



## Geotextiles for Environmental Protection, A review

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### Abstract

Geotextiles are an important part of modern environmental and civil engineering, and they are a fast-growing subset of technical textiles. From the basic raw materials to the final products and their uses, this review covers it all, giving a comprehensive picture of the industry. It investigates the features of natural fibres such as jute and synthetic fibres like polyester and polypropylene and combines important findings on their production methods and main roles, including drainage, stability, strengthening, and filtration. Infrastructure demands and environmental laws are driving the worldwide geotextile market, which is witnessing tremendous expansion. The study also explores this market. This analysis concludes with a summary of recent advances, a discussion of the important issues of sustainability, cost-effectiveness, and long-term durability, and a plan for future research to produce creative and environmentally friendly geotextile solutions.

Keywords: Technical textiles; geotextiles; Manufacturing Process; Geotextile Functions.

### 1. Introduction

The term 'Geotextiles' is a fusion of two nouns. The term 'Geo' originates from the Greek word for 'Earth' and textiles. Geotextile is defined in Textile Terms and Definitions, published by The Textile Institute, as 'any permeable textile material utilized for filtration, drainage, separation, reinforcement, and stabilization within civil engineering structures composed of earth, rock, or other construction materials' [1-3]. Geotextiles are defined as permeable textiles utilized alongside soils or rock as a fundamental component of a constructed project [4].

Geosynthetics are products composed of synthetic or natural polymeric substances utilized in conjunction with soil, rock, and other geotechnical elements. Geosynthetics primarily encompass geotextiles, geogrids, geocells, geonets, geomembranes, erosion control mats, geosynthetic clay liners, and geo-composites [5, 6]. Geotextiles represent the predominant category of geosynthetics [7]. The initial documented usage of geotextiles is attributed to the nylon bags filled with sand utilized in the Dutch Delta Works in 1956 [8]. Over the past six decades, geotextiles have been extensively utilized in geotechnical engineering. Geotextiles serve at least one of the following purposes in geotechnical engineering: separation, filtration, drainage, reinforcing, stabilization, barrier, and erosion prevention [9, 10]. Currently, about 1.4 billion square meters of geotextiles are utilized globally each year (2023 estimate), and the trend is increasing. Approximately 98% of geotextiles are composed of non-degradable polymers belonging to the polyolefin, polyester, or polyamide categories. The prolonged use of geotextiles, due to several environmental conditions including wind, moisture, friction, and UV radiation, may lead to the degradation of synthetic polymers, resulting in the accumulation of microplastics in the surrounding environment [11, 12]. Moreover, the utilization of geotextiles in geotechnical engineering may face intricate environmental variables, such as complex acid-base scenarios [13], hence necessitating elevated performance standards for geotextiles. Consequently, geotextiles must evolve towards enhanced performance and multifunctionality [14]. Due to the rising popularity of the green idea, numerous scholars have investigated the feasibility of natural geotextiles such as jute (tensile strength: 10–30 kN/m, biodegradation period: 6–12 months) and synthetic polymers like polypropylene (tensile strength: 50–120 kN/m, permittivity: 1–5 s<sup>-1</sup>) that are tailored to meet diverse filtration and reinforcement needs, substituting non-biodegradable polymer geotextiles [11, 15].

Half of all geotextile applications can now be filled with natural geotextiles instead of synthetic ones [16, 17]. Geotextiles are also progressing into the area of multi-functional intelligence with the use of optical fibre sensors [18]. When smart geotextiles are used to reinforce geotechnical structures, they can also monitor their health.

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This helps find places where the structures are likely to fail or sustain damage early on, which allows for preventative maintenance and damage prevention [19]. New high-performance geotextiles, such as wicking geotextiles [20, 21] and basalt fibre needling geotextiles, have arisen as a result of advancements in fibre materials.

To pre-treat landfill effluents, Silva & Palmeira (2019) investigated the usage of nonwoven geotextiles as filters [22]. To decrease the possibility of pollution in the landfill's effluent, experimental geotextile panelling was utilized in this instance. In addition to its long-established role in drainage and filtration, geotextile has found new uses in preventing mechanical damage to geomembranes and acting as capillary barriers to prevent rainwater infiltration through cover layers in trash disposal locations. Geomembranes have other uses in environmental protection, such as creating vertical barriers to contain polluted areas and prevent the contamination from spreading laterally (Lima et al., 2018) [23].

Antonio and his team evaluate geotextiles against weeding as a sustainable soil erosion treatment. Their mathematical models assess and rank possibilities comprehensively [24]. The team used the Single Price Model to rank all options. Geotextiles showed their promise as a solution for managing soil erosion by considering economic efficiency as a key factor. Model 4, manufactured from recyclable materials, was the most efficient model behind the traditional plough. They observed that geotextiles can replace traditional weeding methods for economic efficiency and sustainable soil management.

In 2024, Palmeira stressed geosynthetics and sustainability as means to protect the environment and combat climate change [25]. Geosynthetics are typically inexpensive, environmentally friendly, and simple to deploy in climate change crises. Geosynthetics can be used to create reinforced embankments, stacked geotextile tubes, or mattresses to protect structures or mitigate environmental damage in the case of tailings dam collapses, flooding, or leaks. If mining tailings are non-toxic and have acceptable geotechnical properties, they can be used to construct barriers, which is a superior application for them.

Waterproof natural geotextiles coated with *Syagrus coronata* fibres were the subject of Francisco and his classmates' discussion about the resistance of these materials to environmental degradation [26]. The results show that compared to untreated or double-layer-treated fibres, those treated with a single layer of resin had a much longer mechanical viability (120 days) and greater ultimate tensile strength (220). Without treatment, fibres became nonviable after 60 days, but double-layer resin increased tensile resistance at first but speed up structural breakdowns after 90 days. A single-layer resin application provides the ideal combination of mechanical resilience and flexibility, as demonstrated by these data, which emphasize a trade-off between stiffness and durability.

In 2025, Narain and his colleagues explored the potential of creating geotextiles from jute and coir fibres [27]. These materials can be used in a variety of applications, including the production of plant pots and mulch mats, the construction of railway lines and highways, and the development of retaining walls. Jute and coir fibres can be used individually or in innovative combinations. Geotextiles made from jute and coir demonstrate significant promise for preventing slope erosion in various contexts, such as earthen embankments, hill slopes, landfill sites, and thermal power heaps that contain granular waste, like fly ash.

Amarnath and his colleagues reviewed the most recent developments in textile materials for use in smart sensors [28]. Incorporating nanomaterials and functional coatings that improve their electrical conductivity, flexibility, and durability, they showcase the most recent trends and advancements in the production of different e-textiles. They delve into the various ways smart fabrics may be used to monitor health, measure athletic performance, and detect environmental changes, highlighting how these technologies can transform individual healthcare and improve daily life.

"In 2023, the global geotextile market was worth more than 4.2 billion USD. Nearly 45% of that consumption was in the Asia-Pacific region, with 25% coming from North America. Because of their vital role in geotechnical engineering, geotextiles have seen a steady increase in demand around the world [27]. Predictions indicate that the worldwide geotextile market will reach \$4.6 billion in 2024, growing at a CAGR (compound annual growth rate) of 13%. Driven by giants like India and China, the Asia-Pacific region hosts the largest geotextile market on the planet. Demand for geotextiles was high in 2024, with 47% of the Asia-Pacific market coming from China due to the country's large-scale infrastructure development projects [29]. Renewal of infrastructure and environmental protection measures will be pushing the economy to an 8.5% yearly growth rate until 2028 [27-29].

The three main benefits of geotextiles are their low cost, long lifespan, and user-friendliness. Today, geotextiles play an increasingly crucial role in geotechnical engineering. This article provides a synopsis of geotextiles, including their construction and their use in geotechnical engineering. Furthermore, geotextiles—specifically, green, intelligent, and high-performance geotextiles—have recently emerged as a topic of discussion,

drawing on literatures that include the most current data. This paper provides an overview of the history of these innovative geotextiles and how they have been used in geotechnical engineering.

There have been several evaluations on geotextiles, but most of them have narrowed down on certain uses, materials, or functional properties. In order to give a complete picture of their important purpose, a review is required that incorporates all of these different elements, from the basic materials and production methods to the many functional uses and market trends. The fundamental goal of this study is to gather all the existing information on geotextiles, particularly as they pertain to their use in protecting the environment. The purpose of this paper is to provide an overview of geotextiles, including their composition, production process, and various uses. It will also go over some of the more recent developments in the field, address some of the existing difficulties, including those related to recycling and durability, and suggest some potential avenues for further study. Geotextiles have been an integral part of sustainable engineering for quite some time, and this overview focuses light on their history and future prospects.

This review takes a novel approach by combining market analytics with technical performance measurements. Its primary objective is to first assess geotextiles' global and regional growth trajectories, market volumes, and demand projections in the agricultural, environmental remediation, and civil engineering industries. Secondly, it is important to establish a systematic relationship between the following: the type of material (polymer, biobased vs. petrochemical feedstocks), the manufacturing process (woven vs. nonwoven, stitch-bonded), the structural attributes (fibre orientation vs. pore size distribution), and the performance indicators (tensile and puncture strength, permeability, filtration efficiency) with the results of actual use. In conclusion, to guide future research goals, it is important to emphasize emerging innovations, sustainability problems, regulatory factors, and sustainability issues, such as biodegradable geotextiles and recycled-content products.

## 2. Raw materials

Taking into account both the product cost and the performance needs of geotextiles at the site, the selection of geotextile materials must be sufficient for the project's actual condition. The majority of geotextiles are currently made of synthetic fibres. Most geotextiles are made of polypropylene (PP), then polyethylene terephthalate (PET), and finally polyethylene (PE) [30-32]. The most popular polymers utilized as geotextiles are shown in Table 1.

Typically, synthetic thermoplastics are the fibres of choice in geotextile engineering due to their adaptability in terms of chemical, physical, and mechanical characteristics to meet the needs of specific ground-contact applications. Because of their tendency to biodegrade, natural fibres are rarely used until absolutely necessary (for example, as a short-term solution to erosion control while vegetation grows). The thermoplastic materials most commonly used to make geotextiles and related goods are listed in Table 1, with their utilization in decreasing order.

These materials are all thermoplastic polymers, which means they are made up of giant molecules that are formed from a long chain of smaller molecules with similar shapes. The name of the group is determined by the chemical makeup of the smaller units [30, 33, 34].

For geotextiles, polypropylene is a popular choice due to its inexpensive cost, acceptable tensile qualities, and chemical inertness. The incredibly low cost per volume is a further benefit of this fibre due to its low density. The lack of photosensitivity is the biggest drawback of polypropylene. Furthermore, it has weak creep properties and readily degrades in performance at high temperatures [35-37].

Polyethylene terephthalate (PET) is another significant synthetic fibre utilized in geotextiles. The material exhibits superior tensile properties and significant creep resistance. Polyester fibre geotextiles are suitable for high-temperature applications. Polyester fibre's primary disadvantage is its susceptibility to hydrolysis and degradation in soil with a pH value exceeding 10 [38-40]. Polyethylene fibre is typically employed in the production of geomembranes; however, its limited availability has rendered it an infrequently utilized option in the geotextile sector. Polyamide is infrequently utilized in geotextiles because of its low cost and inadequate overall performance [41, 42]. Additives are commonly incorporated to improve the performance of geotextiles, including antioxidants, hindered amine light stabilizers, UV absorbers and stabilizers, long-term thermal stabilizers, processing modifiers, flame retardants, lubricants, and antibacterial agents [43-47].

**Table 1. Most common polymers used as geotextiles**

| COMMON NAME          | GROUP CHEMICAL NAME        | SYMBOL |
|----------------------|----------------------------|--------|
| Polypropylene        | Polyolefin                 | PP     |
| Polyester (Terylene) | Polyethylene Terephthalate | PETP   |
| Nylon 6, 66          | Polyamide                  | PA     |
| Polyvinyl Chloride   | Chlorofibres               | PVC    |

## 2.1 Types of geotextiles

1. Woven: These geotextiles are produced in a manner akin to apparel materials. It comprises two sets of parallel threads aligned longitudinally, referred to as warp, and one set oriented perpendicularly, known as weft (Figure 1a) [30].
2. Non-woven: These geotextiles are made by mechanically, thermally, chemically bonding, or a mix of these processes short staple fibre or continuous filament yarn. The bonding technique used to create these geotextiles determines their thickness, which can range from approximately 0.5 mm to 3 mm, as shown in Figure 1b.
3. Kitted: These geotextiles are produced by stitching warp and weft threads (Figure 1c); this knitting process, along with other methods such as weaving, is employed (M. Tech.).

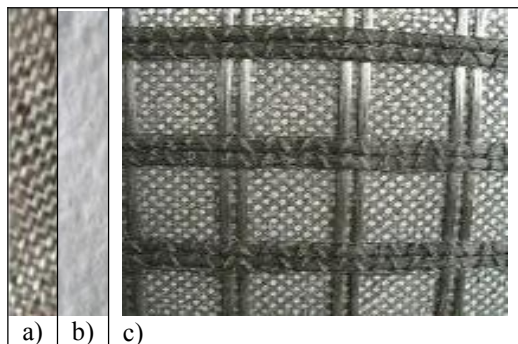


Fig. 1. Classification of geosynthetics by function, a) Woven b) Non-woven c) Kitted.

## 3. Applications

### 3.1 Geotextiles in Separation

The separation function of geotextiles pertains to their ability to distinguish between two materials with differing properties, preventing their intermixing and preserving the integrity and structural cohesion of each material. **Figure 2** illustrates that the placement of stone aggregates on fine-grained soil will result in the simultaneous occurrence of both mechanisms over time. One issue is that the fine soil in the lower layer attempts to infiltrate the voids of the aggregate, thereby compromising its drainage capacity; another issue is that the aggregate in the upper layer seeks to penetrate the fine soil, which undermines the strength of the aggregate [48]. This typically occurs in the absence of geotextiles.

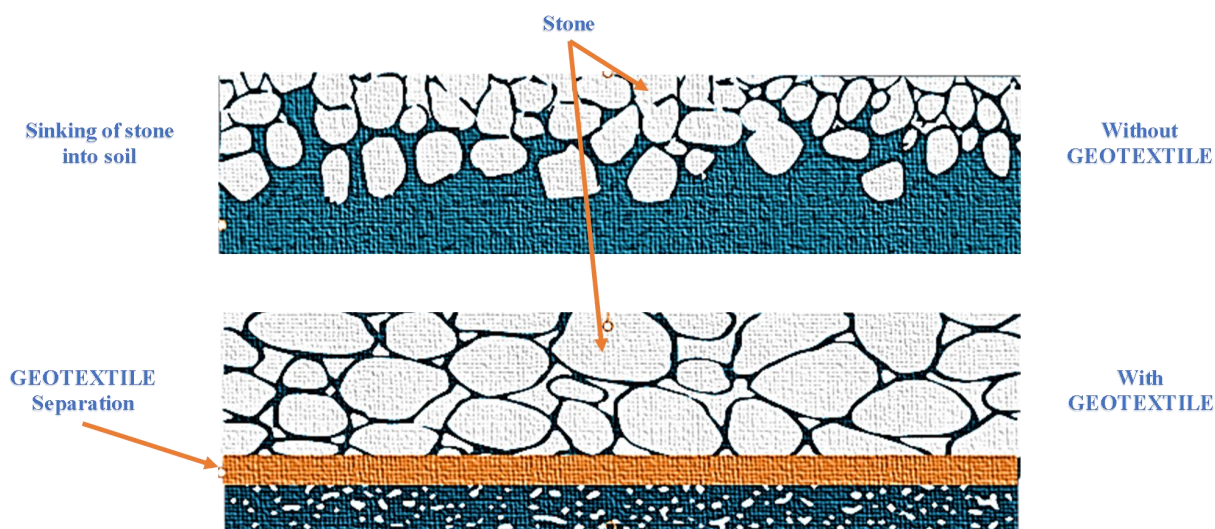


Figure 2. Separation by geotextiles.

### 3.2 Geotextiles in Filtration

Suffusion can occur in soils that are internally unstable due to seepage, which carries small particles together with the collapse of the soil structure [49-51]. Soil conservation is achieved by inserting geotextiles into soil structures, which have positive permeability and air permeability. This allows liquid in the soil to pass through and be discharged while also preventing the upstream loss of soil particles, fine sand, and small stones, as well as soil damage and the suffusion phenomenon [52-54]. You can see the mechanism in action in **Figure 3**. Another common application of geotextiles in geotechnical engineering is their filtration function. When used in conjunction with other protective materials, such as riprap, geotextiles can stop soil erosion and riverbank collapse on coastlines and rivers, and they also keep soil particles from moving into drainage aggregates and pipes without affecting the drainage system's normal operation.

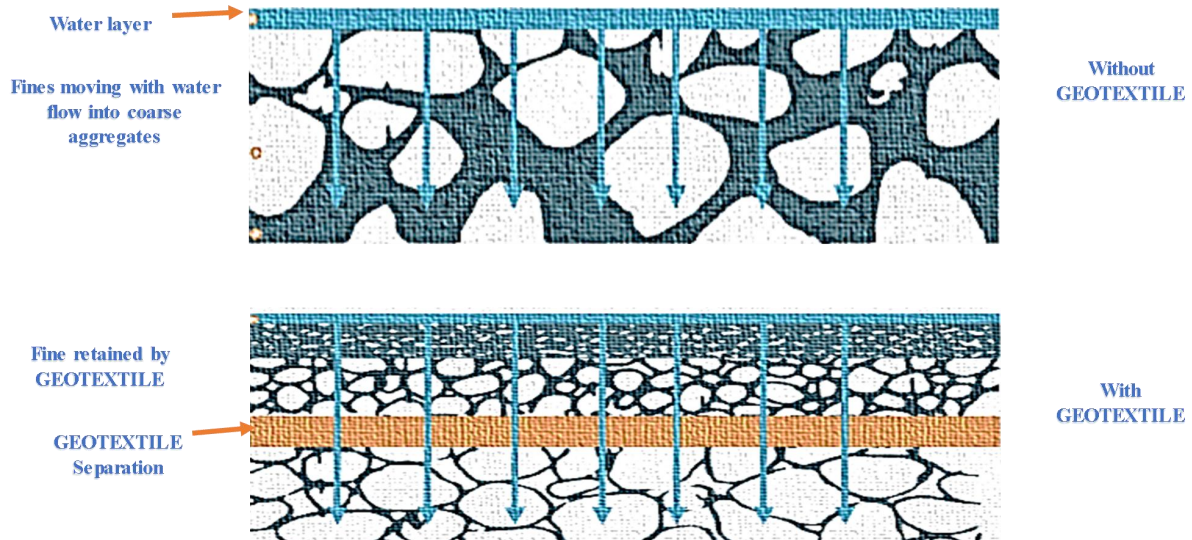


Figure 3. Filtration by geotextiles.

### 3.3 Geotextiles in Drainage

Because of their excellent water conductivity, geotextiles gain widespread application as drainage channels. It is possible to collect and gradually release the water present in the soil structure through the use of geotextiles as illustrated in **Figure 4**. As shown in **Figure 5**, geotextiles are currently utilized extensively in a variety of drainage works, including subgrade drainage, subterranean drainage, and retaining wall drainage [55-58].

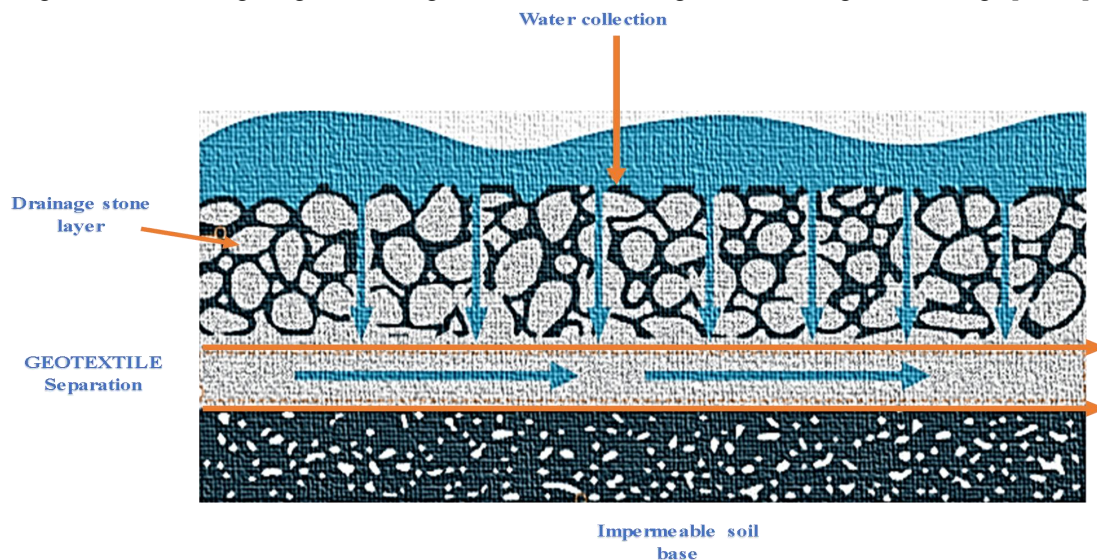


Figure 4. Drainage by geotextiles.



Figure 5. Subsurface drainage by geotextiles.

### 3.4 Geotextiles in Reinforcement

A reinforced composite soil is created by mixing soil with geotextiles, which are inserted within the soil to act as reinforcing elements. Reinforced composite soils significantly outperform unreinforced soils in terms of strength and deformation performance, as illustrated in **Figure 6**. Reinforcement geotextiles must have a high tensile modulus, tensile strength, and surface friction, which are three important mechanical characteristics. Most geotechnical engineering applications use geotextiles' reinforcing function. **Figure 7** shows that it has found extensive usage in reinforcing both hard and soft soil foundations, as well as paved and unpaved roads, railroads, walls, berms, and slopes [13, 59].

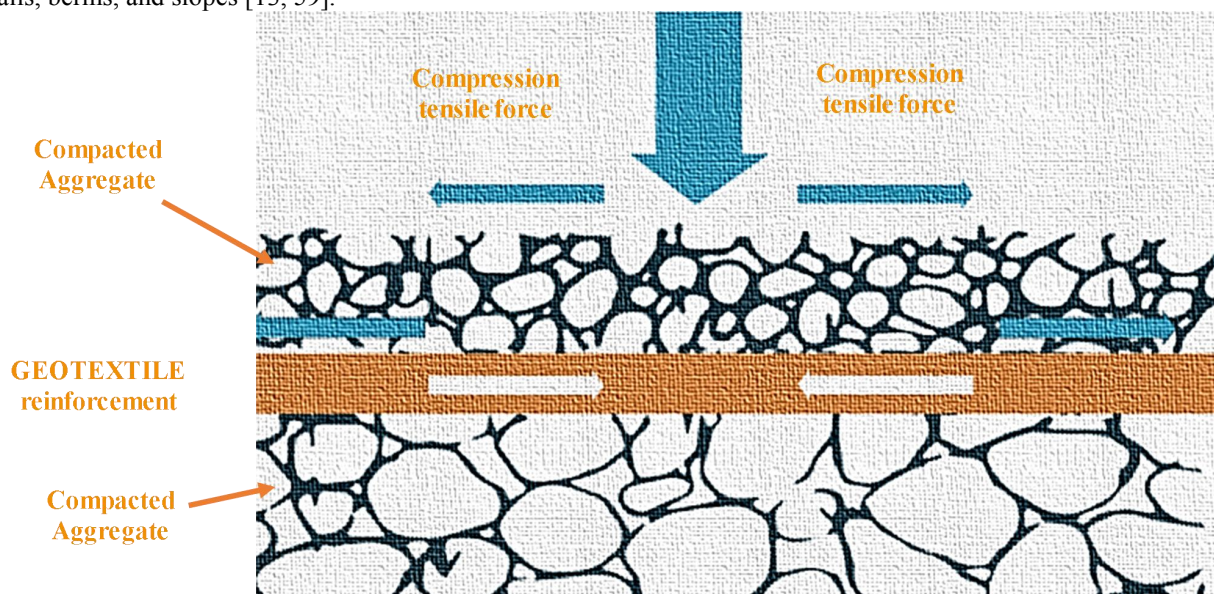


Figure 6. Reinforcement by geotextiles.

Geotextiles serve as barriers and erosion protectors, in addition to their many other primary uses. Common applications for geotextiles with anti-seepage properties include reservoirs, tunnels, and landfills [54, 60]. Laying geotextiles can reduce soil loss due to rainfall impact and surface water runoff, which is the main source of soil erosion [16, 61]. In geotechnical engineering, geotextiles typically serve more than one purpose simultaneously.



Figure 7. A few examples of where geotextile reinforcement can be used are: (a) in hillside reinforcing, (b) in bridge reinforcing, (c) in foundation reinforcing for soft soil, and (d) in load transfer platforms.

#### 4. Analysis of the Application of Geotextiles

There has been consistent expansion in the worldwide need for geotextiles, which have proven to be an essential component of geotechnical engineering. In 2024, the global geotextile market is anticipated to reach 4.6 billion USD, expanding at a compound annual growth rate (CAGR) of 13%. The Asia-Pacific area is home to the world's biggest geotextile market, propelled by major players like China and India. In 2024, 47% of the geotextile market in Asia-Pacific came from China, driven by the country's massive infrastructure development projects and the resulting strong demand for geotextiles. Major uses of geotextiles in road building, erosion control, and drainage systems [27].

Figure 8 shows the global geotextile market application in 2024 (%). Geotextiles have also undergone innovation in response to the rising demand for them. In light of the growing interest in environmentally friendly practices, geotextiles crafted from natural fibres are becoming more attractive. Another current trend in geotextile research and development is intelligent geotextiles. Geotextiles can now serve as reinforcement, structural safety monitors, and early warning systems thanks to the use of optical fibre sensors [62, 63]. Below, we will provide a detailed summary of the newest developments in natural geotextile, intelligent geotextile, and high-performance geotextile [64, 65].

#### 5. Green Geotextiles

The majority of geotextiles are fabricated from non-biodegradable polymers such as PP, PET, and PE. Over time, exposure to elements like wind, water, friction, and UV radiation can lead to the breakdown of synthetic polymers, which in turn can cause microplastics to accumulate in the environment [66, 67]. Additionally, when the polymer breaks down, the additives will leak out of the geotextile and end up in the environment [68]. Geotextiles crafted from natural fibres are ideal for a wide range of uses because of their adaptability, affordability, and biodegradability. The use of natural geotextiles could thus supersede that of synthetic geotextiles in many contexts [69].

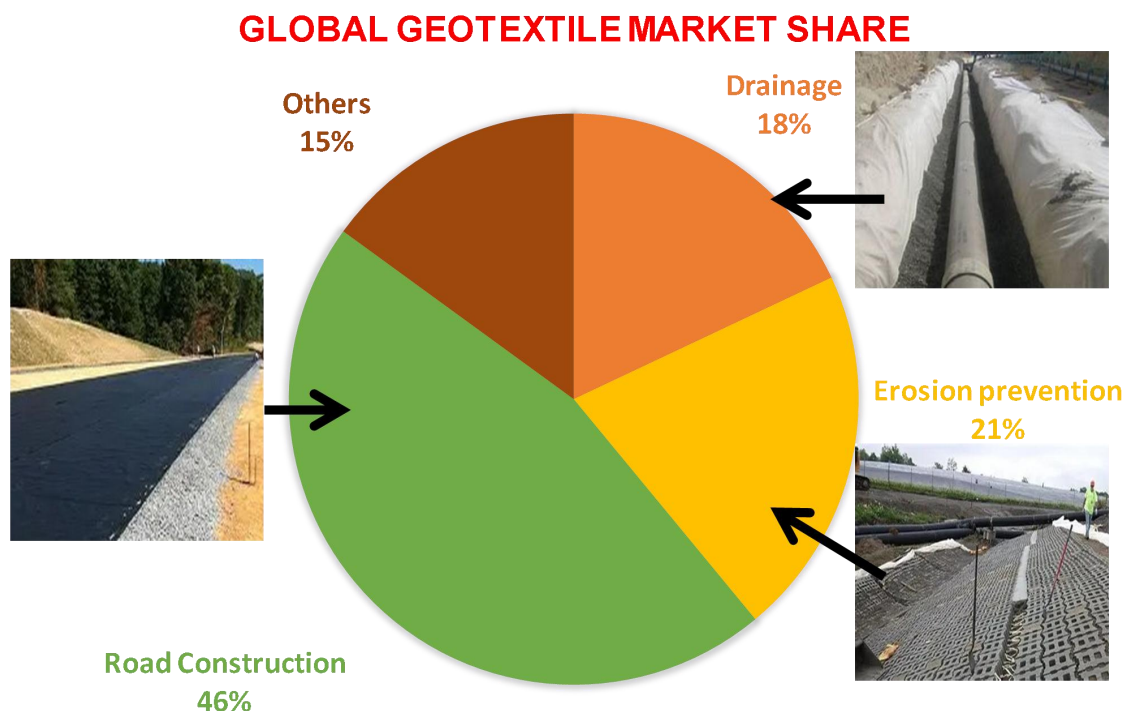


Figure 8. Global geotextile market application in 2024 (%)

## 6. Base Material of Natural Geotextiles

Natural fibres can be either plant-based, animal-based, or mineral-based. Plant fibres are naturally abundant, easy to extract, inexpensive, and very effective, making them the go-to material for natural geotextiles [70, 71]. What makes a natural fibre unique is the combination and arrangement of its constituent parts [72]. Fibres derived from plants typically contain cellulose, hemicellulose, lignin, and pectin as their primary building blocks [73]. Every natural fibre is unique in the proportions of its constituent parts. The fundamental components that dictate the physical characteristics of fibres are cellulose, hemicellulose, and lignin [74]. The most robust and durable organic component of fibre is cellulose [75]. The open structure of hemicellulose houses a plethora of hydroxyl and acetyl groups. Thus, hemicellulose possesses hygroscopicity and is partially soluble in water. Aromatic phenylpropane unit polymers make up the bulk of lignin. An increase in the percentage of cellulose and lignin in the fibre used to make a natural geotextile increases its service life [76].

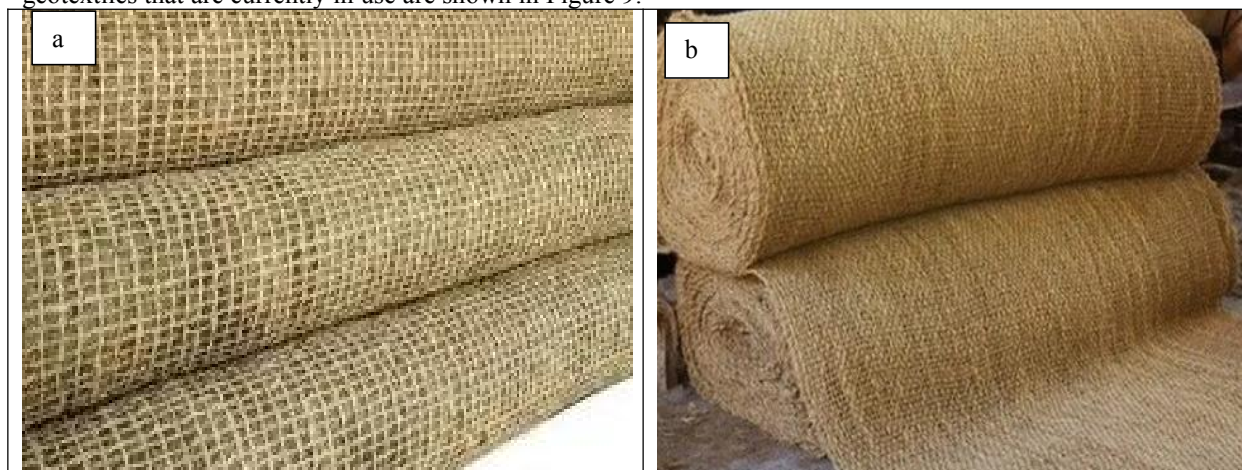
The characteristics of natural fibres can differ depending on the kind. Raw materials for natural geotextiles are typically natural fibres with good mechanical characteristics. A variety of natural fibres are utilized to create geotextiles, and Table 2 lists their composition and characteristics [77]. Because of their exceptional performance, jute and coir fibres have emerged as the top research materials for natural geotextiles; there are also numerous commercial products made from these fibres.

Table 2. Composition and properties of natural geotextiles fibres.

| Type of Fibre | Cellulose (wt%) | Lignin (wt%) | Hemicellulose (wt%) | Density (g/m <sup>3</sup> ) | Strain at Break (%) | Tensile Strength (MPa) | Young's Modulus (MPa) |
|---------------|-----------------|--------------|---------------------|-----------------------------|---------------------|------------------------|-----------------------|
| Flax          | 70-77           | 2.1          | 17-19               | 1.3-1.6                     | 1.3-3.0             | 350-1600               | 26-79                 |
| Hemp          | 56-76           | 3.2-12       | 13-21               | 1.5                         | 1.5                 | 560-850                | 65                    |
| Jute          | 44-70           | 10-25        | 12-20               | 1.2-1.5                     | 1.5-1.9             | 390-780                | 10-29                 |
| Kenaf         | 30-56           | 14-18        | 20-24               | 1.1                         | 2.6-6.0             | 290-900                | 20-55                 |
| Ramie         | 67-75           | 0.5-0.8      | 6-15                | 1.6                         | 2-3                 | 220-920                | 40-120                |
| Nettle        | 85              | 5.2          | 5                   | 1.52                        | 1.9                 | 600                    | 37                    |
| Sisal         | 46-77           | 6-10         | 11-23               | 1.35-1.5                    | 2-13                | 420-750                | 8-37                  |
| Abaca         | 55-62           | 6-8          | 20                  | 1.6                         | 2.6                 | 420-800                | 32-33                 |
| Cotton        | 84-89           | 0.6-1.5      | 6                   | 1.25                        | 3-9                 | 280-590                | 6-12                  |
| Coir          | 33-40           | 40-44        | 0.11-0.2            | 1.3                         | 15-29               | 175-210                | 3-5                   |

## 7. Performance of Natural Geotextiles in Geotechnical Engineering

Geotextiles made of natural materials have come a long way in the last several years. Natural geotextiles have been the subject of much research into their functions and uses in geotechnical engineering [78]. This article examines the use of natural geotextiles in geotechnical engineering and attempts to categorize them. The natural geotextiles that are currently in use are shown in Figure 9.



**Figure 9. Natural-fibre-based geotextiles: (a) jute geotextiles and (b) coir geotextiles.**

When vegetation cover is insufficient or incorrect, wind and surface water can strip and transport soil, a process known as soil erosion [78, 79]. Environmental sustainability and agricultural output are severely compromised by soil degradation induced by erosion. Soil cover made of geotextiles can temporarily shield soil from further degradation and reduce erosion until vegetation stabilizes the soil, which is ideal for situations where vegetation is not yet present. For effective erosion control, use geotextiles manufactured from natural fibres [80]. Natural geotextiles have superior soil adherence and are more effective in controlling erosion than manufactured geotextiles [81]. Even more crucially, natural geotextiles help prevent microplastic accumulation in the environment because they are biodegradable. When it comes to erosion prevention, natural geotextiles aren't very effective due to their short lifespan and hygroscopicity [82]. Geotextiles lose their effectiveness in preventing soil erosion once plants have taken root on a location; hence, natural geotextiles only last for a couple of years before they become ineffective. One advantage of natural geotextiles is their ability to absorb and store water [82]. To begin, soil runoff from heavy rain is lessened by materials with high water absorption. Secondly, during dry weather, the stored water can be steadily released to the ground, making it an optimal condition for plant growth. For erosion control, natural geotextiles are preferred over synthetic ones due to the former's low water absorption rate. Also, young plants can benefit from the soil nutrients found in natural geotextiles' breakdown products [83].

A high initial tensile strength is characteristic of natural geotextiles. It is useful for reinforcing roads during their first stages of development [84]. Research comparing the bearing capacities of reinforced and unreinforced jute geotextile roads indicated that the former has a bearing capacity 1.5-7 times higher than the latter [85]. Because natural fibres break down over time, the effectiveness of natural geotextiles employed for road reinforcement will deteriorate and eventually fail [86]. Researchers have recently determined that natural geotextiles' long-term durability is not an important factor in improving the stability of rural roadway subgrade. Natural geotextiles are being utilized more frequently in India to fortify the subgrade of rural highways [87]. The reason behind this is that the subgrade experiences less stress while the road is being constructed and used, thanks to the high initial tensile strength of the natural geotextiles. The subgrade soil undergoes consolidation and compaction over time due to the traffic stress, which increases its bearing capacity. Once the natural geotextile has degraded, the subgrade's bearing capacity will be sufficient for the intended application [88].

The capacity of natural fibres to remove heavy metals makes natural geotextiles useful for medium- and short-term drainage and filtration as well [89, 90]. Using sand and flax geotextile filters, Abbar et al. [91] investigated how linen geotextile affected soluble heavy metals. The results showed that the filter could absorb soluble metals and connect heavy metals better with flax geotextile. Soluble heavy metal filtration is an area where natural geotextiles clearly shine. Plant fibres are hygroscopic, which means they absorb water and expand when exposed to moisture. When it comes to drainage issues in geotechnical engineering, jute geotextile is determined to be a practical and cost-effective medium [92]. The filter's pore diameter is drastically lowered

because of its rapid water absorption. Filter plugging and total loss of permeability will result in the worst-case scenario. The filtration or drainage function of natural geotextiles is limited by their hygroscopicity and service life.

The previous examples of natural geotextiles in action show that their early biodegradation is the main issue preventing them from serving their intended purpose in the future [11]. Over the past 20 years, a lot of studies have focused on natural geotextiles and how to make them survive longer. Natural geotextiles have recently been enhanced in performance by various approaches, as shown in Table 3. Currently, chemical modifications or adding a certain amount of synthetic fibre are the two most common ways to improve the qualities of natural geotextile. The mechanical and physical characteristics of a natural geotextile can be enhanced by using a specific amount of synthetic fibre. In a number of studies, geotextiles made of natural fibres and polymers, such as nettle and polylactic acid, and geotextiles made of polyethylene terephthalate (PET) and jute (PP) [93], showed encouraging results. Adding adhesion boosters or modifying the material chemically are two other intriguing ways to enhance the mechanical capabilities. Alkali treatment, acetylation, stearic acid treatment, benzylation, TDI treatment, peroxide treatment, anhydride treatment, permanganate treatment, silane treatment, isocyanate treatment, and plasma treatment were all methods of chemical modification of natural fibre that were summarized by La Mantia et al. [94]. Chemically modified geotextiles have been the subject of much research. For example, esterification improves the chemical degradation resistance of jute geotextiles [95, 96], laccase improves the physical properties of jute geotextiles [97], and alkali improves the anti-puncture ability of jute geotextiles [98].

**Table 3. Improving the properties of natural geotextiles.**

| Method                   | Geotextile type                | Research                                                                            | Effect                                                                                                                                          | Ref.  |
|--------------------------|--------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Chemical modification    | jute geotextiles               | Esterification of Jute geotextiles                                                  | Stretching and chemical degradation resistance enhanced                                                                                         | [96]  |
|                          | coir geotextiles               | Durability studies of surface-modified coir geotextiles                             | The surface-modified geotextiles retained more than 70% of their initial tensile strength after burial in the top layer of soil after one year. | [98]  |
|                          | jute geotextiles               | Laccase treatment of Jute Geotextiles Treatment of Jute                             | Physical properties and surface hydrophobicity are improved                                                                                     | [99]  |
|                          | jute geotextiles               | Geotextiles with Isothiazolinone and Fluorocarbon Derivatives                       | Improvement of Antimicrobial and Water-proof Performance                                                                                        | [80]  |
|                          | coir geotextiles               | Lime-treatment                                                                      | Lime treatment promotes the initial retention of cellulose in natural fibres                                                                    | [18]  |
|                          | Kenaf geotextiles              | alkaline treated                                                                    | Compared with untreated kenaf geotextile, the tensile strength of the geotextile treated with 6% NaOH is increased by 51.0%                     | [93]  |
| Blending synthetic fibre | Nettle/PLA geotextiles         | Tests on tensile strength, biodegradability and soil fertility enhancement          | the geotextiles are promising for slope stabilization application                                                                               | [100] |
|                          | jute/polypropylene geotextiles | Mechanical Properties and Damage Analysis of Jute/Polypropylene Nonwoven Geotextile | Tensile properties and puncture resistance were improved                                                                                        | [77]  |
|                          | jute/polypropylene geotextiles | Treatment of Jute/PP Nonwoven Geotextile with Alkali                                | Compared with PP geotextiles, 40/60 jute/PP geotextiles have higher tensile strength and secant modulus                                         | [101] |

## 8. Intelligent Geotextiles

Midway through the 1970s, a novel kind of optical fibre-based sensor called a fibre optical sensor was developed [102, 103]. Benefits include excellent electrical insulation, robust anti-EMR capabilities, high sensitivity, and simple remote signal monitoring [104-106]. Geotextiles incorporate optical fibre sensors into their construction by means of a series of warp knitting set places. Geotextiles are used to strengthen and stabilize geotechnical structures like dams, railways, embankments, and slopes. Optical fibre sensors can track changes in mechanical deformation, temperature, humidity, and pore pressure to keep an eye on how well these structures are doing. This can help find places where geotechnical structures are at risk of failure or are already showing signs of high failure, so they can be repaired or avoided altogether [107]. Intelligent geotextiles, then, are more promising.

"Intelligent" or "smart" geotextiles are the newest geotextile invention, and they're meant to collect data and monitor civil and environmental infrastructure in real time. A crucial component of this technique is the incorporation of sensing elements, mainly optical fibre sensors, within the geotextile framework without any noticeable disruption [108].

The incorporation of optical fibre sensors is a detailed process designed to establish a reliable and effective monitoring system. The sensors are frequently integrated into the production process rather than only being attached. This can be accomplished via weaving or knitting. Optical fibres can be integrated or interlaced directly into the fabric matrix of the geotextile [109]. This technique offers superior mechanical protection and guarantees that the sensor is seamlessly integrated with the material, functioning in harmony with the geotextile. The alternative approach is encapsulation. To improve durability, optical fibres may be encased in a protective polymer sheath prior to their incorporation into the fabric. This protects fragile fibres from the severe geotechnical environment and facilitates a more reliable connection to data collecting devices [110].

By tracking variations in the optical signal that travels through the fibre, these built-in sensors may measure critical physical parameters like as strain, temperature, pressure, and moisture content. Fibre bragg grating (FBG) sensors are among the most common kinds of sensors employed. These give accurate data from discrete locations along the geotextile, making them perfect for localized strain and temperature measurements. Distributed brillouin sensing (DBS) is an alternate. You may map a comprehensive profile of strain or temperature across a vast area using this innovative technology, which allows for continuous, distributed readings along the whole length of the fibre [111].

Recent studies have illustrated the practical utilization of intelligent geotextiles in diverse infrastructure initiatives. A study conducted by Ghazali et al. (2023) demonstrated the application of optical fibre-integrated geotextiles for monitoring strain and deformation in a road embankment. The real-time data facilitated engineers in identifying early indicators of settling and possible failure, hence enabling preventive maintenance [112].

As an alternate environmentally conscious building material, Chatrabhuj and Kundan Meshram used geosynthetics to reinforce the soil [113]. You can further expand their applicability by using a variety of geosynthetic materials, including geotextile, geomembrane, geogrid, geonet, geocomposite, geofibre, geobags, geopipes, geosynthetic clay liner, and geofoam. The use of geosynthetics in soil stabilization is of paramount importance because of the many ways in which they can improve soil quality, including by strengthening weak soil, enhancing stability, protecting against erosion, improving drainage, and effectively retaining soil. As an effective substitute for more conventional building materials, geosynthetics can increase the strength of soil for applications such as subgrade, embankment, slopes, foundations, and earthen dams.

Most academics and industrialists are interested in smart textiles, which were investigated by Pendo and Ngesa [114]. These textiles incorporate active and responsive materials that provide functional and high-performance qualities. Consequently, the development and production of smart textiles have involved electronic devices and sensors, as well as fibres with optical or electrical characteristics, or a combination of both. The authors reviewed the latest innovations in high-performance smart fabrics, discussing the challenges and opportunities they present in the geotechnical and construction industries. Additionally, they provided a survey of the fundamentals of smart textiles, covering topics such as manufacturing techniques and potential future applications in the building and geotextile sectors.

## 9. High Performance Geotextiles

The increasing complexity of our environments and the widening range of geotextile applications have shifted the focus of geotextile research and development toward materials with exceptional strength, versatility, and performance. Additives, chemical modification, and composite geotextiles are now the main ways to enhance geotextile performance [115, 116]. It is a common practice to employ additives like stabilizers and antioxidants to compensate for geotextiles' performance deficiencies; nevertheless, this practice is leading to environmental pollution due to the large quantity of additives used. To increase the added value and broaden geotextile's use range, modification is also essential. Both the strength and anti-degradation properties of the geotextile have been enhanced. One way to construct geotextiles that can drain or filter heavy metals is to covalently graft chitosan or cysteine onto acrylic-modified PP geotextile [117, 118].

To get the greatest properties of many materials, composite geotextiles are often composed of a combination of different fibres. Research into high-performance geotextiles has long focused on identifying appropriate high-performance fibres. Compared to synthetic fibres, inorganic fibres like glass, basalt, and carbon have far higher modulus and strength [119-123]. A broad area of inorganic fibre on geotextiles is limited, nonetheless, because of the high production cost. High water permeability, outstanding anti-filtration, and wear resistance are properties of glass-fibre composite geotextiles [124], which are composed of glass-fibres and short-fibre needled non-woven fabric. Protecting the environment and being highly resistant to heat are two benefits of basalt-fibre geotextiles [125]. Along with the aforementioned fibre materials, there is a plethora of others that could serve as raw materials for high-performance geotextiles; nanofibres stands head and shoulders above the others. Modern geotextiles can benefit substantially from the incorporation of nanofibres, which are among the most cutting-edge

materials due to their malleability and potential for easy design into high-performance materials with distinctive properties [126-128].

## 10. Challenges and Future Directions

There are several significant challenges that must be addressed in the development and application of geotextiles, despite their widespread use and proven effectiveness in environmental engineering. Overcoming these limitations is crucial for the advancement of the field and the promotion of truly sustainable and reliable infrastructure solutions.

### 10.1 Recycling and Sustainability

Polypropylene (PP) and polyethylene terephthalate (PET) are synthetic polymers that present significant challenges for the geotextile sector. While these materials are known for their durability, they are not biodegradable, which creates substantial issues for waste management at the end of their useful life. Current common methods of disposal, such as landfilling and incineration, deplete resources and contribute to environmental contamination.

Two primary approaches should guide future research in this area. Firstly, modern, efficient ways to recycle geotextiles after they have served their useful purpose are urgently required. Continuous efforts are being made to develop mechanical and chemical recycling methods that can produce high-quality recovered fibres. These fibres will be used to create new geotextiles and other goods. Geotextiles that have served their purpose are recycled by shredding, pelletizing, and reprocessing them into either injection-moulded parts or fresh nonwoven fabrics. By mass, conventional industrial equipment may often achieve material recovery yields of 60–70%. The process of hydrocracking or glycolysis is used to break polymer chains back into their individual components in geotextiles made of polyethylene glycol, such as terephthalic acid and ethylene glycol. While it is possible to achieve monomer purities exceeding 90%, the energy requirements and operational expenses would increase by approximately 20% when compared to mechanical methods. Secondly, geotextiles composed of biodegradable polymers and natural fibres (such as hemp, jute, or coir) are among the sustainable options that the industry is actively seeking out. Strength and durability concerns are limiting these materials' employment in geotechnical applications, but they do hold the promise of a more circular economy in the future.

### 10.2 Durability and Long-Term Reliability

There are a number of degradation mechanisms that can affect the long-term durability of geotextiles when they are deployed in severe settings. A few examples are ultraviolet (UV) degradation, Sunlight quickly degrades geotextiles' polymer chains, causing a dramatic drop in their tensile strength. This is of greatest significance for applications at the surface level. As a result of chain-scission rates, geotextiles made of polypropylene and polyester that are exposed to ultraviolet light (200-320 nm) lose 30-40% of their tensile strength after 500 MJ/m<sup>2</sup> of accumulated irradiance, which is equivalent to approximately two years of direct sun exposure in mid-latitude conditions [2, 25]. Secondly, chemical and biological attack, when geotextiles are buried in dirt, they can be broken down over time by harmful bacteria and chemicals. Ester bonds in polyester geotextiles break when exposed to soils that are very acidic or very wet. Over the course of six months, molecular weights decreased by approximately 15% according to accelerated immersion experiments conducted at 60 °C and pH 12. Finally, mechanical damage, the performance of the geotextile can be diminished due to damage, punctures, or tears caused by installation and in-situ forces [28].

In order to address these obstacles, researchers are planning to conduct studies centred around firstly, creating novel polymer blends that are more resistant to natural, chemical, and ultraviolet light (advanced material science). Secondly, Intelligent geotextiles with built-in sensors can monitor strain and degradation in real-time, as mentioned before; this enables preventative maintenance and guarantees the material's functionality throughout its service life (integrated monitoring systems). A 50% increase in UV resistance is possible with the addition of UV absorbers (benzotriazoles) and Hindered Amine Light Stabilizers (HALS). Hydrolysis inhibitors, such as phosphonates free of antimony, have the ability to decrease molecular scission rates by around 20% [129].

### 10.3 Cost-Effectiveness

Although geotextiles can provide significant long-term cost savings by reducing the amount of natural aggregate required and enhancing the durability of infrastructure, their initial costs for materials and installation may pose challenges to implementation. This is particularly true for smaller-scale or low-volume projects. Resolving this issue need necessitates a multifaceted strategy. The first step in reducing the production cost of high-performance geotextiles is to optimize the production processes [130]. A second objective is to promote the use of Life Cycle Cost Analysis (LCCA) models that thoroughly assess the economic and environmental benefits of geotextiles throughout their entire life cycles. By justifying the initial investment through reduced maintenance costs and extended service life, these models provide a more accurate representation than simple comparisons of upfront costs. Despite having 1.5-2 times the initial cost of ordinary materials, sensor-enhanced geotextiles can

facilitate condition-based intervention, which results in a 20-30% reduction in maintenance and unscheduled repairs during a 25-year lifespan [131]. In comparison to landfill disposal, chemical recycling causes an increase of 10-15% in embodied energy but a decrease of approximately 25% in CO<sub>2</sub> equivalent emissions. While mechanical recycling requires the least amount of energy, it frequently leads to products that have been downcycled [30]. By focusing on these areas, geotextiles can continue to enhance their solutions for civil engineering and environmental protection; ultimately, these efforts will yield more cost-effective, reliable, and environmentally sustainable options.

## 11. Conclusions

There has been a dramatic increase in the demand for geotextiles in the geotechnical engineering industry over the past few decades. Polyolefin, polyester, or polyamide series polymers are the building blocks of geotextiles, with additives added for improved performance. In geotechnical engineering, geotextiles can serve to separate, filter, drain, strengthen, create a barrier, or protect against erosion. Despite geotextiles' growing importance in geotechnical engineering, several issues may arise: Some geotechnical engineers have voiced concerns about the possible pollution of the environment, the degradation of geotextiles during application, and the increased demand for these materials. We should give these things some thought.

We examine the current trend in geotextile development using the most recent statistics and a survey of the relevant literature. The natural geotextile is environmentally friendly since it follows the green idea. The primary component of natural fibre geotextiles is the fibre found in plants. It can naturally replace the standard geotextile in some short- and medium-term geotechnical engineering applications. One advantage of using natural geotextile for erosion control is its ability to absorb and store water. The durability of natural fibre geotextile limits its use. Currently, a combination of synthetic fibres and chemical modification can significantly increase the durability of natural geotextiles.

Reinforcing geotechnical structures with intelligent geotextile makes health monitoring of those structures a reality. This enables the early identification of vulnerable areas, which in turn permits preventative maintenance and repair. The ability of the intelligent geotextile to be monitored is dependent on the sensor's quality. Fibre Bragg grating sensors, which rely on Brillouin scattering, and polymer fibre-optic sensors are the most popular kinds of fibre-optic sensors utilized in geotextiles nowadays. Each type has its set of pros and cons. The intelligent geotextile is better suited to POF sensors that have a high measurement strain, high fracture strain, and high elasticity (more than 40%). Graphene is just one of several technologies that can make geotextiles smart, along with optical fibre sensors.

Developing geotextiles with high performance is an important ongoing effort. To compensate for geotextile's performance flaws, additives and modifications are the main focus at the moment. Second, high-performance fibres, like glass or basalt, can be used to create geotextiles with exceptional qualities. Applying nanofibers to geotextiles will allow for the design of geotextiles with exceptional and distinctive qualities in the future.

## Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data Availability

Enquiries about data availability should be directed to the corresponding/submitting author.

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## Contributions

H. Elsayed.: resources, visualization, validation, conceptualization, structuring, characterization, literature search, review writing, and editing.

N. Nagy: supervision, visualization, validation, conceptualization, preparation, structuring, characterization, guidance, writing, and support.

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