosynthetics, in conjunction with digital optimisation and intelligent monitoring, might serve as the cornerstone of the upcoming generation of high-performance, adaptable, and sustainable ground improvement systems (Wang *et al*., 2022; Abedi *et al*., 2023; Acharya and Kogure, 2024).

Numerous studies have measured the ageing of "smart" geosynthetic sensors in real-world settings. For distributed fiber-optic sensing (DOFS), accelerated alkaline exposure (pH≈13.5), freeze-thaw, and immersion/drying cycles demonstrate that coating/interface degradation is the primary cause of accuracy loss; freeze-thaw effects are mild in comparison to high-alkali attack, and bonded surface cables typically outperform embedded ones under the same cycling (Alj *et al*., 2021). The choice of packaging or coating (acrylate vs. polyimide/carbon, for example) determines the drift rate for FBG/DOFS in cementitious media; comparable ocean-salinity research stresses corrosion-resistant packaging for extended service. Independent lab programs report quantifiable decreases in bond/strain-transfer efficiency and sensing range under alkaline conditions (Bremer *et al*., 2019; Liang *et al*., 2022; Liu *et al*., 2025b). Recent lab validation of in-place MEMS chains shows stability and error sources under prolonged operation; peer-reviewed and agency testing for MEMS inclinometers/tilt chains demonstrate high survivorship but temperature-dependent bias that has to be addressed (Freddi *et al*., 2023). FHWA publications that assess fiber-optic systems in bridge applications, ASTM Journal of Testing and Evaluation articles that compare distributed measurements with conventional instrumentation, and an ASTM practice for DOFS deployment in ground-movement monitoring (ASTM F3079/F3079-14(2020)) are all examples of independent validation that design owners can use (ASTM F3079-14, 2020; FHWA-HIF-24-085, 2024; Titilope *et al*., 2020).

3.4. Life Cycle Assessment (LCA) in Foundation Engineering

One of the most important methods for measuring and improving the environmental sustainability of ground improvement technologies is the incorporation of Life Cycle Assessment (LCA) into foundation engineering. The life cycle assessment (LCA) methodically assesses a system's environmental impacts at every stage of its life cycle, including the extraction of raw materials, production, transportation, building, use, maintenance, and recycling or disposal at the end of its useful life (Sakib *et al*., 2024; Singh *et al*., 2024). Traditional foundation methods, which primarily use steel, cement, and virgin aggregates, are a major source of construction waste, resource depletion, and greenhouse gas (GHG) emissions, per this research. For example, it takes almost 0.9 tonnes of CO_2 to produce one tonne of Portland cement, and the cement sector alone is responsible for around 8% of all human CO_2 emissions worldwide. The extraction of natural aggregates also uses a great deal of water and energy and disturbs ecosystems (Almusaed *et al*., 2024; Mishra *et al*., 2024; Ige *et al*., 2024). LCA studies, on the other hand, demonstrate that, in comparison to conventional approaches, the use of recycled concrete aggregate (RCA), fly ash, and geosynthetics in foundation systems may cut GHG emissions by as much as 40–60% during their lifespan. By using geosynthetics, which use less volume and less energy to transport, material consumption and carbon intensity are also decreased. Utilising sensor-embedded geotechnical systems in intelligent design techniques improves performance monitoring even further and lessens the need for premature replacement or frequent maintenance. LCA is not just a best practice but also a strategic necessity for future geotechnical engineering as these sustainable options are in line with international imperatives like the EU Green Deal, the UN SDGs, and national carbon reduction pledges (Pettinaroli *et al*., 2023; Singh *et al*., 2023; Dąbrowska *et al*., 2023; Reddy *et al*., 2024). Life-cycle assessment (LCA) boundaries should cover at least stages A1–A5 (material production through construction) and typical service periods. The reported 40–60% GHG reduction range for recycled-material foundation and pavement-base systems is based on scenarios assuming durability equivalent to conventional materials. According to several recent life cycle assessments and evaluations, this range is supported by optimised logistics and mix designs; however, when use-phase and maintenance are considered, the savings drop to about 15–45% (Azam *et al*., 2024; Zhao & Yang, 2024; Plati & Tsakoumaki, 2023). When compared to deferred corrective interventions, well-timed preventive maintenance frequently lowers whole-life emissions. However, dynamic and time-dependent life cycle assessments show that accelerated deterioration—caused by environmental factors like warming, moisture, or traffic loading—can undermine these benefits by increasing maintenance frequency or bringing forward replacement. Therefore, using published models that demonstrate how maintenance scheduling affects life cycle GHG outcomes, the 40–60% value is combined with an explicit durability-equivalence assumption and sensitivity analyses with shorter maintenance intervals (Chen *et al*., 2021; Yang *et al*., 2024). Post-service "carbon rebound" effects, such as complete replacement cycles and recurring embedded impacts, are being examined more in dynamic life cycle assessments (LCAs) for pavements and buildings, although they are still not well understood in geotechnical applications. Using well-established dynamic-LCA techniques, we will (i) draw attention to the existing research gap, (ii) incorporate an end-of-life module with comparison scenarios for foundation reuse vs full replacement, and (iii) incorporate temporal impacts (Song *et al*., 2020; Salati *et al*., 2025; Su *et al*., 2022; FHWA-HIF-18-055, 2018). Lastly, by referencing independent syntheses and agency reports—such as FHWA and ROSA P compilations—that compile LCA methodology, data ranges, and factorisation pertinent to recycled materials and maintenance, this will reaffirm transparency and repeatability (Gruber & Hofko, 2023). The utilisation of industrial by-products for sustainable geotechnical applications is a cyclical process, as shown in Figure **2**. Production is where everything starts, with materials coming from industrial processes like the production of steel. Slag and fly ash are byproducts of these processes. The by-products are then processed to improve their qualities and make them appropriate for use in geotechnical applications. They are utilised in soil stabilisation at the application stage to increase strength and lessen environmental effect, completing a sustainable cycle.

The analysis emphasises that, in foundation engineering, the most significant environmental effects usually arise during the extraction and manufacturing stages of materials—especially for traditional systems that depend on steel and concrete (Mehta, 2024). Steel has an embodied energy of 20 to 35 MJ/kg, whereas cement manufacturing alone contributes around 8% of world CO_2 emissions. By reducing embodied carbon by 45–70% when compared to virgin materials, alternative resources including fly ash, ground granulated blast furnace slag (GGBS), and recycled concrete aggregates (RCA) can help offset these high environmental costs (Karadumpa & Pancharathi, 2024; KC *et al*., 2025). Furthermore, in addition to conserving raw materials, geosynthetics made from recycled polymers like polypropylene and polyethylene help reduce the weight of foundation systems, which lowers transportation emissions. Engineers may precisely adjust designs using advanced digital technologies like finite element modelling (FEM), Building Information Modelling (BIM), and optimisation algorithms. This allows for material savings of up to 20% without sacrificing structural integrity or safety (Afzal *et al*., 2023; Dąbrowska *et al*., 2023; Wu *et al*., 2025). According to case studies included in this analysis, these eco-friendly practices lead to infrastructure that lasts longer, requires less maintenance, and is more resilient to climate-related pressures like floods and subsidence. To quantify these benefits and support more economical, environmentally friendly, and scientifically supported design choices in contemporary foundation engineering, Life Cycle Assessment (LCA) metrics like Global Warming Potential (GWP), embodied energy (measured in MJ/kg or MJ/m2), and water consumption are being used increasingly (Rohde, 2023; Obar, 2023).

The increasing acknowledgement of the operating and maintenance phases as crucial elements in Life Cycle Assessment (LCA) assessments of foundation systems is another important finding from the literature. The cradle-to-gate phases have historically been the

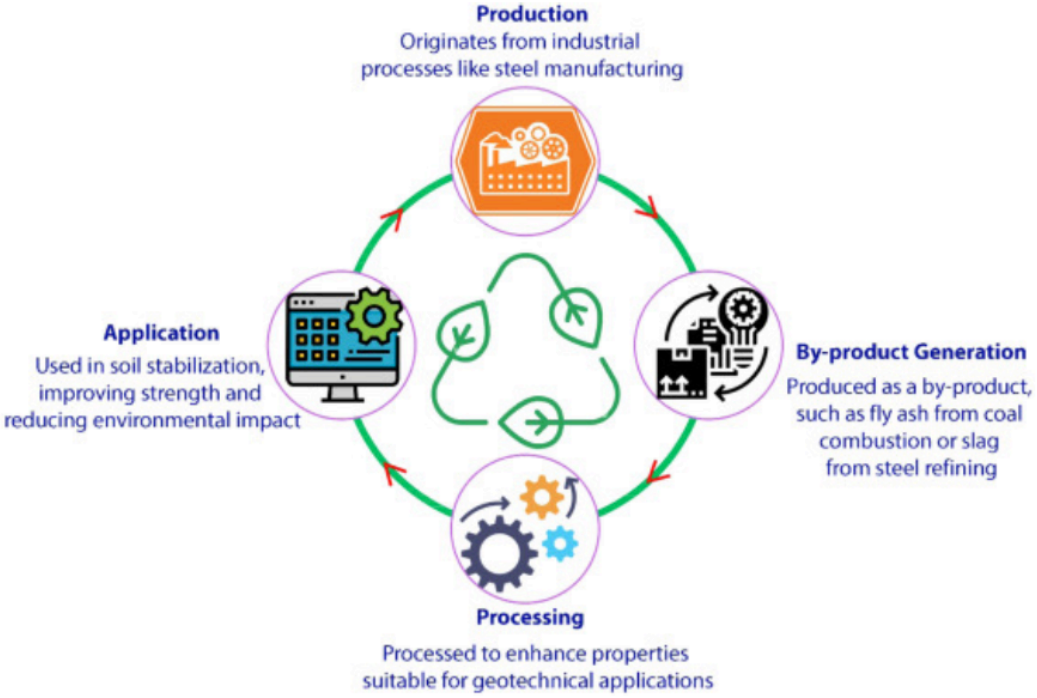

Figure 2: Sustainable Use of Industrial Waste in Geotechnical Engineering (Firoozi *et al*., 2025b).

focus of many LCA studies, ignoring the long-term effects of infrastructure usage and maintenance. However, new research indicates that these long-term effects might be considerably lessened by foundations equipped with smart monitoring technologies, such as wireless data gathering networks, fibre optic sensors, and piezoelectric devices (Fnais *et al*., 2022; Ghoroghi *et al*., 2022; Ju *et al*., 2023; Sivasuriyan *et al*., 2024; Song *et al*., 2025). Sensor-embedded geosynthetics, for example, can identify early indicators of structural distress, pore pressure accumulation, or deformation, allowing for prompt interventions and averting catastrophic failures. When compared to traditional methods, intelligent systems have been shown in studies to reduce maintenance frequency and related environmental impacts by up to 30–40%. These solutions also assist delay the need for resource-intensive restoration by extending the functional service life of foundations by 20% or more (Abedi *et al*., 2023; Ukoba *et al*., 2023; Lekshmi *et al*., 2025). Furthermore, LCA models that include cradle-to-grave or cradle-to-cradle scenarios offer wider co-benefits like less traffic disruptions, which in urban areas can result in large indirect emissions, less material and energy required for repairs, and improved user safety—all of which significantly improve the triple bottom line of sustainability. A comprehensive life cycle approach is necessary to comprehend and maximise the environmental, economic, and social performance of foundation designs as infrastructure systems encounter mounting demands from ageing assets and climatic unpredictability (Roswag-Klinge *et al*., 2022; Amir *et al*., 2023; John *et al*., 2025a).

Despite the obvious benefits, this research identifies several obstacles that continue to restrict the use of LCA in foundation design. The intricacy of modelling long-term environmental interactions such leaching, biodegradation, and the effects of climate change, the absence of standardised LCA databases for geotechnical materials, and the scarcity of site-specific emissions data are some of the main obstacles. Due to of their perceived complexity, time restrictions, and lack of practitioner knowledge, LCA techniques are frequently underutilised in early-stage decision-making. The assessment highlights the necessity of further interaction with Building Information Modelling (BIM), streamlined LCA approaches designed especially for civil engineering applications, and more transparent regulatory incentives to promote adoption. Foundation engineers can make a significant contribution to the worldwide shift towards low-carbon, resource-efficient, and climate-resilient infrastructure systems by integrating life cycle assessment (LCA) into standard engineering practice, backed by solid data, useful tools, and interdisciplinary cooperation (de Melo *et al*., 2024; Kumar *et al*., 2025; El Hajj & Martínez Montes, 2025).

3.5. AI for Optimized Material Selection

The incorporation of Artificial intelligence (AI) in material selection is a groundbreaking development in sustainable foundation engineering that enables more cost-effective, environmentally conscious, and efficient decision-making. The findings of this study show that artificial intelligence (AI)-driven models, such as machine learning algorithms, neural networks, and optimisation frameworks, can evaluate large and intricate datasets to determine the best mixes of soil types, recycled materials, and geosynthetics for geotechnical applications (Rane, 2023; Saad *et al*., 2023). Conventional methods for choosing materials frequently depend on engineer expertise and empirical methods, which might result in conservative designs that could exclude novel or underutilised materials with better performance or sustainability credentials. AI tools, on the other hand, are able to handle multidimensional data, such as material qualities, environmental circumstances, financial considerations, and life cycle implications, to produce suggestions that are optimal and strike a compromise between environmental goals and technical performance. AI's ability to manage complexity and unpredictability makes it a crucial facilitator of sustainable foundation design for the future (Rane, 2023; Wang *et al*., 2024; Liu *et al*., 2025a). Artificial intelligence's (AI) ability to support multi-objective optimization—the simultaneous evaluation of several, frequently conflicting criteria, including strength, durability, cost, embodied carbon, and environmental risk—is one of AI's most revolutionary contributions to sustainable foundation engineering. Several successful case studies are highlighted in the literature review, wherein evolutionary algorithms—specifically, Genetic Algorithms (GA) and Particle Swarm Optimisation (PSO)—have been used to identify the best combinations of recycled aggregates, industrial by-products (such as fly ash and ground granulated blast furnace slag), and soil stabilisers for ground improvement. With their tremendous computational efficiency, these algorithms can traverse large design domains and provide material mix designs that strike a compromise between sustainability and performance (Hussein *et al*., 2024; Jiang *et al*., 2024; Tajadod *et al*., 2025). Simultaneously, supervised machine learning models like Random Forests and Support Vector Machines (SVM) have shown excellent accuracy in predicting important mechanical behaviours like shear strength, modulus of elasticity, and unconfined compressive strength in geosynthetic-reinforced soils, frequently with R^2 values above 0.90. These prediction models leverage massive datasets from lab and field studies to provide more informed and data-driven decision-making. AI-powered tools also make it easier to find new and unusual material synergies, including hybrid blends that include recycled plastics, fly ash, shredded rubber, and geotextiles—combinations that would not be discovered by standard empirical approaches. Engineers can greatly increase the range of sustainable material options while maintaining structural performance and regulatory compliance by incorporating these intelligent models into design workflows. This will hasten the shift to resilient and ecologically conscious foundation systems (Nafees *et al.*, 2022; Madanchian & Taherdoost, 2024).

Real-time decision-making and adaptable design are two other significant benefits of artificial intelligence (AI) in foundation engineering that have been highlighted in the literature. This is especially true when combined with Internet of Things (IoT) technology and geotechnical monitoring systems. This integration enables foundation engineers to use sensor networks embedded in geosynthetics or installed inside the subgrade to continually monitor in-situ data, including pore water pressure, soil settlement, stress distribution, and moisture fluctuation (Rane, 2023; Abedi *et al.*, 2023). Engineers may dynamically modify foundation reinforcement tactics or material utilisation by using AI algorithms, particularly those based on deep learning and time-series analysis, to understand these massive data streams in real time and spot abnormalities or new trends (Rane, 2023). In a case study with a Chinese highway embankment, for instance, the incorporation of AI models with sensor networks resulted in a 20% reduction in construction delays and the early identification of soil deformation, which allowed for prompt remedial measures (Cheng *et al.*, 2024; Lin *et al.*, 2025). Similarly, it has been demonstrated that machine learning-powered predictive maintenance models may effectively anticipate structural degradation or instability based on historical and real-time statistics, reducing the frequency of significant interventions by up to 30% (Chitkeshwar, 2024; Shamim, 2025). By reducing material waste, lifetime carbon emissions, and the need for ecologically disruptive emergency repairs, these AI-driven capabilities not only improve structural resilience and operating efficiency but also advance sustainability goals. Intelligent and flexible foundation systems that are adapted to changing site circumstances have replaced static, one-time design techniques. This dynamic and data-responsive approach represents a paradigm change (Rane *et al.*, 2024; Culberson, 2025).

The incorporation of geographic data, in-situ test results, and sensor input into adaptive learning frameworks, new work has started to handle spatial heterogeneity at project size, even though AI-based mixture optimisation has so far mostly been proven in laboratory or numerical contexts. (Chen *et al.*, 2025; Huang *et al.*, 2024b). AI and mechanistic-empirical design hybrid models enable local mixture parameter calibration in response to change qualities of the soil, recycled material, and reinforcement. Transfer learning and federated learning are two methods that have been used to adapt laboratory-trained models to diverse outdoor situations without requiring complete retraining (Chen *et al.*, 2025; Yang *et al.*, 2025d). Large-scale, publicly reported validations are still few but are becoming more common; examples include highway base-course projects in the US and China that use AI-assisted gradation and binder optimisation, which are tracked over several years using non-destructive testing and embedded geosynthetics (Dwivedi & Suman, 2023; Butle *et al.*, 2025). In the paper, we will point out that although methodological preparedness is improving, there are currently few large, publicly available field datasets for AI-driven mixture optimisation, and more post-construction performance data sharing is required for independent benchmarking.

For complex systems, recent developments in uncertainty-based multidisciplinary design and optimisation (UBMDO) combine optimisation, sensitivity analysis, and uncertainty modelling to enhance reliability forecasts. Recycled-material foundations exposed to varying loads and environmental conditions are directly affected by these changes (Meng & Zhu, 2024). Intelligent optimization-enhanced support vector regression (SVR) modelling, for example, has been demonstrated to produce more conservative durability estimates for offshore structures while increasing prediction accuracy by 31.2% when integrated into a hybrid-uncertainty fatigue framework. These techniques are useful for predicting the long-term performance of foundations made of recycled materials (Meng *et al.*, 2025). Probabilistic fatigue life assessment methods, which are commonly advised for offshore oil and gas structures, specifically address environmental and structural uncertainties. This method can also improve durability assessments of recycled-material foundations (Correia *et al.*, 2025). To improve structural integrity and environmental safety throughout their service life, Huang and Ai (2025) determined key vulnerability parameters (KVPs) for steel pipe pile-supported wharves (SPPSWs). The displacement ductility coefficient was shown to be the most appropriate engineering demand parameter (EDP), while the axial compression ratio, pile diameter, and free length of the landward pile were identified as the most crucial KVPs using pushover and sensitivity studies. Degradation processes such material deterioration, moisture susceptibility, freeze-thaw cycling, and pollutant leaching were taken into consideration throughout this selection process. An extended soft Monte Carlo simulation with SVR (EMCS-SVR), which increases computational accuracy and efficiency in low-failure-probability, high-dimensional structural reliability issues, is one of the additional contributions. Despite the same degradation causes, this method maintains environmental safety and long-term structural integrity (Yang *et al*., 2025a). Furthermore, the evaluation of hydrogen-induced damage (HID) in steel pipes X65 and X80 has been conducted using reliability models that incorporate an upgraded first-order reliability approach (FORM). Results indicate that internal pressure, wall thickness, and model error continue to be the key affecting variables, while HID considerably lowers structural dependability, particularly in X80 grade (Yang *et al*., 2025b).

There are several affordable retrofit techniques available, but data silos continue to be a significant barrier to achieving complete BIM–IoT–AI integration in smart foundation applications. Using wireless low-power wide-area network (LPWAN) technologies (such as LoRaWAN and NB-IoT), sensor networks may be set up in modular or staged configurations to save installation costs and eliminate the need for substantial cabling in already-existing infrastructure. Without needing a complete conversion, edge gateways can integrate with existing BIM platforms by aggregating data from many sensor types and converting it into common interchange formats, most frequently IFC (Industry Foundation Classes) or CityGML (Ouaissa *et al*., 2024; Islam *et al*., 2024). IoT devices and BIM databases are increasingly being connected via middleware solutions that enable RESTful APIs for cloud-based services and OPC UA (Open Platform Communications Unified Architecture) for real-time industrial data in older BIM systems. The open-source FIWARE ecosystem, which supports NGSI-LD standards for semantic interoperability across smart-infrastructure platforms, MQTT (Message Queuing Telemetry Transport, ISO/IEC 20922) for lightweight publish-subscribe messaging, and OPC UA (IEC 62541) for secure, platform-independent machine-to-machine communication are examples of mature open APIs and communication protocols that are already in use (Ieva *et al*., 2024). The bSDD (buildingSMART Data Dictionary) and the IFC format of buildingSMART offer a reliable foundation for connecting sensor data streams to model entities in BIM integration. Near-real-time monitoring and long-term archiving in pre-existing BIM settings are made possible by merging open communication standards (OPC UA, MQTT) with open BIM standards (IFC, bSDD). An open-standards-based retrofit architecture—edge gateways, standardised data models, and interoperable protocols—offers a tried-and-true, economical approach to avoid data silos and extend smart-foundation capabilities to outdated infrastructure, even while proprietary connections still rule some industries (Sadeghi *et al*., 2023; Ieva *et al*., 2024).

The research highlights several obstacles that need to be overcome to fully utilise AI, even if it has the potential to optimise the selection of materials for sustainable foundations. These include the lack of high-quality, comprehensive datasets, which are necessary for training strong AI models; worries about the interpretability and transparency of models, which can affect practitioner confidence and regulatory approval; and the requirement for interdisciplinary cooperation between sustainability specialists, data scientists, and geotechnical engineers. Additionally, it is imperative to link AI technologies with platforms for Building Information Modelling (BIM) and Life-Cycle-Assessment (LCA) to make sure that material selections support more general sustainability and resilience objectives. The results indicate that in addition to technology advancement, industrial practice, educational reform, and governmental framework modifications will be necessary to further AI adoption in this area. When these obstacles are removed, AI-driven material selection might greatly improve foundation engineering's efficiency, sustainability, and responsiveness to changing social and environmental demands (Rane, 2023; Rane *et al*., 2024; Adewale *et al*., 2024; Eke & Shuib, 2025).

3.6. Environmental and Economic Implications

Significant environmental benefits result from the shift to using recycled materials and geosynthetics in foundation engineering, which directly supports global sustainability goals including resource efficiency, carbon reduction, and the adoption of the circular economy. This study demonstrates that using recycled and waste-derived materials instead of conventional foundation materials, including cement, steel, and virgin aggregates, may greatly lessen environmental impacts without compromising structural integrity. For example, it has been demonstrated that using recycled asphalt pavement (RAP) and crushed concrete in base and subgrade layers may reduce embodied carbon by as much as 40% when compared to virgin aggregates (Dąbrowska *et al*., 2023; Peng *et al*., 2025; Yaro *et al*., 2023). Similarly, as Portland cement contributes around 8% of global CO_2 emissions, using fly ash and ground granulated blast furnace slag (GGBS) as partial cement substitutes can reduce CO_2 emissions by up to 70%. The use of geosynthetics, such as geotextiles and geogrids composed of recycled polymers, improves environmental performance by minimising the need for deep excavation, minimising the use of heavy machinery, and maximising load distribution to prolong the service life of infrastructure. Foundation systems using geosynthetics can minimise land disturbance and habitat degradation while reducing greenhouse gas emissions by 20–50%, according to Life Cycle Assessment (LCA) research (Ahmad *et al*., 2022; Dąbrowska *et al*., 2023; Liu *et al*., 2024; Chatrabhuj and Meshram, 2024). By reducing soil disturbance, reducing construction waste, and improving ecosystem preservation, these developments collectively make a compelling argument for the widespread adoption of sustainable foundation techniques that are in line with the Sustainable Development Goals (SDGs) of the UN (Nanehkaran *et al*., 2023; Brandão & Verissimo, 2024; Naskar *et al*., 2025).

The study also emphasises how important sustainable foundation design is to promoting resource saving and efficient waste disposal. Large amounts of material that would otherwise end up in landfills or incinerators are converted into high-value building materials by repurposing industrial by-products like fly ash, slag, and silica fume, as well as post-consumer waste like crushed concrete, rubber tires, and plastics, into geotechnical applications. The U.S. Environmental Protection Agency (EPA) claims that only utilising recycled concrete may save the disposal of more than 70 million tonnes of garbage every year. Moreover, geosynthetics, particularly those made from recycled polypropylene or polyethylene, have 50-year or longer lifespans, which greatly lowers the need for frequent repairs and conserves raw resources throughout the course of the infrastructure's life cycle. The review's case studies show that using recycled materials in foundation systems can reduce greenhouse gas emissions associated with materials by as much as 40% (Joseph, 2018; Forster, 2022; Al-Sharif *et al*., 2024; Keskin *et al*., 2024). It also improves soil performance in difficult environmental conditions like high salinity, acid sulphate soils, and seismic loading. For example, it has been demonstrated that fly ash increases strength and resistance to sulphate attack, whereas shredded tyre rubber enhances energy absorption and damping under dynamic loading situations. Together with intelligent monitoring systems that maximise material use, identify wear or deterioration early, and provide predictive maintenance, these functional and environmental advantages are further enhanced. By reducing needless repairs and material waste, this integration strengthens the ideas of sustainable infrastructure development and the circular economy (Saad *et al*., 2024; Molęda *et al*., 2023; Kandpal *et al*., 2024).

From an economic perspective, there are significant immediate and long-term financial gains when recycled materials and geosynthetics are used into foundation engineering. Reduced dependency on pricey virgin materials like steel, cement, and natural aggregates, as well as more compact foundation designs that need less excavation and material handling, result in immediate cost savings. For instance, it has been demonstrated that geosynthetic-reinforced foundations require 25–50% less material volume than conventional systems, which leads to considerable savings in labour, installation, and transportation expenses. The International Geosynthetics Society reports that the usage of geogrids and geotextiles can up to 30% lower building costs in some infrastructure applications (Abedi *et al*., 2023; Dąbrowska *et al*., 2023; Esen d*et al*., 2023; Chatrabhuj and Meshram, 2024; Zornberg *et al*., 2024). Additionally, these systems' increased robustness and longer lifespan result in fewer maintenance procedures and less long-term repair expenses. Comparing sustainable foundation designs with conventional alternatives, Life Cycle Cost Analysis (LCCA) studies regularly show that using recycled aggregates, fly ash, or polymer-based geosynthetics can result in savings of 10–20% over a 30-year period. Furthermore, Net Present Value (NPV) analyses show that initial expenditures on sustainable materials and intelligent design are usually recouped within the first ten years of operation because of lower operating and maintenance costs. These cost benefits could increase as the market for recycled materials expands and processing methods improve, making eco-friendly foundation systems more cost-effective and competitive in both developed and growing nations (West *et al*., 2024; Gaur *et al*., 2024; Husainy *et al*., 2024; Firoozi *et al*., 2025a). In the development of international standards for recycled-material geotechnical systems, such as within ISO/TC 221, a balanced approach is best achieved by coupling a concise, performance-based core set of generic clauses with regionally configurable annexes. The generic clauses should specify universal performance objectives, essential durability and mechanical property requirements, and reference standardized ISO test methods to ensure global consistency in measurement. Regional annexes—following models such as the Eurocode 7 National Annex framework—would allow each country or climatic zone to select parameter values, partial or resistance factors, exposure classifications, and calibration procedures tailored to local geotechnical, climatic, and loading conditions (Fagone *et al*., 2023; Rianna *et al*., 2023; Abou Chaz, 2024). A practical governance mechanism for this is a three-tier compliance framework: Tier 1 (prescriptive rules) for low-risk, routine works with limited testing; Tier 2 (performance-based) for typical infrastructure projects requiring project-level testing and statistical property reporting; and Tier 3 (advanced calibrated design) for high-risk or innovative applications involving comprehensive site characterization, probabilistic reliability calibration, and long-term monitoring. This tiered structure supports both rapid adoption in data-limited contexts and high-precision design in complex projects. To ensure continual improvement and harmonization, the standard should require statistical descriptors (mean, bias, standard deviation or coefficient of variation, distribution type, and spatial cwasorrelation) in Tier 2 and Tier 3 submissions and promote data sharing through an international repository or template system managed jointly by ISO, CEN, and IGS. Such a framework maintains global comparability, preserves flexibility for regional adaptation, and creates a clear pathway for progressively calibrated, reliability-based design factors as local datasets mature (Soomro *et al*., 2025; Sapkota *et al*., 2025; Liu *et al*., 2025c).

This study identifies several enduring obstacles that impede the wider use and scalability of sustainable foundation engineering, despite the many economic and environmental advantages linked to it. The quality, gradation, and physical characteristics of recycled materials, including materi ash, reclaimed asphalt pavement (RAP), and crushed concrete, vary widely, which is a major cause for concern. This can result in unpredictable geotechnical performance and present risks to engineering and finances. In a survey conducted by the European Environment Agency (EEA), over 40% of civil engineering firms stated that quality variability is one of the primary barriers to employing recycled materials (Mariyappan *et al*., 2023; Armistead, S. J., & Babaahmadi, 2025; Oshilalu, 2024). Additionally, even if smart technologies like wireless data gathering systems and fiber-optic sensors have become less expensive recently, the initial capital expenditure is still prohibitive, especially in areas with low and moderate incomes. The absence of standardised testing procedures and legal frameworks controlling the use of secondary materials in ground improvement exacerbates this, reducing design confidence and fostering ambiguity. In addition, practitioners lack sufficient information about life cycle assessment (LCA), circular economy tactics, and the long-term advantages of sustainable design, all of which impede well-informed decision-making. Policymakers, business stakeholders, and academic institutions must work together to create clear performance requirements, offer financial incentives, and provide focused training programs, according to the analysis. In the face of global environmental and infrastructure challenges, the incorporation of recycled materials and geosynthetics, along with intelligent monitoring and quality assurance, can become a cornerstone of resilient, low-carbon, and economically viable foundation systems if such enabling mechanisms are in place (Abedi *et al*., 2023; Fuentes-Peñailillo *et al*., 2024; De Feo & Ferrara, 2024; Panagiotidou *et al*., 2025).

3.7. Limitations and Future Direction

This study identifies several significant constraints that should be carefully considered, although the encouraging environmental, technological, and financial advantages shown by the incorporation of recycled materials and geosynthetics in sustainable foundation systems. The uneven quality, unpredictability, and lack of standardisation of recycled materials used in foundation engineering and ground improvement constitute one of the biggest obstacles. Crushed concrete, recycled asphalt, plastic debris, and industrial by-products are examples of waste-derived components that, in contrast to virgin materials, frequently show notable variation in terms of particle size, chemical content, and mechanical qualities. Due to this diversity, practitioners and regulators may be hesitant to completely utilise these materials in critical infrastructure applications due to concerns about strength development, durability, and long-term performance. The lack of widely recognised standards and standardised testing procedures makes this problem even worse and raises questions about the dependability and security of foundation systems made of recycled materials (Saini & Ledwani, 2024; Naskar *et al*., 2025; Nagaraju & Ravindran, 2025).

The limited incorporation of intelligent design tools and real-time monitoring with material selection and performance optimisation is another significant constraint found in the existing body of knowledge. Although the potential of AI, machine learning, and sensor-embedded geosynthetics has been investigated in discrete applications, there is still a significant lack of fully integrated systems capable of managing the full foundation project lifecycle, from design to construction to maintenance. Large, high-quality datasets are necessary to increase accuracy and dependability of many AI models used in material optimisation, which are currently in the experimental or pilot stages. Widespread use of intelligent monitoring technology is also still hampered by issues with cybersecurity, data interoperability, and their high initial cost. To develop flexible, scalable, and financially feasible solutions, geotechnical engineers, data scientists, material scientists, and digital infrastructure experts will need to work together more closely to narrow this technological divide (Rane *et al*., 2023; Lone *et al*., 2023).

The research also emphasises how important it is to consider socioeconomic and environmental factors that go beyond technical performance and material economy. Even though geosynthetics and recycled materials have quantifiable environmental benefits, thorough Life Cycle Assessment (LCA) studies are still scarce, especially when it comes to assessing long-term environmental effects like leaching of pollutants from industrial byproducts or microplastic pollution from polymer-based geosynthetics. The socioeconomic aspects of implementing these innovations, including their effects on local employment, material supply chains, community acceptability, and policy frameworks, are also still not well studied in the literature. To close these gaps, a multifaceted strategy integrating social justice, environmental science, and governance analysis is needed to make sure that the drive for sustainable foundations doesn't unintentionally introduce new environmental or social hazards (Dąbrowska *et al.*, 2023; Chatrabhuj and Meshram, 2024).

The creation of next-generation materials, digital integration, and governmental support should be the main areas of concentration for sustainable foundation engineering going ahead. Research on carbon-negative additives, advanced composites made with nanomaterials, and bio-based geosynthetics has great potential to improve structural and environmental performance even more. The design, construction, and maintenance of foundations may also be completely transformed by the development of digital twins for foundation systems, which seamlessly incorporate automated decision-making, predictive analytics, and real-time monitoring. To facilitate this shift, governments, business associations, and educational institutions must collaborate to create uniform standards, performance criteria, and incentive programs that encourage the broad use of these advancements. In the end, the combination of intelligent systems, circular economy concepts, and material innovation presents a convincing route towards foundation engineering that is robust, flexible, and sustainable for the challenges of the twenty-first century (Omrany *et al.*, 2023; Asmara, 2025).

3.8. Recommendations

Standardised guidelines that clearly define material specifications, design codes, and performance standards for the use of recycled materials and geosynthetics must be developed and put into place to hasten the shift towards more intelligent and sustainable geotechnical foundation systems. These rules will guarantee safety, uniformity, and wider acceptability across projects in addition to boosting industry trust. Simultaneously, it is critical to develop intelligent monitoring capabilities and incorporate artificial intelligence (AI) into geotechnical practice. Throughout the asset lifespan, adaptive, predictive, and data-informed decision-making may be made possible by the development of real-time monitoring systems, digital twin models, and AI-driven material selection and performance optimisation tools, eventually enhancing sustainability and resilience. The long-term environmental, economic, and social ramifications of using sustainable building materials and methods must also be thoroughly understood by increasing the use of thorough environmental assessments, such as social impact analyses and cradle-to-grave life cycle assessments (LCA). Geotechnical design may further promote material efficiency, waste reduction, and resource recovery by using circular economy concepts. The broad adoption of sustainable practices should be promoted by implementing specific policy incentives, including as tax breaks, green procurement regulations, and capacity-building initiatives for engineers, contractors, and developers, to support these technological breakthroughs. Finally, to push the boundaries of innovation and meet the challenging environmental standards needed for future infrastructure systems, consistent investment in research on next-generation materials—such as carbon-neutral or carbon-negative alternatives, nanomaterial-enhanced composites, and bio-based geosynthetics—will be essential. These steps collectively provide a thorough route towards geotechnical engineering solutions that are safer, more intelligent, and more sustainable.

Even though green public procurement (GPP) has promoted circular geotechnics, evidence from World Bank and EU markets shows that poorly designed schemes can lead to supplier opportunism, reduced competition, and adverse selection. These failures often stem from vague environmental standards, limited market capacity, or weak verification. Reviews by the European Court of Auditors and multilateral agencies warn that without measurable life-cycle performance specifications, third-party verification, and staged rollouts, GPP may favour incumbents offering lower-priced but lower-quality products, undermining durability and environmental goals. Key regulatory lessons include: (i) requiring quantifiable performance-based criteria over generic “green” labels; (ii) assessing market readiness and piloting before full rollout; (iii) enforcing life cycle costing and rejecting abnormally low bids; (iv) demanding robust certification and traceability; and (v) fostering SME competition to prevent market concentration. To ensure incentives support sustainable foundation practice, we will summarise these lessons in a policy subsection with international examples and safeguards such as performance specifications, phased procurement, and strict post-award monitoring.

4. CONCLUSIONS

Geotechnical engineering's use of smart and sensor-embedded technology signifies a revolutionary change in the planning, building, monitoring, and maintenance of infrastructure. The current trends, technological advancements, and prospects of intelligent geotechnical systems have been critically examined in this paper. It has also highlighted the role that advanced sensing technologies like fibre optic sensors, wireless sensor networks, and Internet of Things (IoT)-based solutions play in enabling accurate, continuous, and real-time monitoring of geotechnical assets. By improving building processes, extending the service life of vital infrastructure, and identifying early warning indicators of failure, these technologies are radically changing engineers' abilities to increase safety, resilience, and sustainability. Additionally, the conversation has highlighted the increasing need of predictive maintenance, artificial intelligence, and data analytics in improving decision-making in geotechnical asset management. Engineers may lower risks and operating expenses by switching from reactive to proactive maintenance procedures by using the massive volumes of data produced by sensor-embedded systems. The use of these technologies in slopes, embankments, retaining walls, and foundations shows how broadly they may be applied to address technical issues and environmental concerns in geotechnical engineering practice.

However there are still a lot of obstacles in the way of these developments. The broad use of intelligent geotechnical systems is still constrained by problems with sensor robustness, data standardisation, interoperability, cost, and the requirement for interdisciplinary integration. Comprehensive study is also desperately needed to fill up the information gaps that now exist, especially in the areas of long-term performance, environmental effects, and the creation of strong design and monitoring criteria. Facilitating cooperation among academics, business, and politicians will also be essential in developing the training curricula, regulatory frameworks, and financial incentives required to speed up innovation and adoption. Looking ahead, the combination of digital twin models, smart materials, sophisticated sensing, and sustainable design techniques will shape geotechnical engineering in the future. To construct infrastructure systems that are not only safer and more robust but also in line with global sustainability and circular economy goals, it will be crucial to embrace intelligent and adaptive geotechnical solutions as urbanisation, climate change, and infrastructure demands increase. Smart geotechnical systems will be able to realise their promise as a key component of next-generation civil infrastructure if research, standardisation, and capacity building are sustained.

CONFLICTS OF INTEREST

The author declared no conflicts of interest.

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