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Review

Sustainability of Geosynthetics-Based Solutions

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Abstract: Sustainability emphasises the importance of increasing the resource efficiency of infrastructure. The usage of geosynthetic materials in civil and environmental engineering can significantly influence sustainability at the planning and design stages of infrastructure construction projects. They are used in many different applications in construction and environmental engineering, as they provide a better and longer performance and less costly solutions than traditional materials (such as sand, gravel, concrete and cement). Additional benefits can be achieved by combining geosynthetics with various recycled materials as substitutes for high-quality natural materials. In this paper, the importance of sustainability in geosynthetics-based solutions is discussed. The possibilities of using geosynthetics in sustainable development have been analysed and the benefits resulting from their application, such as the reduction in carbon footprint and release of greenhouse gases and saving water and other natural resources, have been assessed. Innovative solutions that support mitigation measures, adaptation to climate change and achievement of sustainable development goals have been presented.

Keywords: sustainable development; geosynthetics; recycled materials; waste materials; environmental protection; climate change; SDGs; carbon footprint; life cycle assessment; embodied carbon

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1. Introduction

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 [1–5]. 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 [2,4,6]. 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 [7–14].

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, introduced 17 Sustainable Development Goals (SDGs). In addition to the 17 Sustainable Development Goals, the Agenda contains 169 related targets that reflect the three dimensions of sustainable development—economic, social and environmental. The United Nations Sustainable Development Goals are set to be achieved by 2030 [15,16]. While the construction sector is affected by all 17 SDGs, the following should be considered particularly relevant: SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production) and SDG 13 (climate action). In their paper, Ogunmakinde et al. describe the relationships between the Circular Economy (CE), construction waste minimisation and the SDGs. According to the authors, the adoption of the CE in the construction industry can achieve about 10 SDGs [17]. In turn, an overview of the barriers, drivers and stakeholders towards the Circular Economy in the construction sector is provided in an article by Munaro et al. [18]. The authors indicate that the construction sector is dealing with three major issues: lack of a governance plan towards CE, lack of an efficient construction and demolition waste management program and the need for greater awareness and communication about circular principles. Basu and Lee emphasise that for engineering projects (i.e., also geotechnical projects), the earlier sustainability considerations are taken into account, the better the outcome will be. Environmental and social aspects should also be considered at the design stage [12].

By using new materials and technologies, civil engineers can significantly lower the environmental impact of their projects, e.g., by reducing embodied and operational carbon. In addition to the re-use of construction and demolition waste, waste generated in other industries can also be used [8,12,19–21]. Geosynthetics may be applied for the above-mentioned purposes, in addition to being utilised in constructions that serve climate change mitigation [7,12,19,22].

Geosynthetics are defined as products with at least one of whose components is made from a synthetic or natural polymer, in the form of a sheet, a strip or a three-dimensional structure, used in contact with soil and/or other materials in geotechnical and civil engineering applications. They have been in use since the 1960s [23,24]. Geosynthetics (GSY) are divided into:

- Geotextiles (GTX)—planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted or woven, used in contact with soil and/or other materials in geotechnical and civil engineering applications.
    - Woven geotextiles (GTX-W);
    - Knitted geotextiles (GTX-K);
    - Non-woven geotextiles (GTX-NW).
- Geotextile-related products (GTP)—planar, permeable, polymeric (synthetic or natural) material used in contact with soil and/or other materials in geotechnical and civil engineering applications, which do not comply with the definition of geotextiles.
    - Geogrids (GGR);
    - Geonets (GNT);
    - Geocells (GCE);
    - Geostrips (GST);
    - Geomats (GMA);
    - Geospacers (GSP);
    - Geoblankets (GBL).
- Geosynthetic barriers (GBR)—low-permeability geosynthetic material, used in geotechnical and civil engineering applications, with the purpose of reducing or preventing the flow of fluid through the construction.
    - Polymeric geosynthetic barriers (GBR-P)—also called geomembranes;
    - Clay geosynthetic barriers (GBR-C)—also called geosynthetic clay liners (GCL);

  - Bituminous geosynthetic barriers (GBR-B)—also called bituminous geomembranes.
- Geocomposites (GCO)—manufactured, assembled material using at least one of the geosynthetic products among the components [24–26].

The main functions of geosynthetics include separation, barrier, filtration, drainage, reinforcement, surface erosion control, protection, stress relief (for asphalt interlayer) and stabilization. Possible applications for geosynthetics include but are not limited to reservoirs and dams, canals, liquid waste disposal sites, solid waste disposal sites, transportation infrastructure and roads, foundations and retaining walls, railways, surface erosion-control systems, tunnels and underground structures, drainage systems, coastal erosion control, asphalt reinforcement, secondary containment, waterproofing and underground structures [24,25]. Year after year, with the development of technology, new possibilities for the use of geosynthetics emerge [27,28]. In the function of separation and filtration, woven and non-woven geotextiles are most commonly used; for drainage—non-woven geotextiles and geocomposites; for containment—woven and non-woven geotextiles, geomembranes and geocells; for reinforcement—woven geotextile, geogrids and geocells; for hydraulic barrier—geomembranes and clay geosynthetic barriers; and for erosion protection—woven and non-woven geotextiles, geocomposites, geogrids and geocells [29].

Geosynthetics are mainly produced from PP (polypropylene), PET (polyethylene terephthalate (polyester)) and PE (polyethylene), but are also produced in biodegradable versions from natural fibres (jute, hemp, coir, cotton, sisal, kenaf, wool, straw, bamboo) and biodegradable polymers [23,30–32]. In recent years, work has been ongoing to develop a new generation of biodegradable geosynthetics. In this application, most testing concerns the use of a biodegradable polymer of natural origin—poly(lactic acid) (PLA) [33]. The term *green geosynthetics* has also been introduced, which Jeon [34] defines as follows: *green geosynthetics are made of eco-environmental biodegradable polymeric resins or natural materials that maintain their needed performance such as durability, design strength, hydraulic property, etc., during the service period. Then, after the service period, they degrade, leaving no harmful effects within the soil structure*.

Among the functions that are particularly important from the point of view of sustainable development, climate change adaptation and environmental protection are the use of geosynthetics in green roofs, vertical greening systems, urban greenery, blue-green infrastructure, erosion control, sustainable urban drainage systems, flood protection and erosion control (dams and dykes/levees), coastal protection and waste disposal sites [22,26–29,32,35,36].

There have been reports in the literature regarding the need to study the potential release of microplastics from structures containing geosynthetics. While in most cases geosynthetics are not exposed to the main agents of degradation and mechanical stress due to abrasion, this risk must be taken into account when responsibly choosing or specifying a geosynthetic product [37]. In addition, an article by Giglio et al. [38] suggests that the available literature on geosynthetics is very fragmented, and is characterized by ambiguity and a lack of widely accepted understanding of some topics, particularly those related to environmental and commercial aspects.

The aim of this paper is to examine the applicability of geosynthetic materials, given the demands posed by sustainable development, and to create a comprehensive and cross-cutting review taking into account current issues and challenges, knowledge gaps, major limitations and future research directions.

The article has been divided into three thematic parts reflecting current problems for the studied topic: I. reducing the environmental impact of construction through the use of geosynthetics, II. the combination of geosynthetics and waste construction materials, III. geosynthetics in climate change adaptation and mitigation solutions.

2. Reducing the Environmental Impact of Construction through the Use of Geosynthetics

Climate change and the adverse effects of pollutant emissions on the environment have also led to more conscious behaviour in construction and environmental engineering, aiming to provide solutions in accordance with the principles of sustainable development. Therefore, life cycle assessment procedures for products and geosystems are increasingly being implemented. Geosynthetics are used as alternative materials to methods traditionally used in construction. The benefits of using these materials in engineering structures can be divided into the immediate and long term. Immediate benefits include savings from the reduction in the use of natural soils, replacement of natural soils with recycled materials, ease of installation, faster construction times and lower transport costs. Long-term benefits include savings related to performance, reliability, maintenance and improved sustainability [12,13,39–41].

Thanks to geosynthetics, more practical and cost-effective solutions can be provided than with traditional building materials. By using geosynthetics, the consumption of raw materials is significantly reduced. In addition, raw materials used on construction sites, e.g., sand and aggregates, are usually available a long distance from the application site. Transporting materials, on the other hand, incurs costs associated with their shipping and fuel consumption and thus generates a high carbon footprint. Moreover, increasingly stringent environmental regulations prohibit or restrict the use and application of certain traditional construction materials. The use of geosynthetics may also allow the reuse of existing materials on-site that would otherwise require off-site disposal, and thus they can be even more beneficial in terms of cost when used with waste materials. Geosynthetics are lighter (with tangible benefits during transport) and easier to install (shorter installation time, lower fuel and energy consumption, reduced need to use some of the construction machinery) than natural soils. Therefore, the use of geosynthetics may significantly reduce greenhouse gas emissions during the construction of geotechnical structures [12–14,40,42]. Nowadays, comparative life cycle assessment studies of geosynthetics to conventional building materials are increasingly being carried out with the use of environmental impact indicators [14].

Geosynthetics such as geogrids, geotextiles and geocomposites used for ground reinforcement decrease the thickness of the bearing layer, reduce the use of traditional materials (e.g., gravel, sand), lower construction costs (e.g., transport costs, construction time, energy consumption, etc.) and at the same time increase the reliability, durability and performance of earthen structures [13,42].

The use of geosynthetic materials to reinforce soft soils during road construction leads to a reduction in the thickness of the base layers (Figure 1), enables the use of poor subgrade, which in turn leads to savings associated with soil disposal and possible storage, and enhances the performance of pavement constructed over soft subgrade [42,43].

Similar benefits have been observed in the use of geosynthetics with a filtering function. These are primarily high quality and cost reduction compared to traditional drainage, the possibility of using less or lower-quality aggregate for drainage systems, reduced risk of contamination and improper segregation of aggregate for drainage during construction, reduced excavation volume and less material waste. The cost of installing geosynthetics is 50% lower than the cost resulting from the use of granular material, increasing drainage capacity [23,39]. A geosynthetic filtration layer has a lower environmental impact than, for example, gravel. The difference is significant for indicators such as energy demand, climate change, acidification, eutrophication and water consumption. The use of gravel has a much greater impact on individual indicators due to its extraction and transport to the construction site [14].

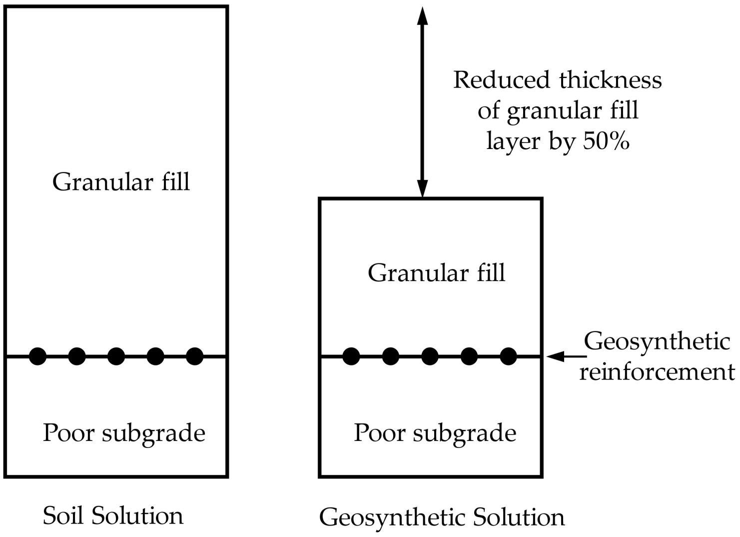

Figure 1. Scheme of road profiles without/with reinforcement of geosynthetics, adapted from [42].

Geosynthetic materials acting as geosynthetic barriers (geomembranes and clay geosynthetic barriers) are durable and at the same time environmentally friendly. The use of geomembranes as a cover layer on landfill sites leads to a reduction in infiltration and thus in leachates, resulting in the production of more biogas, which may be used as a renewable energy source. With the use of geomembranes, the thickness of landfill capping significantly decreases, making it possible to landfill a greater mass of waste (Figure 2) [42,44].

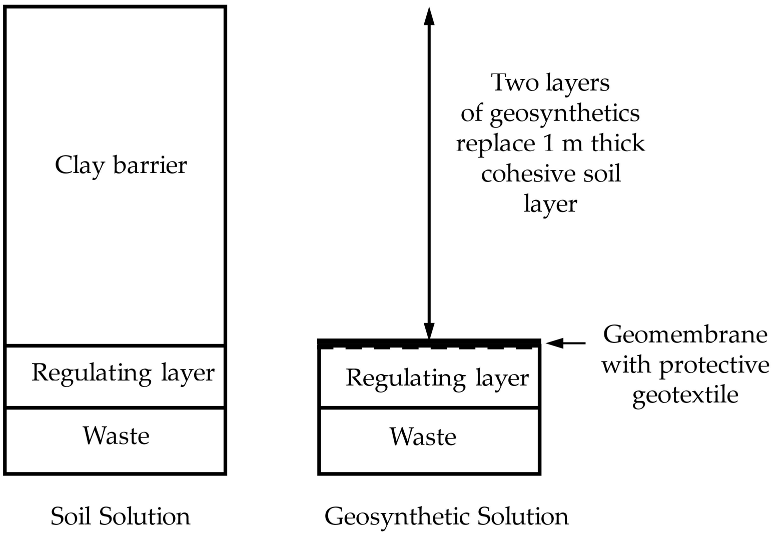

Figure 2. Scheme of the capping systems without/with geosynthetics, adapted from [42].

Geomembranes are one of the main elements in the construction of sealing systems, working with the soil to prevent the migration of contaminants in liquid or gas form. Geomembranes and clay geosynthetic barriers used for sealing flood embankments are characterised by the ease and speed with which work can be carried out with a guarantee of tightness that is unattainable with traditional methods, e.g., sealing with a clay layer [14,35,44].

An extensive analysis of the benefits of geosynthetics was carried out by Stucki et al. [14]. They compared the environmental performance of geosynthetics in various application cases to the environmental performance of traditional materials (i.e., concrete, cement, lime, gravel). The authors took into account eight impact category indicators: cumulative energy demand (CED), climate change (Global Warming Potential, GWP100), photochemical ozone formation, particulate formation, acidification, eutrophication, land competition and water use.

Although geosynthetic materials are very diverse in terms of function and application, they share common characteristics that are important for sustainable development, such as the ease and speed with which geotechnical structures can be constructed, their durability and trouble-free operation and the lack of the need for large construction sites [12,13,40,42].

A Life Cycle Assessment (LCA) is used to determine the environmental impact of products and systems throughout their period of use. A LCA covers all life cycle stages of products and systems (from the cradle to the grave), such as raw materials extraction and processing, manufacturing, transport, construction, maintenance and repair and end-of-life [12,42,45,46]. Recycling and the re-supply of materials to industry and society are increasingly being considered in this method (promoting the principles of the Circular Economy). A LCA is also used to compare two competing products or systems. At present, it is desirable to strive to minimise the environmental impact of a product or system in all phases of its life, but especially in those where this impact is the greatest. Such an approach, in addition to minimising negative environmental impacts, may also lead to a reduction in the costs of manufacturing, using and disposing of products.

The LCA process consists of four steps (Figure 3):

- Goal and scope definition;
- Life cycle inventory analysis (LCI);
- Life cycle impact assessment (LCIA);
- Interpretation of the results (including critical review, determination of data sensitivity, presentation of results) [47–49].

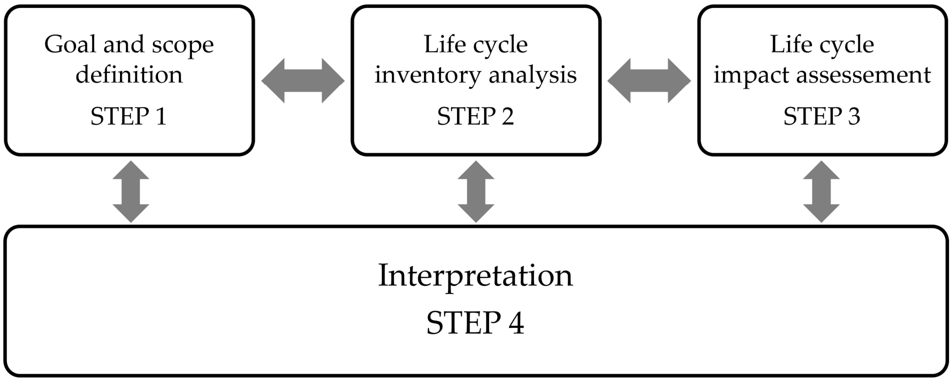

Figure 3. Methodological steps—Life Cycle Assessment, adapted from [7,46].

A Life Cycle Assessment (LCA) involves the combination and evaluation of input and output data of possible environmental impacts of a product or system throughout its life cycle. The basic tasks of a LCA from an environmental aspect are:

- Documenting potential environmental impacts of a product or system at each stage of its life cycle;
- Analysing the potential for interrelated environmental impacts in such a way that remedial measures do not lead to new environmental problems (i.e., transfer of pollution);
- Setting priorities for improving the production of goods;
- Comparing different solutions to the same problem;
- Ways of carrying out the same process [50].

It is important to set prerequisites, i.e., the same scope of application, the same technology and the same range of functions, before establishing the life cycle for different products or systems. In order to apply a LCA, comparisons are made within:

- Extraction of raw materials, e.g., sand, gravel, clay, kaolin, limestone, metal ores, crude oil;

- Production using extracted raw materials, e.g., lime, sand, gravel and polymer granulates (PE, PP), and the subsequent use of these products in the manufacturing of, e.g., concrete and geosynthetics;
- Use of products obtained on the construction site;
- Each stage is accompanied by the transport of, for example, extracted raw materials to the producer or received products of the construction site [46].

When making life cycle comparisons between products or systems, aspects of environmental emissions are taken into account. An extremely important and now very frequently discussed issue is the phenomenon of the greenhouse effect, which is caused by the increase in emissions of gases such as carbon dioxide, methane and nitrous oxide into the atmosphere [51,52]. The largest contributor to emissions is carbon dioxide (CO_2), which accounts for as much as 75% of global emissions of all greenhouse gases [53]. A measure of the volume of greenhouse gas emissions into the environment is the carbon footprint, which is defined by ISO 14067 [54]. The carbon footprint is the total greenhouse gas emissions caused directly and indirectly by an individual, organization, activity, process, product or event from within a specified boundary. It is measured in carbon dioxide equivalent (CO_2e)—a metric measure used to compare the emissions from various greenhouse gases on the basis of their global warming potential (GWP). CO_2 is the reference gas against which other GHGs are measured (its GWP = 1). The time period usually used for GWP is 100 years. The carbon footprint equivalent value can be presented in different units, for example, per product (kg/kg), per soil (kg/m^3) or per sealed area (kg/m^2) [46,55–59]. According to the Kyoto Protocol, the carbon footprint takes into account the emissions of six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFC) and sulphur hexafluoride (SF_6) [52]. The new mandatory Kyoto Protocol greenhouse gas is nitrogen trifluoride (NF_3). The United Nations Framework Convention on Climate Change (UNFCCC) decided to include nitrogen trifluoride in the second Kyoto compliance period 2013–2020, increasing the number of officially recognised GHGs from six to seven [60].

The 25 geosynthetics-based applications presented at the GRI-24 conference [40] achieved an average of 65% reduction in carbon footprint compared to traditional solutions. The average carbon savings for individual case studies amounted to 69% for walls, 65% for embankments and slopes, 76% for armouring, 75% for landfill covers, 30% for landfill liners, 61% for retention and 40% for drainage pipes.

Basu and Lee [12] report average carbon savings for analysed geosynthetics-based projects in the following applications: 31–82% for embankments and slopes, 67–85% for slope protection, 70–87% for retaining walls, 27–69% for landfill liners, 49–59% for bridge abutment and 70% for erosion control.

Attention should be drawn to difficulties in determining embodied carbon for geosynthetics. Embodied Carbon (EC) refers to carbon dioxide emitted during the manufacturing, transport and construction of all building materials, together with end of life emissions [40]—cradle to grave approach (Figure 4). In 2015, Raja et al. [61] signalled that geosynthetic products are not included in the databases of the embodied carbon of construction materials most commonly used in Europe, and generic values for polypropylene and polyethylene are often used. In their work, they presented embodied carbon calculations for geosynthetic products using first-hand data on the manufacturing process. The calculated values for the two categories of geosynthetics were significantly lower than the commonly used values from the databases. The calculations were performed for a cradle-to-gate approach.

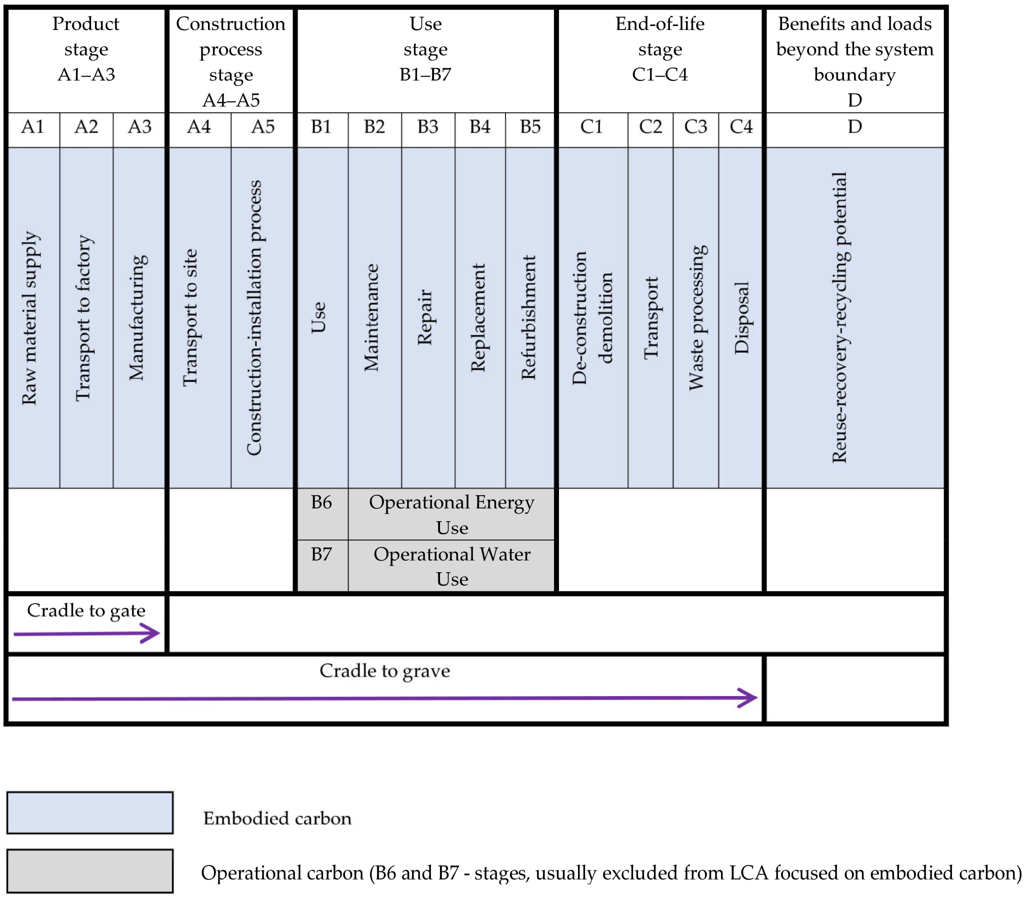

Figure 4. Life cycle stages and boundaries for construction products and works, adapted from [62,63].

3. Combination of Geosynthetics and Waste Construction Materials

The construction sector has been using waste materials for many years, i.e., various types of ash and slags, rock, coal and ore mining waste, steelworks waste, tire rubber, construction and demolition waste, animal and plant fibres, glass waste, foundry sand and plastic waste. The highly intensive development of the various branches of the construction industry is resulting in an increasing demand for high-quality granular materials (i.e., coarse aggregate, sand, gravel and clay). Deposits of natural soil and especially sand are over-exploited. The demand for granular materials is growing exponentially with urbanization and population growth. Even when natural soil material is available, the distance from the deposit to construction is often too great, which generates high transport costs and associated negative environmental impacts and increases the carbon footprint of the soil material. Utilising waste materials in engineering structures reduces the exploitation of natural resource deposits, energy consumption, water consumption, fuel consumption, etc. In addition, it is an economical, environmentally friendly and sustainable way to reuse waste and relieve landfills and incineration plants, and thus to reduce pollution from these facilities [8,20,30,64–70]. Recycled coarse aggregates produced from construction and demolition waste can reduce GHG emissions by 65% and save 58% of non-renewable energy consumption. On the other hand, recycled fine aggregates from waste glass save 54% of energy consumption and reduce GHGs by 61%, and SO_2 eq emissions by 46%, compared with the production of natural fine aggregates from river sand [71].

Geosynthetics allow an even more efficient use of waste materials and can be used as substitutes for soil and aggregates of lower quality. Furthermore, despite the previous lack of confidence in the quality and consistency of waste materials' characteristics, geosynthetics are more and more frequently manufactured from recycled material [19,30,37,72].

4. Geosynthetics in Climate Change Adaptation and Mitigation Solutions

Geosynthetics can be applied in solutions that mitigate the adverse effects of climate change such as flash floods, urban heat islands and drought, and improve the quality of life in cities—green roofs, living walls and sustainable urban drainage systems (SUDS). They are also used in a substantial number of effective Nature-based Solutions (NBS)—soft engineering approaches for societal challenges that are inspired by processes and the functioning of nature and applied in coastal, freshwater and urban implementations to enhance the resilience of ecosystems. NBS are solutions that support adaptation to climate change. They are efficient and cost-effective, providing environmental, economic and social benefits at the same time. They introduce elements and processes of nature into cities through systemic measures adapted to local conditions and are efficient in their use of resources [22,26,27,29,35,73].

An example of geosynthetics solutions that match sustainable uses and SDG goals is water-absorbing geocomposites (WAGs). The geocomposite consists of a geotextile, a superabsorbent (SAP) and a framework that provides space for the swelling SAP. The water stored in the SAP is used by plants during droughts and is more than 95% available to plants [74–77]. WAGs are used extensively to support plant vegetation in environmental engineering, civil engineering, agriculture, horticulture and forestry. They are receiving a lot of attention in urban areas, where they contribute to solving problems related to the maintenance of urban green areas (e.g., noise barriers, green retaining structures, green roofs and walls). Recently, WAGs have been gaining a lot of popularity as a supporting element in the operation of green and blue-green urban infrastructure and sustainable stormwater management systems. Their use in agricultural and urbanised areas supports resilience building and climate change adaptation. Studies have shown that water-absorbing geocomposites can reduce the water stress of drought-prone plants, save 50% of water for irrigation or watering and increase several-fold the biomass of above- and below-ground parts of plants. New biodegradable geocomposites made from waste fibres are an example of the use of waste to produce geosynthetics. Biodegradable fibres also play an important role in supplying plants with nutrients [27,30,75].

5. Conclusions and Future Directions

In sustainable development, resource efficiency is extremely important. The use of geosynthetic materials may have a significant impact on reducing the adverse environmental impact of investments and promote a resource-efficient and low-carbon economy. Already at the planning and design stages of infrastructure, calculations related to the reduction in greenhouse gas emissions can be made. Compared with conventional solutions, CO_2 emissions and energy consumption can be significantly reduced. Geosynthetics are extensively used in construction and environmental engineering. They have a positive effect on the durability and strength of structures, save natural resources and time as well as reduce investment costs.

Additional benefits may be achieved by combining geosynthetics with recycled materials as substitutes for high-quality natural materials. Geosynthetics can be used in solutions that reduce the adverse effects of climate change such as floods and droughts or urban heat islands. The increase in precipitation extremes, either heavy rainfall events or droughts, which are nowadays observed all over the world, has a destructive effect on the condition of earthen constructions, especially dams, levees and road embankments. Geosynthetics play a significant role in protecting slopes against erosion, providing efficient drainage or supporting vegetation of plants for biotechnical soil stabilization. In addition, they are used in sustainable stormwater management systems, green roofs and green walls, and are also used in other effective systems to mitigate the adverse effects of climate change such as Nature-based Solutions and in the development of green-blue urban infrastructure.

Future research should address the possible release of microplastic from geosynthetics-based solutions and the related responsible selection of geosynthetic products. The difficulties in determining embodied carbon for geosynthetics also need to be resolved, and the correct data for geosynthetics need to be placed in databases. Further research and promotion of knowledge on the environmental aspects of the use of geosynthetics, including the use of recycled materials for their production, is necessary. The ambiguity and lack of understanding of topics related to the sustainability of geosynthetics ought to be minimized, and knowledge gaps need to be continuously filled. In addition, the development of new geosynthetics and the expansion of their areas of application should continue to be pursued.

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References

1. Zeng, Z.; Ziegler, A.D.; Searchinger, T.; Yang, L.; Chen, A.; Ju, K.; Piao, S.; Li, L.Z.X.; Ciais, P.; Chen, D.; et al. A reversal in global terrestrial stilling and its implications for wind energy production. *Nat. Clim. Change* **2019**, *9*, 979–985. [CrossRef]
2. Qi, J.; He, B.J.; Wang, M.; Zhu, J.; Fu, W.C. Do grey infrastructures always elevate urban temperature? No, utilizing grey infrastructures to mitigate urban heat island effects. *Sustain. Cities Soc.* **2019**, *46*, 101392. [CrossRef]
3. IPCC. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2021: The Physical Science Basis*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.
4. Mishra, V.; Sadhu, A. Towards the effect of climate change in structural loads of urban infrastructure: A review. *Sustain. Cities Soc.* **2023**, *89*, 104352. [CrossRef]
5. Trach, Y.; Trach, R.; Kalenik, M.; Koda, E.; Podlasek, A. A Study of Dispersed, Thermally Activated Limestone from Ukraine for the Safe Liming of Water Using ANN Models. *Energies* **2021**, *14*, 8377. [CrossRef]
6. Zięba, Z.; Dąbrowska, J.; Marschalko, M.; Pinto, J.; Mrówczyńska, M.; Leśniak, A.; Petrovski, A.; Kazak, J.K. Built environment challenges due to climate change. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2020; Volume 609, p. 012061.
7. Zhu, Y.; Zhang, F.; Jia, S. Embodied energy and carbon emissions analysis of geosynthetic reinforced soil structures. *J. Clean. Prod.* **2022**, *370*, 133510. [CrossRef]
8. Lei, J.; Huang, B.; Huang, Y. Life cycle thinking for sustainable development in the building industry. *Life Cycle Sustain. Assess. Decis. Methodol. Case Stud.* **2020**, 125–138. [CrossRef]
9. Min, J.; Yan, G.; Abed, A.M.; Elattar, S.; Amine Khadimallah, M.; Jan, A.; Elhosiny Ali, H. The effect of carbon dioxide emissions on the building energy efficiency. *Fuel* **2022**, *326*, 124842. [CrossRef]
10. Ryłko-Polak, I.; Komala, W.; Białowiec, A. The Reuse of Biomass and Industrial Waste in Biocomposite Construction Materials for Decreasing Natural Resource Use and Mitigating the Environmental Impact of the Construction Industry: A Review. *Materials* **2022**, *15*, 4078. [CrossRef]
11. Purchase, C.K.; Al Zulayq, D.M.; O'brien, B.T.; Kowalewski, M.J.; Berenjian, A.; Tarighaleslami, A.H.; Seifan, M. Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits. *Materials* **2022**, *15*, 76. [CrossRef]
12. Basu, D.; Lee, M. Sustainability considerations in geosynthetic applications. In *ICE Handbook of Geosynthetic Engineering: Geosynthetics and Their Applications*; Shukla, S.K., Ed.; ICE Publishing: Fitchburg, MA, USA, 2021; pp. 427–457. ISBN 9780727765000.
13. Basu, D.; Lee, M. A combined sustainability-reliability approach in geotechnical engineering. In *Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering*; Roshni, T., Samui, P., Tien Bui, D., Kim, D., Khatibi, R., Eds.; Elsevier Inc.: Amsterdam, The Netherlands, 2022; pp. 379–413. ISBN 9780323856980.
14. Stucki, M.; Büsser, S.; Itten, R.; Frischknecht, R. *Comparative Life Cycle Assessment of Geosynthetics versus Conventional Construction Materials Holger Wallbaum*; Zürich on Behalf of the European Association for Geosynthetic Manufacturers (EAGM); Swiss Federal Institute of Technology: Uster, Switzerland, 2011.
15. UN. General Assembly Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1. 2015. Available online: https://www.refworld.org/docid/57b6e3e44.html (accessed on 5 January 2023).
16. D'Adamo, I.; Gastaldi, M. Sustainable Development Goals: A Regional Overview Based on Multi-Criteria Decision Analysis. *Sustainability* **2022**, *14*, 9779. [CrossRef]

17. Ogunmakinde, O.E.; Egbelakin, T.; Sher, W. Contributions of the circular economy to the UN sustainable development goals through sustainable construction. *Resour. Conserv. Recycl.* **2022**, *178*, 106023. [CrossRef]
18. Munaro, M.R.; Tavares, S.F. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Clean. Responsible Consum.* **2023**, *8*, 100107. [CrossRef]
19. Palmeira, E.M.; Araújo, G.L.S.; Santos, E.C.G. Sustainable solutions with geosynthetics and alternative construction materials—A review. *Sustainability* **2021**, *13*, 12756. [CrossRef]
20. Vo, T.L.; Nash, W.; Del Galdo, M.; Rezania, M.; Crane, R.; Mousavi Nezhad, M.; Ferrara, L. Coal mining wastes valorization as raw geomaterials in construction: A review with new perspectives. *J. Clean. Prod.* **2022**, *336*, 130213. [CrossRef]
21. Kiersnowska, A.; Fabianowski, W.; Koda, E. The Influence of the Accelerated Aging Conditions on the Properties of Polyolefin Geogrids Used for Landfill Slope Reinforcement. *Polymers* **2020**, *12*, 1874. [CrossRef]
22. Cascone, S. Green Roof Design: State of the Art on Technology and Materials. *Sustainability* **2019**, *11*, 3020. [CrossRef]
23. Markiewicz, A.; Koda, E.; Kawalec, J. Geosynthetics for Filtration and Stabilisation: A Review. *Polymers* **2022**, *14*, 5492. [CrossRef]
24. *CEN ISO 10318-1:2015*; Geosynthetics—Part 1: Terms and Definitions.European Committee for Standardization. Rue de la Science 23: Bruxelles, Belgium, 2015.
25. *CEN ISO 10318-1:2015/Amd 1:2018*; Geosynthetics—Part 1: Terms and Definitions—Amendment. Rue de la Science 23: Bruxelles, Belgium, 2018.
26. Touze, N. Healing the world: A geosynthetics solution. *Geosynth. Int.* **2021**, *28*, 1–31. [CrossRef]
27. Lejcuś, K.; Burszta-Adamiak, E.; Dąbrowska, J.; Wróblewska, K.; Orzeszyna, H.; Śpitalniak, M.; Misiewicz, J. *Good Practice Catalogue—The Rules for Sustainable Management of Stormwater from Road Surface*; Municipality of Wroclaw: Wrocław, Poland, 2017.
28. Han, J.; Guo, J. Geosynthetics used to stabilize vegetated surfaces for environmental sustainability in civil engineering. *Front. Struct. Civ. Eng.* **2017**, *11*, 56–65. [CrossRef]
29. PIANC. PIANC REPORT No 113. In *The Application of Geosynthetics in Waterfront Areas*; PIANC: Brussels, Belgium, 2011.
30. Marczak, D.; Lejcuś, K.; Misiewicz, J. Characteristics of biodegradable textiles used in environmental engineering: A comprehensive review. *J. Clean. Prod.* **2020**, *268*, 122129.
31. Prambauer, M.; Wendeler, C.; Weitzenböck, J.; Burgstaller, C. Biodegradable geotextiles—An overview of existing and potential materials. *Geotext. Geomembr.* **2019**, *47*, 48–59. [CrossRef]
32. Shukla, S.K. Geosynthetics and Ground Engineering: Sustainability Considerations. *Int. J. Geosynth. Gr. Eng.* **2021**, *7*, 1–3. [CrossRef]
33. Cislaghi, A.; Sala, P.; Borgonovo, G.; Gandolfi, C.; Bischetti, G.B. Towards More Sustainable Materials for Geo-Environmental Engineering: The Case of Geogrids. *Sustainability* **2021**, *13*, 2585. [CrossRef]
34. Jeon, H.Y. Geotextile composites having multiple functions. In *Geotextiles: From Design to Applications*; Koerner, R.M., Ed.; Woodhead Publishing: Sawston, UK, 2016; pp. 413–425. ISBN 9780081002346.
35. Rimoldi, P.; Shamrock, J.; Kawalec, J.; Touze, N. Sustainable use of geosynthetics in dykes. *Sustainability* **2021**, *13*, 4445. [CrossRef]
36. Richardson, G.N.; Zhao, A. *Geosynthetic Fundamentals in Landfill Design*; Springer: Berlin/Heidelberg, Germany, 2010.
37. Fontana, F. Opportunities and limits of recycling in the production of geosynthetics in a circular economy perspective. In Proceedings of the XXXII Convegno Nazionale Geosintetici, Bologna, Italy, 20 October 2022; pp. 23–27.
38. Giglio, C.; Vocaturo, G.S.; Palmieri, R. A Scientometric Study of LCA-Based Industrialization and Commercialization of Geosynthetics in Infrastructures. *Appl. Sci.* **2023**, *13*, 2328. [CrossRef]
39. Christopher, B.R. Cost savings by using geosynthetics in the construction of civil works projects. In Proceedings of the 10th International Conference on Geosynthetics, ICG 2014, Berlin, Germany, 21–25 September 2014; pp. 1–19.
40. Koerner, R.M.; Koerner, J.R.; Koerner, G.R. *Relative Sustainability (i.e., Embodied Carbon) Calculations with Respect to Applications Using Traditional Materials versus Geosynthetics*; Geosynthetic Institute: Folsom, CA, USA, 2019.
41. Touze, N. The role of geosynthetics in sustainable development and the circular economy. In Proceedings of the XXXII Convegno Nazionale Geosintetici, Bologna, Italy, 20 October 2022; pp. 7–21.
42. Dixon, N.; Raja, J.; Fowmes, G.; Frost, M. Sustainability aspects of using geotextiles. In *Geotextiles: From Design to Applications*; Koerner, R.M., Ed.; Woodhead Publishing: Sawston, UK, 2016; pp. 577–596. ISBN 9780081002346.
43. Abu-Farsakh, M.; Hanandeh, S.; Mohammad, L.; Chen, Q. Performance of geosynthetic reinforced/stabilized paved roads built over soft soil under cyclic plate loads. *Geotext. Geomembr.* **2016**, *44*, 845–853. [CrossRef]
44. Popov, V. A new landfill system for cheaper landfill gas purification. *Renew. Energy* **2005**, *30*, 1021–1029. [CrossRef]
45. Fifer Bizjak, K.; Lenart, S. Life cycle assessment of a geosynthetic-reinforced soil bridge system—A case study. *Geotext. Geomembr.* **2018**, *46*, 543–558. [CrossRef]
46. Heerten, G. Reduction of climate-damaging gases in geotechnical engineering practice using geosynthetics. *Geotext. Geomembr.* **2012**, *30*, 43–49. [CrossRef]
47. *CEN ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. European Committee for Standardization. Rue de la Science 23: Bruxelles, Belgium, 2006; pp. 1–20.

48. *CEN ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. European Committee for Standardization. Rue de la Science 23: Bruxelles, Belgium, 2006; pp. 1–46.
49. Muralikrishna, I.V.; Manickam, V. *Environmental Management, Science and Engineering for Industry*; Butterworth-Heinemann: Oxford, UK, 2017.
50. Lewandowska, A. *LCA Środowiskowa Ocena Cyklu Życia Produktu*; Wydawnictwo Uniwersytetu Ekonomicznego w Poznaniu: Poznań, Poland, 2006.
51. Chen, R.; Kong, Y. A comprehensive review of greenhouse gas based on subject categories. *Sci. Total Environ.* **2023**, *866*, 161314. [CrossRef]
52. UN. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Doc FCCC/CP/1997/7/Add.1; New York, USA. 1988. Available online: https://unfccc.int/documents/2409 (accessed on 3 January 2023).
53. IPCC. Climate Change 2022: Mitigation of Climate Change. In *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPPC: Cambridge, UK; New York, NY, USA, 2022.
54. *CEN ISO 14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. Rue de la Science 23: Bruxelles, Belgium, 2018; pp. 1–46.
55. Labaran, Y.H.; Mathur, V.S.; Muhammad, S.U.; Musa, A.A. Carbon footprint management: A review of construction industry. *Clean. Eng. Technol.* **2022**, *9*, 100531. [CrossRef]
56. IPCC. Climate change 2001, Synthesis Report. In *Contribution of Working Groups I, II, and III to the Third Assessment Report*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2001.
57. Pandey, D.; Agrawal, M.; Pandey, J.S. Carbon footprint: Current methods of estimation. *Environ. Monit. Assess.* **2011**, *178*, 135–160. [CrossRef] [PubMed]
58. Kiersnowska, A.; Koda, E.; Fabianowski, W. Study of the accelerated aging on the mechanical parameters of polyethylene geogrids used on waste dumps. *Przem. Chem.* **2018**, *97*, 1349–1352.
59. Dixon, N.; Fowmes, G.; Frost, M. Global challenges, geosynthetic solutions and counting carbon. *Geosynth. Int.* **2017**, *24*, 451–464. [CrossRef]
60. UNFCCC. Doha Amendment to the Kyoto Protocol UNFCCC Doc. FCCC/KP/CMP/2012/13/Add.1, Decision 1/CMP.8; Doha. 2012. Available online: https://unfccc.int/process/the-kyoto-protocol/the-doha-amendment (accessed on 3 January 2023).
61. Raja, J.; Dixon, N.; Fowmes, G.; Frost, M.; Assinder, P. Obtaining reliable embodied carbon values for geosynthetics. *Geosynth. Int.* **2015**, *22*, 393–401. [CrossRef]
62. Lewis, M.; Huang, M.; Waldman, B.; Carlisle, S.; Simenon, K. *Environmental Product Declaration Requirements in Procurement Policies: An Analysis of EPD Definitions in Buy Clean and Other North American Procurement Policies*; Carbon Leadership Forum; University of Washington: Seattle, WA, USA, 2021.
63. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montañes, B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build.* **2017**, *135*, 286–301. [CrossRef]
64. Mandloi, P.; Hegde, A. Performance evaluation of reinforced earth walls with sustainable backfills subjected to railway loading. *Front. Built Environ.* **2022**, *8*, 1–13. [CrossRef]
65. Abedi, M.; Gomes Correia, A.; Fangueiro, R. Geotechnical and piezoresistivity properties of sustainable cementitious stabilized sand reinforced with recycled fibres. *Transp. Eng.* **2021**, *6*, 100096. [CrossRef]
66. Benahsina, A.; El Haloui, Y.; Taha, Y.; Elomari, M.; Bennouna, M.A. Natural sand substitution by copper mine waste rocks for concrete manufacturing. *J. Build. Eng.* **2022**, *47*, 103817. [CrossRef]
67. Petrella, A.; Notarnicola, M. Recycled Materials in Civil and Environmental Engineering. *Materials* **2022**, *15*, 3955. [CrossRef]
68. Gayarre, F.L.; López-Colina, C.; Carral, L.; Serrano, M.A.; Suárez, J.M.; Martínez, R. Recycled aggregates and their properties. *Recycl. Concr.* **2023**, 119–159. [CrossRef]
69. Hana, J.; Thakur, J.K. Sustainable roadway construction using recycled aggregates with geosynthetics. *Sustain. Cities Soc.* **2015**, *14*, 342–350. [CrossRef]
70. Vieira, C.S.; Pereira, P.M. Influence of the Geosynthetic Type and Compaction Conditions on the Pullout Behaviour of Geosynthetics Embedded in Recycled Construction and Demolition Materials. *Sustainability* **2022**, *14*, 1207. [CrossRef]
71. Hossain, M.U.; Poon, C.S.; Lo, I.M.C.; Cheng, J.C.P. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resour. Conserv. Recycl.* **2016**, *109*, 67–77. [CrossRef]
72. Ramsey, B.J. Geosynthetics and Sustainability: How is our Industry doing? *Geosynth. Mag.* **2022**, 14–23.
73. Li, J.H.; Hsieh, J.C.; Lou, C.W.; Hsieh, C.T.; Pan, Y.J.; Hsing, W.H.; Lin, J.H. Using nonwoven fabrics as culture mediums for extensive green roofs: Physical properties and cooling effect. *Fibers Polym.* **2016**, *17*, 1111–1114. [CrossRef]
74. Śpitalniak, M.; Lejcuś, K.; Dabrowska, J.; Garlikowski, D.; Bogacz, A. The influence of a water absorbing geocomposite on soil water retention and soil matric potential. *Water* **2019**, *11*, 1731. [CrossRef]
75. Wróblewska, K.; Chohura, P.; Dębicz, R.; Lejcuś, K.; Dąbrowska, J. Water absorbing geocomposite: A novel method improving water and fertilizer efficiency in Brunnera macrophylla cultivation. Part I. Plant growth. *Acta Sci. Pol. Hortorum Cultus* **2018**, *17*, 49–56. [CrossRef]

76. Lejcuś, K.; Dąbrowska, J.; Garlikowski, D.; Śpitalniak, M. The application of water-absorbing geocomposites to support plant growth on slopes. *Geosynth. Int.* **2015**, *22*, 452–456. [CrossRef]
77. Śpitalniak, M.; Bogacz, A.; Zięba, Z. The assessment of water retention efficiency of different soil amendments in comparison to water absorbing geocomposite. *Materials* **2021**, *14*, 6658. [CrossRef]

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