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REVIEW PAPER

Eco-Friendly Geosynthetics- A Sustainable Shift in Construction

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ABSTRACT

Geosynthetics, synthetic materials used in civil engineering, have revolutionized the way we approach geotechnical problems. This review paper provides an overview of the different types of geosynthetics, their functions, and their applications in various civil engineering projects. By understanding the benefits and limitations of geosynthetics, engineers can make informed decisions to optimize the design and construction of infrastructure projects. As technology and demand continue to evolve, the future of construction looks increasingly green, with eco-friendly geosynthetics playing a central role in shaping a more sustainable built environment.

HIGHLIGHTS

- Geosynthetics have been widely used in construction for decades due to their ability to improve soil stabilization, drainage, erosion control and other foundational functions
- These synthetic materials, composed of polymers, are manufactured in various forms, including sheets, nets, and grids.
- By strategically placing geosynthetics within soil structures, engineers can achieve significant improvements in terms of strength, stability and permeability.

Keywords: Geosynthetics, biodegradable, Soil erosion, stabilization, sustainable

Geotechnical engineering deals with the behaviour of earth materials and their interaction with structures. Over the years, various techniques and materials have been employed to improve soil properties and enhance the performance of structures. Geosynthetics, a relatively recent innovation, have emerged as a powerful tool in the geotechnical engineer's toolkit. These synthetic materials, composed of polymers, are manufactured in various forms, including sheets, nets, and grids. By strategically placing geosynthetics within soil structures, engineers can achieve significant improvements in terms of strength, stability and permeability. The shift toward eco-friendly geosynthetics represents a significant step in the construction industry's move toward sustainability. By embracing innovative, biodegradable, recyclable and energy-efficient alternatives, the industry can reduce its environmental impact while maintaining the high performance and durability required for modern infrastructure projects. As technology and demand continue to evolve, the future of construction looks increasingly green, with eco-friendly geosynthetics playing a central role in shaping a more sustainable built environment.

The construction industry is a cornerstone of economic growth and the choice of materials significantly impacts a project's cost, durability,

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sustainability and aesthetic appeal. Current climate models indicate that rising temperatures are intensifying the Earth's water cycle. Climate change affects precipitation—rainfall distribution and intensity are changing and floods and droughts are becoming more frequent. Wind speeds are increasing worldwide. Maximum and minimum temperatures, frost depths and the length and thickness of snow cover are changing and rising sea levels have a devastating impact on coastal areas. All these changes affect the design, construction and maintenance of engineering structures. The damaging action of water is becoming more frequent and intense, requiring the creation of new flood defences and more effective protection against the destructive effects of water erosion. Heat waves are also becoming more common, requiring the use of appropriate building materials and air-conditioning equipment, which increases energy consumption. Due to climate change, engineering structures must be designed to new load and foundation standards or statistical river flows.

Current research indicates that in civil engineering structure failures and disasters are mainly triggered by weather and climate-related hazards. On the other hand, the construction sector undoubtedly influences human-caused climate change and is the major contributor to greenhouse gas emissions (almost 40%), excavation and consumption of raw materials (50%), energy consumption (40%) and global waste production (30%). Moreover, construction activities cause significant land, water and air degradation, including eutrophication, acidification and particulate formation, ozone depletion, desertification, deforestation, soil erosion and high-water resources consumption.

Before the advent of geosynthetics, construction relied heavily on natural materials such as sand, clay and gravel. These materials often exhibited inconsistencies in quality and performance, requiring large quantities and additional layers for desired outcomes. For instance, clay was used for waterproofing and as a barrier, but it had limitations in terms of permeability and durability. Gravel and sand were used for drainage and filtration, but they were prone to clogging and erosion.

The objective of this review is to contribute to the growing body of knowledge on the role of eco-friendly geosynthetics in creating a more sustainable, climate-resilient and resource-efficient built environment, while highlighting the challenges and opportunities for the construction industry to adopt these materials on a larger scale in driving a sustainable shift in construction practices. This review paper explores key research and findings related to eco-friendly geosynthetics, their types, environmental impact and potential applications in construction.

The need for change

A combination of factors propelled the construction industry towards more sustainable and efficient solutions. Growing awareness of environmental issues, such as soil erosion, pollution and resource depletion, necessitated eco-friendly alternatives. The rising costs of traditional materials and the need for long-term infrastructure durability drove the search for cost-effective solutions. Traditional construction materials, such as concrete, steel and asphalt, often have significant environmental impacts. The production and use of these materials consume large amounts of energy, release greenhouse gases and contribute to resource depletion. Geosynthetics, on the other hand, offer a more sustainable alternative, as the geosynthetics, especially those made from natural fibers or biodegradable materials, typically have lower energy consumption during manufacturing, thus helping reduce greenhouse gas emissions (Mwasha, 2009). In many construction projects, weak soils or unstable ground conditions require additional reinforcement to support structures like roads, bridges, and buildings. Traditional methods, such as deep foundations or soil stabilization using cement, can be expensive and disruptive to the environment. Geogrids and geotextiles can increase the load-bearing capacity of weak or loose soils, reducing the need for expensive excavation or soil replacement.

The Emergence of Eco-Friendly Geosynthetics

The increasing demand for sustainable practices in the construction industry has led to the development and adoption of eco-friendly geosynthetics, materials designed to minimize environmental impact while maintaining performance standards. One of the most promising developments is the creation of biodegradable geosynthetics. These materials are designed to break down over time, reducing long-term environmental impact, especially in applications like erosion control or temporary soil stabilization. Some biodegradable geosynthetics are made from natural fibers like jute, coir, or hemp, while others use biodegradable polymers. Materials made from renewable resources such as bamboo, hemp, flax, and kenaf are gaining popularity due to their lower environmental impact (Saba *et al.* 2015). These fibers are fast-growing, biodegradable, and have minimal carbon footprints compared to synthetic alternatives. Hemp fibers are durable, biodegradable and highly effective in soil reinforcement and erosion control applications (Ochi, 2011). Flax fibers and bamboo are being used in the development of geosynthetics for road construction, reinforcement, and landscaping. These fibers offer sustainable alternatives to synthetic polymers (Abdel, 2014).

Understanding geosynthetics and their traditional environmental impact

Geosynthetics have been widely used in construction for decades due to their ability to improve soil stabilization, drainage, erosion control and other foundational functions. Koerner, (2012) discussed the extensive use of geosynthetics in civil engineering and their environmental challenges, particularly focusing on the long-term sustainability of traditional materials. Traditionally, these materials have been manufactured from petroleum-based products, such as polypropylene, polyethylene and polyester, which contribute significantly to carbon emissions, environmental pollution and resource depletion. The manufacturing of geosynthetics from petroleum-based materials has a high energy demand, which contributes significantly to the carbon footprint of these products (Cislaghi *et al.* 2021). Recycling of traditional geosynthetics is often limited. Many geosynthetics are designed for single-use applications, and even if they could theoretically be recycled, the processes involved are complicated and not always economically viable. Traditional geosynthetics, when used in landfills, may not allow for the complete containment of harmful waste. Over time, even small amounts of leachate can escape, contaminating surrounding environments. Because geosynthetics are not biodegradable, they accumulate in landfills, contributing to long-term waste management issues (Touze, 2021). The decomposition of organic matter in landfills can also release methane—a potent greenhouse gas, into the atmosphere.

Development of Eco-Friendly Geosynthetics

The demand for sustainable alternatives in the geosynthetics industry has led to the development of materials that reduce the carbon footprint, are recyclable and utilize bio-based or biodegradable components. Several advancements have been made in developing eco-friendly geosynthetics that can replace traditional, environmentally harmful materials. Studies have shown that geotextiles made from natural fibers such as jute, hemp, coir and cotton offer a biodegradable alternative to synthetic geosynthetics (Desai & Kant, 2016). These materials decompose naturally after serving their purpose, reducing long-term environmental impact. (Binici, *et al.* 2005; Shalchian & Arabani, 2023) explored the use of natural fiber-based geotextiles for soil reinforcement and erosion control, demonstrating their effectiveness and biodegradability. The use of post-consumer recycled plastics, such as PET (Polyethylene Terephthalate) from bottles, has gained traction in producing geosynthetics like geogrids and geomembranes. Recycling reduces the need for virgin plastic and mitigates waste accumulation (Devasahayam *et al.* 2019). Wallbaum *et al.* (2014**)** analyzed the benefits of using recycled PET in geosynthetics, highlighting its lower environmental footprint and cost-effectiveness. The adoption of bio-based polymers such as PLA (Polylactic Acid) and PHA (Polyhydroxyalkanoates) has been studied as a way to further reduce reliance on petroleum-based products. Research indicates that these bio-polymers are renewable, biodegradable, and can be produced with lower energy inputs (Adeleye *et al.* 2020). (Tiso *et al.* 2021) discussed the potential of bio-based polymers in geosynthetics, particularly focusing on their biodegradability and lower environmental impact compared to traditional materials.

Performance and Durability of Eco-Friendly Geosynthetics

Eco-friendly geosynthetics are designed to offer the same level of performance and durability as traditional materials. Their ability to perform under stress, resist degradation, and maintain structural integrity over time has been a focal point in recent research. Eco-friendly geosynthetics have been shown to exhibit comparable or superior longevity in various conditions, including resistance to UV radiation, chemical exposure, and mechanical stress (Koerner *et al.* 2008). Long-lasting materials reduce the need for frequent replacements, ultimately lowering the overall environmental footprint of construction projects. Santos *et al.* 2021) conducted a study on the durability of eco-friendly geosynthetics, finding that recycled and bio-based materials maintained strong performance in long-term field conditions. Eco-friendly geosynthetics made from biodegradable fibers like jute and coir have been successfully used in applications such as soil stabilization, slope protection, and erosion control. Research has demonstrated that these materials provide effective soil reinforcement while decomposing naturally over time, contributing to sustainable land management practices (Beena, (2013), Lekha, K.R. (2004), Lekha & Kavitha, (2006), Subaida *et al.* (2008) and Vinod & Bhaskar, (2012)) studied the performance of biodegradable geosynthetics in erosion control applications, strength and interface properties, emphasizing their effectiveness in stabilizing soil without harming the environment.

The Life Cycle Assessment (LCA) of eco-friendly geosynthetics is an essential tool for evaluating their environmental impact throughout their life span, from raw material extraction to production, use, and disposal. Several studies have shown that eco-friendly geosynthetics, particularly those made from recycled materials and bio-based polymers, offer lower carbon emissions and energy consumption compared to their traditional counterparts (Figiela, B. & Korniejenko, K. 2020, Tiza *et al.* 2024; Zhou *et al.* 2018 and Monrose, 2020). Morsy, K. M., & Thakeb, H. (2022) performed a life cycle assessment comparing eco-friendly geosynthetics with conventional geosynthetics, concluding that the former had a significantly lower environmental footprint in terms of carbon emissions and resource depletion.

Types of Geosynthetics

Several types of geosynthetics are commonly used in civil engineering. Below is an overview of the different **types of** geosynthetics.

Geotextiles

Woven or non-woven fabrics used for separation, filtration, reinforcement and protection. They are the core of geosynthetic material, with properties like a strong, porous, thin, flexible, planner or sheet-like structures made from fibres. Fibers are made up of polyester, polyamide, polypropylene etc. which results in very strong as well as thin fibres, which are either weaved by machines known as woven geotextile or joined together by making mechanical, thermal or chemical bonds between fibres are known as non-woven geotextile.

Fig. 1: Geotextile lining

Geotextiles provide properties like separation, drainage, reinforcement and filtration when used in soil. Due to their properties, they are used in many civil constructions works like roadways, landfills, drainage structures, erosion control, railways and many more. The use of geotextile (Fig. 1) makes pavements strong, rigid and durable helping in the reduction of maintenance costs and improving the life of infrastructure. It is proven that as the depth of the geotextile increases the strength of the soil increases up to a certain limit after which it remains constant.

Geogrids

It is a material that is in a net or grid-like structure used for reinforcement, particularly in soil reinforcement applications (Fig. 2). There is a wide opening in them known as aperture. Polyester, polyvinyl and polyethene are the base materials for its manufacturing.

Fig. 2: Geogrids as soil reinforcement

They are made by processes like extrusion and weaving. The working principle is that these materials are very strong in tension which can easily distribute and transfer the load into large areas over the soil surface, which ultimately improves the stability of the soil. It is used in sub bases on pavements for its reinforcement properties. Other than road pavements it is used in dams and retaining structures. The addition of other additives like lime and cement, Geogrid improves the mechanical properties of soil.

Geo-nets

Honeycomb-like structures used for drainage and dissipation of pore water pressure. These are very similar to Geogrid. They are constructed by overlapping or joining fibres at acute angles which reassemble as a net-like structure (Fig. 3). Polymers used to make Geonets are of thermoplastic type which can be cast into different shapes easily. They have a hardness which makes them useful to bear the load. For their hydraulic properties like the transfer of fluid these can be used in various fields like foundations, landfills, pavements and drainage areas.

Fig. 3: Geonets

Geo-membranes:

High-density polyethylene sheets used for containment of liquids and gases. Geomembranes are synthetic sheets that provide an impermeable barrier in engineering projects. It is a thin, strong and impervious sheet which is used to deal with the liquid flow by using them as a liner in landfills, and liquid storage facility, to control soil expansion by reducing soil exposure to water, act as a barrier for dams and coffer dams (Fig, 4).

Fig. 4: Geo-membranes

These materials have very low permeability due to this they can easily control harmful contaminants and diffusion and are helpful in liner and control systems for radioactive and hazardous liquid waste. With all these properties and applications geomembranes are expensive compared to other geosynthetics. It is used in many water conservation projects like the making of ponds, lakes, and canals. They have many advantages over traditional barriers, such as, durability, rapid to install, economical, have a high deformability, require low maintenance and improve hydraulic efficiency of the system, Because of these advantages, geomembrane systems are used worldwide.

Geo-synthetic Clay Liners (GCLs)

Composite materials consisting of a bentonite clay core sandwiched between geotextiles, used for low-permeability barriers (Fig. 5). Geosynthetic clay liners (GCLs) are composite materials used for environmental containment that consist of layers of geotextile fabric encasing a core of sodium bentonite clay.

It is a type of geosynthetic material that is made into layers, it consists of two layers of geosynthetic sandwiched with a layer of bentonite clay. This specific architecture forms a highly effective barrier to the movement of liquids and gasses.

Fig. 5: Geo-synthetic Clay Liners

GCLs provide various advantages over standard compacted clay liners, such as speedier installation, lower costs, and better hydraulic performance. They are widely used in landfill liner systems, canal liner systems, landfill caps, mining operations, and containment ponds to prevent contaminants from migrating into the surrounding environment. GCLs play an important role in current environmental engineering by providing long-lasting and efficient solutions for hazardous material containment and management.

Geo- pipes:

It is a type of geosynthetic material that is in a circular shape. They are flexible conduits made of materials such as high-density polyethylene (HDPE) and used to transport fluids or gasses through the soil. Perforated pipes include small holes along their length, which aids drainage in applications such as highway subsurface systems, whereas non-perforated geo-pipes are solid and suitable for culverts or sewage systems (Fig. 6).

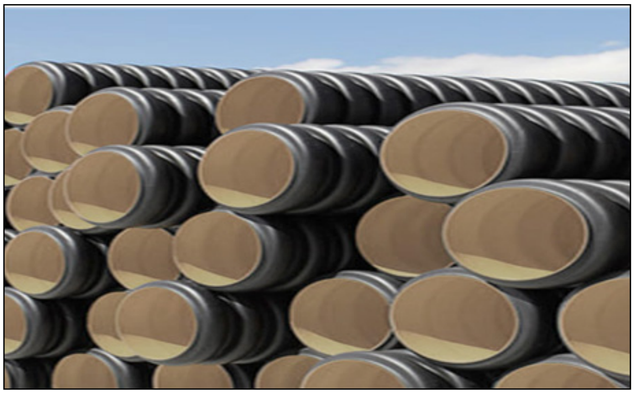

Fig. 6: Geo-pipes

Their installation consists of trenching, laying, and backfilling, with geotextile wraps used to prevent soil incursion. Geo-pipes provide several advantages, including flexibility, corrosion resistance, cost-effectiveness, and environmental benefits. Geo-pipes are widely used in drainage, sewerage, and environmental projects. They provide sustainable solutions for water management, gas extraction, and leachate collection.

Geo-bags

They are bag-like structures made of geosynthetic material. Which are typically filled with sand resulting in geotextile sand containers. It comes under three different specifications small, medium, and large. Small ones are used for temporary structures, medium-sized ones are for milder conditions and emergency works, and large ones are used for permanent structures. The bigger the size, the better their durability and lifespan, even under harsh conditions. They are easy to install, have less impact on the environment, can be used for a temporary and permanent structure, used in river bank stabilization, and erosion control.

Fig. 7: Geo-bags

It is very simple to make and install. First, a frame is developed in which first geo-bag is placed then soil as shown in Fig. 7, either naturally available soil or soil transported from other sources filled in the geo- bag. The geo- bag is stitched so that soil does not escape from the filled then placed in desired locations.

Geo-fibres

Geo-fibres are small, thin, hair-like structures made up of artificial fibre. They are made by using raw materials namely polypropylene, polyethene, polyester, polyvinyl etc. These fibres are available in various sizes like 3 mm, 6 mm, 10 mm, 12 mm, 15 mm, 30 mm, 50 mm, 60 mm and various other sizes, with diameters ranging from 10–100 microns.

Fig. 8: Geo-fibres

These fibres mixed with soil act as a reinforcement, because the soil is weak in tension and fibre acts as a reinforcement and improves its strength. From much research, it is concluded that generally, fibres are hand mixed with soil and if too many fibres are mixed in the soil there is a possibility of the formation of lumps in soil and uneven distribution of fibres which results in a lack of fibre and soil interaction.

Practical case studies demonstrating the effectiveness of geosynthetics

There are several case studies where eco-friendly geosynthetics have been successfully applied in various civil engineering, environmental and construction projects. These examples showcase how the integration of sustainable materials and methods can improve both performance and environmental outcomes.

The municipal landfill of Bucharest, known as the "Glina Landfill," is located in the south-eastern part of the city. It has been a critical waste management facility for the capital city of Romania for several decades. Over time, the landfill has faced significant environmental challenges, including the need for better waste management practices, pollution control, and compliance with European Union environmental standards. Lining the landfill with eco-friendly geomembranes, such as those made from recycled polyethylene or biodegradable materials, could help contain leachate and prevent it from contaminating the surrounding soil and groundwater. These geomembranes would act as a barrier to toxic liquids that seep out of the waste (Mihai *et al.* 2020).

The organic waste landfill for a pig farm in Vasilati, Romania, was designed to manage the disposal of organic waste generated by the farm. The landfill utilized high-density polyethylene (HDPE) geomembranes to line the base and slopes, ensuring effective waterproofing and preventing the leakage of leachate into the surrounding environment. This eco-friendly solution helped mitigate the environmental impact of waste disposal by controlling potential contamination of soil and groundwater. Additionally, the use of HDPE geomembranes contributed to the long-term stability and safety of the landfill structure (Feodorov *et al.* 2000).

The Storm water Drainage System for Urban Development in Sydney, Australia, incorporated eco-friendly geosynthetics to manage storm water runoff effectively. The project utilized permeable geotextiles and drainage geocomposites to facilitate water infiltration and filtration while reducing the risk of flooding and water pollution. These geosynthetics allowed rainwater to percolate through the ground, filtering out contaminants before the water reached natural bodies like rivers or lakes. The system helped improve water quality, reduced surface runoff and minimized the urban heat island effect, contributing to the sustainability of the development. The use of these eco-friendly materials also aligned with green building practices, enhancing the environmental performance of the urban infrastructure (Frost & De Silva, 2002).

Future Directions and Research Needs

The application of geosynthetics in civil engineering and construction has made significant strides over the years, offering solutions for soil stabilization, erosion control, drainage and environmental protection. However, as sustainability and climate resilience become more pressing priorities, there are still many avenues for improvement and innovation in geosynthetics. The future of geosynthetics will be shaped by advancements in material science, new technologies, sustainable practices and research to address evolving challenges in the built environment. The potential of geosynthetics holds great promise for advancing sustainable construction practices, environmental protection and climate resilience. Ongoing research in areas such as eco-friendly materials, smart technologies, climate change adaptation and advanced manufacturing will continue to drive innovation and improve the performance of geosynthetics. As these materials become more sophisticated, cost-effective and sustainable, their role in shaping the future of civil engineering and infrastructure development will only continue to grow. The next generation of geosynthetics will be central to achieving the goals of sustainable development and environmental stewardship in the construction industry.

Future research is needed to further improve the performance, durability and cost-effectiveness of eco-friendly geosynthetics. Innovations in biodegradable composites, nano-materials and biotechnologies could further enhance the sustainability of geosynthetics, reducing their environmental impact across the entire life cycle (Shafiee *et al.* 2021).

CONCLUSION

The shift towards eco-friendly geosynthetics represents a pivotal move towards more sustainable, cost-effective and environmentally responsible construction practices. These materials offer effective solutions to some of the most pressing challenges in civil engineering, including soil erosion, soil stabilization, water management and climate resilience. The literature reviewed highlights the significant progress made in developing eco-friendly geosynthetics for construction, emphasizing their potential to replace traditional synthetic materials and reduce the environmental footprint of civil engineering projects. While challenges remain in terms of cost and performance, ongoing research and innovation are expected to overcome these barriers and expand the use of sustainable geosynthetics in the near future. By replacing traditional materials with more sustainable alternatives, the construction industry can contribute to a healthier environment while also improving the durability and cost-efficiency of infrastructure projects. The continued evolution and adoption of eco-friendly geosynthetics will be crucial in creating a more sustainable future for the built environment.

REFERENCES

Abdel Mohsen, R. 2014. Investigation of reinforced foam waste with natural or synthetic fibers.

Adeleye, A.T., Odoh, C.K., Enudi, O.C., Banjoko, O.O., Osiboye, O.O., Odediran, E.T. and Louis, H. 2020. Sustainable synthesis and applications of polyhydroxyalkanoates (PHAs) from biomass. *Process Biochemistry*, **96**: 174-193.

Beena, K.S. 2013. Case studies on application of coir geotextiles for soil stabilization.

Binici, H., Aksogan, O. and Shah, T. 2005. Investigation of fibre reinforced mud brick as a building material. *Construction and Building Materials*, **19**(4): 313-318.

Bouazza, A., Zornberg, J.G. and Adam, D. 2002. Geosynthetics in waste containment facilities: recent advances.

Cislaghi, A., Sala, P., Borgonovo, G., Gandolfi, C. and Bischetti, G.B. 2021. Towards more sustainable materials for geo-environmental engineering: The case of geogrids. *Sustainability*, **13**(5): 2585.

Desai, A.N. and Kant, R. 2016. Geotextiles made from natural fibres. In *Geotextiles* (pp. 61-87). Woodhead Publishing.

Devasahayam, S., Raju, G.B. and Hussain, C.M. 2019. Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry. *Materials Science for Energy Technologies*, **2**(3): 634-646.

Feodorov, V., Manea, S., Batali, L. and Sofrone, D. 2000. Use of geosynthetics in landfills. Case studies from Romania. In *Proceedings of the second European geosynthetics conference. Patron Editore, Bologna, Italy* (pp. 509-514).

Figiela, B. and Korniejenko, K. 2020. The possibility of using waste materials as raw materials for the production of geopolymers. *Acta Innovations*, **36**: 48-56.

Frost, S. and De Silva, N. 2002. Restoring the waters project: from vision to reality. In *Global Solutions for Urban Drainage* (pp. 1-13).

Koerner, R.M. (2012). *Designing with geosynthetics-Vol. 1* (Vol. 1). Xlibris Corporation.

Lekha, K.R. 2004. Field instrumentation and monitoring of soil erosion in coir geotextile stabilised slopes—A case study. *Geotextiles and geomembranes*, **22**(5): 399-413.

Lekha, K.R. and Kavitha, V. 2006. Coir geotextile reinforced clay dykes for drainage of low-lying areas. *Geotextiles and Geomembranes*, **24**(1): 38-51.

Mehta, S. 2023. Biodegradable textile polymers: a review of current scenario and future opportunities. *Environmental Technology Reviews*, **12**(1): 441-457.

Mihai, D., Pogurschi, N.E., Sarbu, N.D., Tudor, C.V., Horablaga, A., Salcianu, R. and Mircea, L.C. 2020. Polymeric Geomembranes Used in Municipal Waste Facilities. *Materiale Plastice*, **57**(3): 117-124.

Morsy, K.M. and Thakeb, H. 2022. Comparative evaluation of the environmental impacts of geosynthetic Mechanically Stabilized Earth walls. *J. of Cleaner Production*, **374**: 133912.

Mwasha, A. 2009. Using environmentally friendly geotextiles for soil reinforcement: A parametric study. *Materials & Design*, **30**(5): 1798-1803.

Ochi, S. 2011. Durability of starch based biodegradable plastics reinforced with manila hemp fibers. *Materials*, **4**(3): 457-468.

Saba, N., Jawaid, M., Hakeem, K.R., Paridah, M.T., Khalina, A. and Alothman, O.Y. 2015. Potential of bioenergy production from industrial kenaf (*Hibiscus cannabinus* L.) based on Malaysian perspective. *Renewable and Sustainable Energy Reviews*, **42**: 446-459.

Santos, A.S., Ferreira, P.J.T. and Maloney, T. 2021. Bio-based materials for nonwovens. *Cellulose*, **28**(14): 8939-8969.

Shalchian, M.M. and Arabani, M. 2023. Application of plant-derived fibers in soil reinforcement on experimental, numerical, and case study scales: a review. *Bulletin of Engineering Geology and the Environment*, **82**(1): 19.

Subaida, E.A., Chandrakaran, S. and Sankar, N. 2008. Experimental investigations on tensile and pullout behaviour of woven coir geotextiles. *Geotextiles and Geomembranes*, **26**(5): 384-392.

Tiso, T., Narancic, T., Wei, R., Pollet, E., Beagan, N., Schröder, K. ... and Blank, L.M. 2021. Towards bio-upcycling of polyethylene terephthalate. *Metabolic Engineering*, **66**: 167-178.

Tiza, M.T., Imoni, S., Akande, E.O., Mogbo, O., Jiya, V.H. and Onuzulike, C. 2024. Revolutionizing Infrastructure Development: Exploring Cutting-Edge Advances in Civil Engineering Materials. *Recent Progress in Materials*, **6**(3): 1-68.

Touze, N. 2021. Healing the world: A geosynthetics solution. *Geosynthetics International*, **28**(1): 1-31.

Vinod, P. and Bhaskar, A.B. 2012. Model studies on woven coir geotextile-reinforced sand bed. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, **165**(1): 53-57.

Wallbaum, H., Büsser, S., Itten, R. and Frischknecht, R. 2014. Environmental benefits by using construction methods with geosynthetics. In *Proc. of the 10th Int. Conf. on Geosynthetics*.

Zhou, C., Shi, S.Q., Chen, Z., Cai, L. and Smith, L. 2018. Comparative environmental life cycle assessment of fiber reinforced cement panel between kenaf and glass fibers. *Journal of Cleaner Production*, **200**: 196-204.