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CARBON EMISSION FACTORS OF GEOSYN- THETICS: COMPARABILITY ASSESSMENT AND DETERMINATION OF REPRESENTATIVE VALUES FOR THE FINNISH MARKET

Master's Thesis
Faculty of Engineering and Natural Sciences
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September 2026

ABSTRACT

Mojgan Abbasian: Carbon Emission Factors of Geosynthetics: Comparability Assessment and Determination of Representative Values for the Finnish Market

Master's Thesis

Tampere University

Master's Degree Program in Environmental Engineering

September 2026

Geosynthetics can reduce the carbon footprint of infrastructure construction by lowering the demand for natural aggregates. Quantifying that reduction requires reliable emission factors, and in Finland these are compiled in the national CO2data database. For geosynthetics the factors are drawn from Environmental Product Declarations, but differences in the rules, standards, databases, and assumptions behind individual declarations make the declarations difficult to compare, and it is unclear which values are representative of the products used on the Finnish market.

This thesis determined representative emission factors for the manufacturing of geosynthetics used in Finnish infrastructure, covering raw material supply, transport to the factory, and production up to the factory gate. A total of 72 Environmental Product Declarations, yielding 84 product entries, were screened against four comparability criteria and sorted into groups of products made from the same polymer and serving the same function. Within each group, the relationship between the declared emissions of a product and its mass per unit area was examined statistically. Transport to Finland was recalculated on a common basis, and 3 expert interviews with manufacturers and a program operator supported the documentary analysis.

The carbon footprint of a geosynthetic follows the polymer it is made from and the amount of material it contains. Expressed per kilogram of product, the factors ranged from 0.90 kg CO₂eq for recycled polyethylene grids to 4.44 for virgin polyester geotextiles, and within groups made from a single polymer the mass of the product explained 84% to 100% of the variation in emissions between products. Raw material supply accounted for 82% of the manufacturing footprint on average, recycled feedstock reduced emissions by 23% to 63%, and transport from the factory to Finland typically added less than 5%. Geomembranes and geosynthetic clay liners proved uniform enough for a single value to represent the group, although this rests on a small number of declarations, since not all products on the market are covered. Products whose footprint follows their mass, about three fifths of those examined, are better represented by a factor per kilogram applied to the mass of the specified product, which turns the strong mass relationship into a directly usable input. Multi-material composites are reported with the range of values found within the group, and products made from recycled material are kept separate from their virgin equivalents rather than averaged with them.

The method of screening and grouping developed here gives a representative emission factor for every product group examined, matched to the precision the underlying data supports, and it is transferable to other product groups and national databases. The main barrier to comparability is the heterogeneity of the declarations themselves, in their category rules, background databases, and transport assumptions, so the value of such factors will grow as EPD practice matures and reporting becomes more consistent. Further work should compare geosynthetic and conventional aggregate solutions quantitatively and extend the dataset where a product type rests on a single declaration.

Keywords: geosynthetics, Environmental Product Declaration, global warming potential, emission factor, life cycle assessment, CO2data

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PREFACE

This thesis was carried out as part of my Master's studies at Tampere University. I would like to express my sincere gratitude to my supervisors, Hannele Auvinen and Minna Leppänen, for their invaluable guidance, constructive feedback, and continuous support throughout this research. Their expertise, encouragement, and insightful advice were essential to the successful completion of this thesis.

I would also like to thank Viacon, Meltex Oy, and the Finnish Geotechnical Society (SGY) for providing the opportunity, resources, and support that made this work possible. My appreciation also extends to my friends for their valuable discussions, encouragement, and support throughout this project.

Finally, I would like to express my deepest gratitude to my family, especially my husband, father, and mother, for their unwavering love, patience, and encouragement throughout my studies. Their constant belief in me has been a source of strength and motivation.

Tampere, 6 September 2026

Mojgan Abbasian

CONTENTS

1 INTRODUCTION	1
2 GEOSYNTHETIC PRODUCTS	3
2.1 Types and Functions of Geosynthetic Products	3
2.2 Raw Material and Material Properties	6
2.3 Production Methods of Geosynthetics	9
2.3.1 Production Methods of Geotextiles	10
2.3.2 Production Methods of Geotextile-Related Products	14
2.3.3 Production Methods of Geosynthetic Barriers	16
2.3.4 Production Methods of Geocomposites.....	19
2.4 Environmental Role of Geosynthetics in Infrastructure Construction	20
3 LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL PRODUCT DECLARATIONS.....	22
3.1 Principles of LCA	22
3.2 Life Cycle Stages and System Boundaries	24
3.3 Environmental Indicators and the Focus on Global Warming Potential	26
3.4 Environmental Product Declarations (EPDs).....	27
3.5 Product Category Rules and Their Impact on EPDs	29
3.6 Development and Verification of EPDs	30
3.7 Factors Affecting the Comparability of EPDs	32
3.8 National Emission Databases and the Finnish CO2data Service	33
4 MATERIALS AND METHODS	35
4.1 Research Design and Data Collection	35
4.2 Comparability Assessment	37
4.3 Data Extraction and Unit Harmonization	39
4.4 Grouping of Products.....	40
4.5 Statistical and Regression Analysis	41
4.6 Calculation of Transport Emissions to the Finnish Market.....	42
4.7 Expert Interviews	44
5 RESULTS	46
5.1 Comparability Assessment	46
5.2 Preliminary Grouping Within Product Categories	48
5.3 Mass Per Unit Area Analysis and Mass-Based Emission Factors	49
5.4 Consolidated Representative Values	52
5.5 Products Reported Outside the Group Structure.....	55
5.6 Representative values for NorGeoSpec filter geotextile classes	58
5.7 Effect of Recycled Raw Materials	61

5.8	Stage-Level Analysis	63
5.9	Transport to the Finnish Market	65
5.10	Expert Interview	67
6	DISCUSSION.....	71
6.1	Reliability and Form of the Representative Values.....	71
6.2	Sources of Variation and the Need for Screening	73
6.3	Limitations and Sensitivity of the Results	74
7	CONCLUSIONS.....	77
	REFERENCES.....	80
	APPENDIX A: MASTER DATASET OF ENVIRONMENTAL PRODUCT DECLARATIONS.....	84
	APPENDIX B: SCREENING JUSTIFICATIONS	89
	APPENDIX C: TRANSPORT ROUTES AND MODULE A4 RESULTS	92
	APPENDIX D: INTERVIEW GUIDE AND PARTICIPANTS.....	96
	APPENDIX E: PRODUCT-LEVEL COMPARISON	99

LIST OF SYMBOLS AND ABBREVIATIONS

AR	Alkali-resistant (glass fiber)
A1–A3	Product stage life cycle modules (raw material supply, transport, manufacturing)
A4	Transport to the construction site life cycle module
CML	Centrum voor Milieukunde Leiden characterization method
CO ₂ eq	Carbon dioxide equivalent
CV	Coefficient of variation
DESNZ	Department for Energy Security and Net Zero, United Kingdom
EF	Environmental Footprint characterization factors
EPD	Environmental Product Declaration
EPDM	Ethylene propylene diene monomer
EPS	Expanded polystyrene
FTIA	Finnish Transport Infrastructure Agency
GCL	Geosynthetic clay liner
GHG	Greenhouse gas
GWP	Global warming potential
GWP-total	Total global warming potential (sum of fossil, biogenic, and land use change)
HDPE	High-density polyethylene
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MDPE	Medium-density polyethylene
PCR	Product Category Rules
PE	Polyethylene
PET	Polyethylene terephthalate
PEF	Product Environmental Footprint
PP	Polypropylene
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
SD	Standard deviation
Syke	Finnish Environment Institute (Suomen ympäristökeskus)
UV	Ultraviolet
UVEK	Swiss federal life cycle inventory dataset, based on <i>ecoinvent</i> 2.2
XPS	Extruded polystyrene
a	Regression slope, mass-based emission factor (kg CO ₂ eq/kg)
b	Regression intercept (kg CO ₂ eq/m ²)
d	Transport distance of a route leg (km)
m	Mass per unit area (kg/m ² or t/m ²)
R^2	Coefficient of determination
$\bar{x}$	Arithmetic mean

1 INTRODUCTION

Reducing greenhouse gas (GHG) emissions has become a central objective in the development of sustainable infrastructure systems. Excluding the operational energy use of buildings, construction activity accounts for approximately 13% of global carbon emissions (Reddy & Janga 2025). Part of this burden originates below ground level, since earthworks, ground improvement, and foundation construction consume soil and aggregate in large volumes even on routine projects (Marschalko et al. 2023). Material efficiency in geotechnical works is therefore a meaningful means of reducing the carbon footprint of infrastructure projects.

Geosynthetics are polymer-based products used in geotechnical and geoenvironmental engineering for functions such as reinforcement, separation, filtration, drainage, and containment (Palmeira 2025). Through their interaction with soil, they improve mechanical performance and stability, which makes it possible to replace natural aggregates with locally available or lower-quality materials and to reduce both material consumption and transport (Jayakrishnan & Lugli 2025).

The environmental performance of construction materials is commonly evaluated using Life Cycle Assessment (LCA), which assesses impacts from raw material extraction to end-of-life (Hasselsteen et al. 2025). Environmental Product Declarations (EPDs) present LCA results in a standardized format and are widely used in the construction sector, and the revised European Construction Products Regulation strengthens their role by introducing requirements for declaring the environmental performance of construction products (EU 2024). The most consistent information in an EPD concerns the product stage, modules A1 to A3, covering raw material extraction, upstream transport, and manufacturing. Differences in Product Category Rules (PCRs), system boundaries, data sources, and calculation methods nevertheless produce variation in reported values that limit their direct use for defining representative emission factors (Passer et al. 2015).

In Finland, the national emissions database CO2data provides standardized emission factors to support carbon footprint calculations for infrastructure projects. Its geosynthetic factors are largely derived from EPD data supplied by manufacturers, so the variation described above carries directly into the national reference data, and it is unclear how representative those factors are of the products used on the Finnish market. Existing

emission data therefore need to be analyzed systematically to identify values that reflect both the technical characteristics of the products and the conditions of the Finnish market.

The aim of this thesis is to determine representative product-stage carbon emission factors for geosynthetic products used in Finnish infrastructure, based on data reported in existing EPDs. The study is limited to modules A1 to A3, expressed as global warming potential per square meter of product, and covers geotextiles, geogrids, geocomposites, geomembranes, and geosynthetic clay liners. The documentary analysis is supplemented by expert interviews with manufacturers and an EPD program operator in order to collect their experiences of preparing and verifying declarations. The main research question is: **which emission factors for geosynthetic products are representative for the Finnish market?** The question is examined through four sub-questions:

- What emission data do EPDs report for geosynthetic products, and under what conditions can declarations issued by different manufacturers and programs be compared with one another?
- How does polymer type, product mass per unit area, manufacturing conditions, and transport to the market influence the reported product-stage emissions?
- What effect does the use of recycled raw materials have on the product-stage carbon footprint of geosynthetic products?
- In what form should representative emission factors be expressed so that they remain valid across the range of products within each category?

The thesis is structured as follows. Chapter 2 introduces geosynthetic products, their raw materials, production methods, and role in infrastructure construction. Chapter 3 presents life cycle assessment and Environmental Product Declarations, including the factors that affect their comparability. Chapter 4 describes the materials and methods used to collect, screen, and analyze the declarations. Chapter 5 presents the results. Chapter 6 discusses the reliability of the derived values, the sources of variation between declarations, and the limitations of the analysis. Chapter 7 presents the conclusions, the recommended emission factors, and directions for further research.

2 GEOSYNTHETIC PRODUCTS

This chapter provides an overview of geosynthetic products used in civil and geotechnical engineering. It introduces their main types and functions, their typical raw materials and production methods, and the role of geosynthetics in Finnish infrastructure construction. The chapter then describes the role of geosynthetics in Finnish infrastructure construction, including their use in replacing natural aggregates and the resulting effects on material consumption and transport.

2.1 Types and Functions of Geosynthetic Products

Geosynthetics can be categorized according to their structural configuration and functional role within geotechnical systems, since variations in geometry, composition, and manufacturing processes give rise to distinct mechanical and hydraulic behaviors. The principal categories comprise geotextiles, geogrids, geonets, geomembranes, geocells, geofoams, and geocomposites, each tailored to specific performance requirements (Rawal et al. 2010; Shukla 2016). Of these, geotextiles, geogrids, geocomposites, geomembranes, and GCLs are the categories examined in this thesis. Geonets, geocells, and geofoams are not considered, since no environmental product declarations meeting the inclusion criteria of Section 4.1 were found for them. These categories describe how products are constructed and sold rather than what they are made from or what they do, and as Chapter 5 shows, a grouping based on polymer and structural function proves more informative for carbon footprint purposes. Representative examples of common geosynthetic products are presented in Figure 2.1.

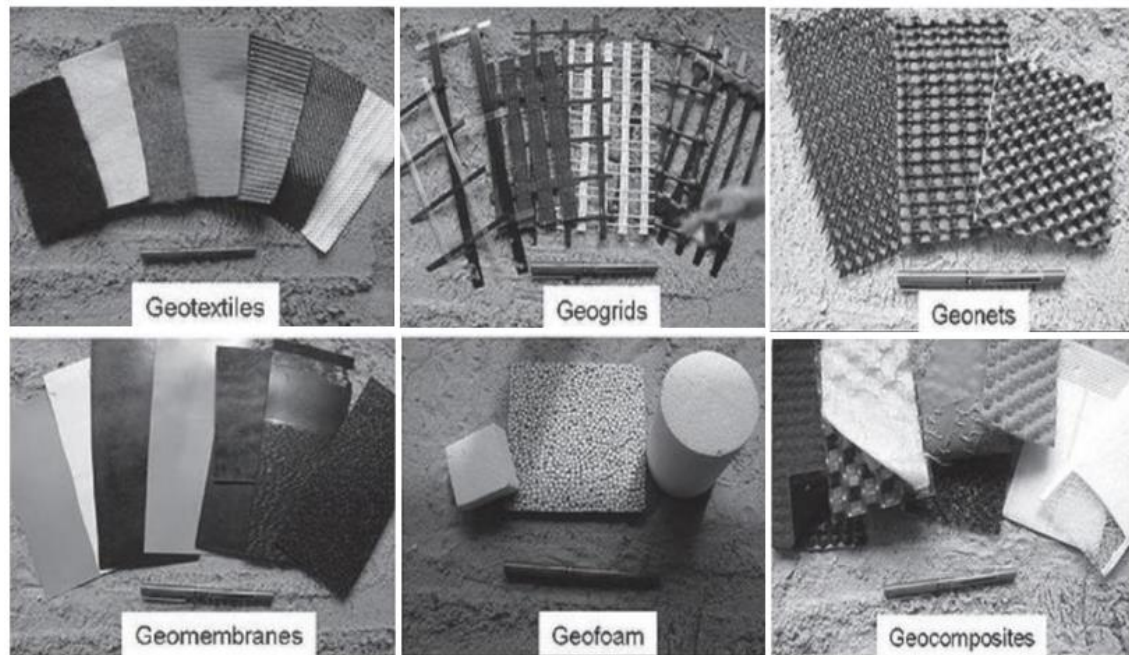


Figure 2.1 Examples of common geosynthetic products (Koerner 2012)

Geotextiles represent a fundamental category of geosynthetic materials and are typically manufactured as permeable polymeric sheets by weaving, knitting, or bonding fibers. These manufacturing methods result in different structural characteristics that influence both hydraulic and mechanical behavior (Rawal et al. 2010; Shukla 2016).

Geogrids, by contrast, are open network structures composed of interconnected ribs that provide tensile resistance and promote interlocking with surrounding soils. Their performance is governed by geometric properties including aperture size and orientation, and they are manufactured in uniaxial, biaxial, triaxial, and polyaxial forms, enabling their application under different loading conditions (Al-Barqawi et al. 2021). Large-scale direct shear testing has shown that interface shear strength increases with aperture size, the interlocking of soil particles within the apertures providing the largest contribution to interface resistance (Lakirouhani et al. 2024).

Geomembranes are low-permeability sheets that act as barriers to liquid and gas migration, and geonets are interconnected polymeric ribs that enable in-plane flow and form the drainage core of many geocomposites (Shukla 2016). Geocells provide confinement and improve the load-bearing capacity of soils, geofoms are lightweight blocks that reduce structural loads, and geocomposites combine two or more components to achieve multiple performance characteristics in a single product (Rawal et al. 2010; Shukla 2016).

Geosynthetics can also be grouped by permeability rather than structure. As shown in Figure 2.2, this divides them into permeable materials, comprising geotextiles and geotextile-related products such as geogrids, geocells, and geonets; impermeable materials,

comprising geosynthetic barriers subdivided by composition into polymeric, bituminous, and clay-based; and geocomposites, which may behave as either depending on their structure (Shukla 2016; IGS 2021). This scheme organizes the production methods described in Section 2.3.

The functional roles of geosynthetics are related to these groupings but not determined by them, since one product type may fulfill several functions depending on the application. Hydraulic functions include filtration, drainage, barrier action, erosion control, and containment, whereas mechanical functions include separation, reinforcement, stabilization, protection, and stress relief (Rawal et al. 2010; IGS 2021). Through these functions geosynthetics modify the stress–strain response of soil systems, enabling more efficient load transfer, improved stability, and reduced deformation under load (Wu et al. 2020).

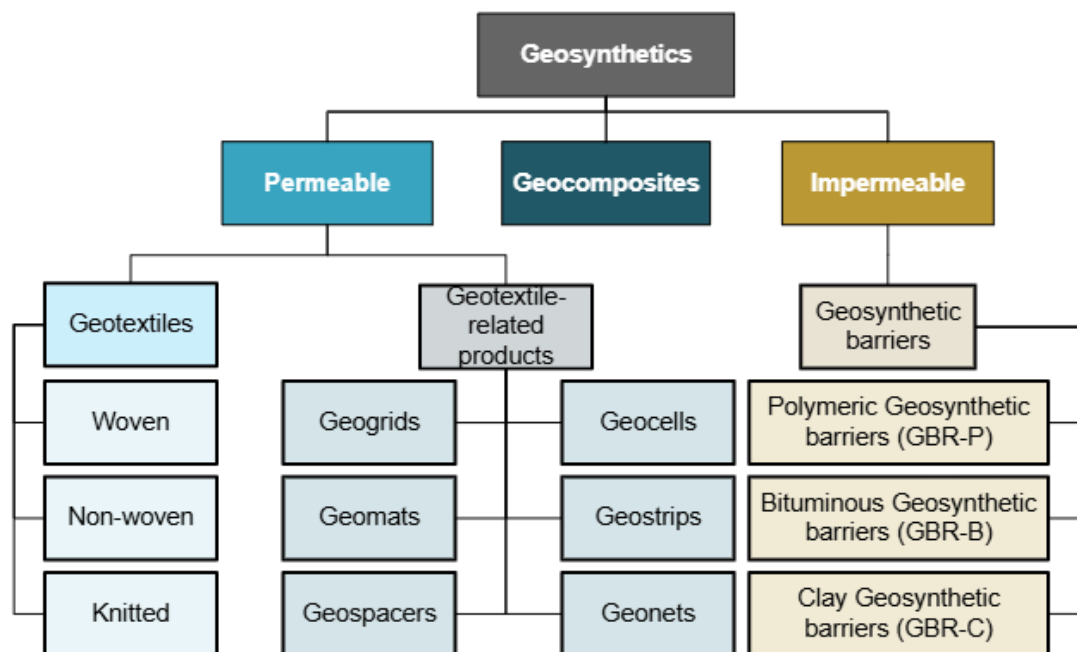


Figure 2.2 Permeability-based classification of geosynthetics (adapted from IGS 2021)

Reinforcement is among the primary mechanical contributions, where geotextiles and geogrids provide tensile resistance within the soil mass, mobilizing forces that limit lateral deformation and reduce settlement and thereby increasing the strength and stiffness of the composite system (Paiva et al. 2024). In unbound granular layers they also restrict particle movement, prevent intermixing of materials, and improve structural integrity in applications such as pavements and embankments (Loulizi et al. 2001). Among the hydraulic functions, nonwoven geotextiles and geonets regulate water flow while retaining soil particles, which maintains effective stress conditions and reduces the risk of pore pressure buildup (Markiewicz et al. 2022), while geomembranes and geosynthetic clay

liners restrict fluid migration in applications such as landfill lining and water retention structures (Shukla 2016; IGS 2021).

The diversity of product types has a direct consequence for environmental assessment. Because each category is built from different polymers and manufactured by different processes, products that fulfill the same engineering function may differ considerably in their production emissions. Establishing representative emission factors therefore requires grouping that reflects both material composition and function, an issue applied in the analysis presented in this thesis.

2.2 Raw Material and Material Properties

Geosynthetic materials are manufactured primarily from polymeric raw materials characterized by high molecular weight and versatile engineering properties. These polymers are typically derived from petrochemical sources such as crude oil and natural gas and are supplied in the form of pellets or granules for further processing (Shukla 2016). Polymer selection directly governs the mechanical performance, durability, and long-term behavior of geosynthetics (Koerner 2012).

Polymers used in geosynthetics can be broadly classified into thermoplastics and thermosetting polymers based on their thermal behavior. Thermoplastics can be reheated and reshaped repeatedly without chemical degradation, whereas thermosetting polymers undergo irreversible cross-linking during curing and cannot be remelted (Scheirs 2009). In geosynthetic applications, thermoplastics are more commonly used due to their ease of processing and recyclability (Shukla 2016). Common examples include polyethylene (PE), polypropylene (PP), and polyester, specifically polyethylene terephthalate (PET), while ethylene propylene diene monomer (EPDM) is an elastomer that becomes cross-linked during vulcanization and therefore behaves as a thermoset (Scheirs 2009).

At the molecular level, polymers consist of long chains formed by the polymerization of repeating monomer units, and the structure of these chains influences the physical and mechanical properties of the material (Shukla 2016). Semi-crystalline polymers tend to exhibit higher strength and stiffness, whereas amorphous polymers are more flexible but mechanically weaker (Scheirs 2009).

Among the various polymers used in geosynthetics, PP, PE, and PET are the most widely applied. PP is extensively used in geotextile production due to its low density and strong resistance to chemical degradation (Koerner 2012). PE, particularly as high-density polyethylene (HDPE), is commonly used in geomembranes because of its low per-

meability and high chemical resistance (Shukla 2016). PET is frequently used in reinforcement applications such as geogrids due to its high tensile strength and resistance to creep (Koerner 2012).

PE can be further classified into different types based on its density, which reflects differences in molecular structure and branching. These types include HDPE, medium-density polyethylene (MDPE), linear low-density polyethylene (LLDPE), and low-density polyethylene (LDPE). Higher density grades generally exhibit greater stiffness and strength, while lower density grades tend to be more flexible and ductile (Scheirs 2009). The selection of a specific PE grade therefore depends on the required balance between strength, flexibility, and durability (Koerner 2012). Table 2.1 summarizes the relationship between the main product types, the functions they perform, and the polymers most commonly used for each.

Table 2.1 Relationship between geosynthetic types, primary functions, and commonly used polymers (adapted from Shukla 2016)

Geosynthetic Type	Primary Functions	Typical Polymers
Geotextiles	Filtration, separation, drainage, protection	PP, PET, PE
Geogrids	Reinforcement	PET, PP, HDPE
Geonets	Drainage, erosion control	HDPE, MDPE
Geomembranes	Barrier and containment	HDPE, LLDPE, PVC, EPDM, bituminous
Geofoams	Lightweight fill, insulation	EPS, XPS
Geocomposites	Multiple functions, for example drainage mats and GCLs	Combination of polymers and other materials

The choice of polymer also affects how much energy is required to produce the material itself. Polymer resins are manufactured from crude oil and natural gas through refining and chemical conversion, and the energy consumed in these steps differs from one polymer to another. Tenhunen-Lunkka et al. (2022) report emission factors for European polymer production, covering resource extraction through to the finished resin. Among the polymers used in geosynthetics, these range from 1.91 kg CO₂eq/kg for PP and 1.93 to 1.98 kg CO₂eq/kg for PE, through 2.51 for PVC and 2.94 for PET, to 3.68 for polystyrene. Converting resin into a finished product adds a further 0.294 to 1.14 kg CO₂eq/kg depending on the polymer and the mix of conversion processes typical for it, and across plastics generally a virgin fossil-based product has caused approximately 2.9 kg CO₂eq/kg by the time it reaches the market. Producing material from recycled rather than

virgin feedstock reduces this burden substantially, with the recycling process itself reported at approximately 0.32 kg CO₂eq/kg (Tenhunen-Lunkka et al. 2022). These two steps, resin production and conversion, correspond to the raw material supply and manufacturing modules of the system boundary applied in this thesis. The differences between polymers at the material level are one reason why two geosynthetic products of similar weight and function may carry different emissions. The methods used to quantify such differences are described in Chapter 3.

A second material property determines how much of that polymer a product contains. Mass per unit area is a fundamental property of geotextiles and geotextile-related products and is determined according to EN ISO 9864 (CEN 2005). Within a single product family, manufacturers supply a range of mass per unit area so that mechanical or hydraulic performance can be matched to the requirements of a given application, with heavier grades providing greater tensile strength or puncture resistance and lighter grades specified where lower performance is sufficient. The relationship between mass and performance is not always proportional. In geogrids, for example, the proportion of open area governs the interlocking of soil particles within the apertures, and grids with a larger open area, and therefore less material per unit of area, have been found to produce higher interface shear strength coefficients than more closely spaced grids made from the same polymer (Lakirouhani et al. 2024). Emissions, however, do scale with mass, since mass per unit area determines how much polymer is consumed to produce one square meter of product and with it the material input attributable to that product.

Not all geosynthetics are made entirely from synthetic polymers. Natural fibers such as jute, coir, flax, and sisal are used in biodegradable geotextiles and geogrids, particularly for temporary applications such as erosion control (Rawal et al. 2010). Because these materials are susceptible to biological degradation, they are generally unsuitable for long-term engineering applications, although their biodegradability makes them well suited to short-term uses in landscaping and agriculture, where gradual degradation can be beneficial (Koerner 2012). Interest in biodegradable alternatives is nonetheless growing, since the non-degradable polymers that dominate the market can contribute to soil pollution and to the accumulation of microplastics, and recovering the material after use is time-consuming where it is required at all. Two material classes are available for this purpose, natural fibers and biodegradable polymers, of which natural-fiber products are already established on the market while the use of biodegradable thermoplastic biopolymers remains comparatively unexplored (Prambauer et al. 2019).

Other products incorporate non-polymeric materials to achieve specific functional properties. GCLs contain bentonite, a clay mineral whose capacity to swell on hydration gives

it very low hydraulic conductivity and allows it to reseal after damage (Egloffstein 2001). Geosynthetic cementitious composite mats combine a geotextile with a cementitious layer that hardens on hydration and are used mainly as an alternative to conventional concrete in erosion control (ASTM 2021).

Besides the base polymer resin, geosynthetic materials contain additives that enhance durability and long-term performance, including antioxidants, ultraviolet (UV) stabilizers, and carbon black to resist oxidative and UV degradation, and plasticizers, fillers, and processing aids to modify flexibility and manufacturability (Shukla 2016; Koerner 2012). Although present in small proportions, these additives are important for maintaining performance under long-term environmental exposure. Their share of the product-stage carbon footprint cannot be determined from published declarations, since an EPD reports module A1 as an aggregate rather than by individual input (Ramesh & Lee 2025).

A geosynthetic product is therefore defined by four things: the function it performs, the polymer from which it is made, any non-polymeric constituents it contains, and its mass per unit area. Additives are present throughout but in small proportions and are not separately declared, so they cannot be treated as a fourth variable in the analysis that follows. Polymer type and mass per unit area are both stated in manufacturers' technical data sheets, and both are examined in Chapter 5 as explanations for the differences in emissions between products. The following section describes how these materials are converted into finished products.

2.3 Production Methods of Geosynthetics

Geosynthetic products are manufactured using a range of general production methods, which vary depending on the type of material and its intended engineering function. The selection of an appropriate manufacturing method is closely linked to the required mechanical and hydraulic performance of the final product (IGS 2021; Shukla 2016). Figure 2.3 illustrates the common manufacturing techniques associated with each major group of geosynthetics.

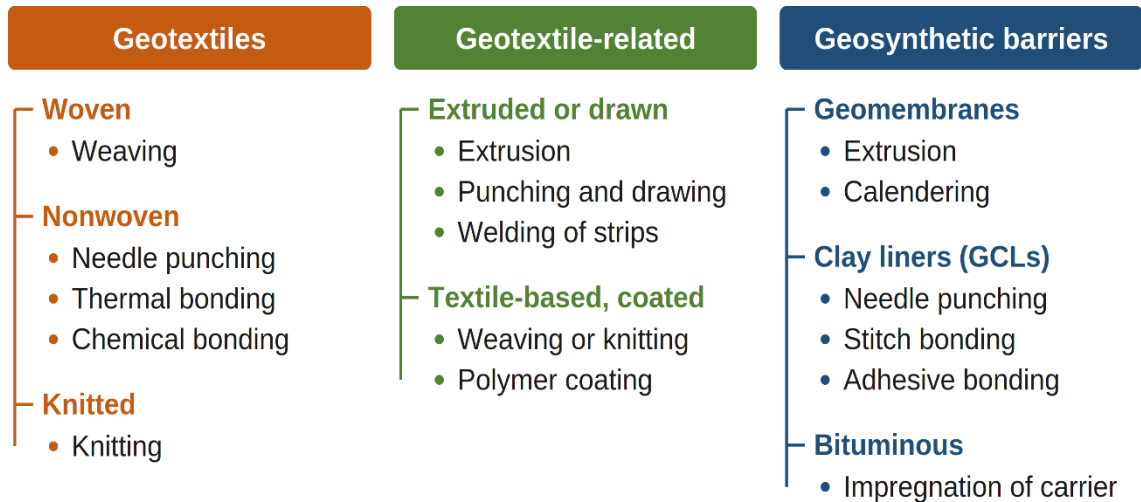


Figure 2.3 General production methods of geosynthetics, grouped by the permeability-based classification introduced in Section 2.1 (compiled from IGS 2021 and Shukla 2016; figure produced with generative AI)

Geotextiles are produced by processes adapted from conventional textile engineering, in which polymeric materials are transformed into fibers or yarns and then assembled into planar forms (Koerner 2012; Shukla 2016). Geotextile-related products are manufactured by extrusion, by punching and drawing, by welding of extruded strips, or as woven or knitted fabrics that are subsequently coated. Geosynthetic barriers are produced by extrusion or calendering in the case of geomembranes, by encapsulating a mineral layer between geotextiles in the case of geosynthetic clay liners, and by impregnating a carrier geotextile in the case of bituminous barriers (IGS 2021). The subsections below are organized according to the permeability-based classification introduced in Section 2.1.

2.3.1 Production Methods of Geotextiles

Geotextiles are permeable, polymer-based materials that form a primary class of geosynthetics, reflecting their versatility and extensive applicability in geotechnical and environmental engineering (Muniyappa et al. 2026; Shukla 2016). Based on their manufacturing technique and structural configuration, geotextiles are generally classified into three primary categories: woven, knitted, and nonwoven. Each exhibits distinct mechanical, hydraulic and durability characteristics, which directly influence their functional performance in engineering applications (IGS 2021; Rawal et al. 2010). Figure 2.4 presents a comparative illustration of these three geotextile types, highlighting differences in fiber arrangement, pore structure, and overall fabric morphology.

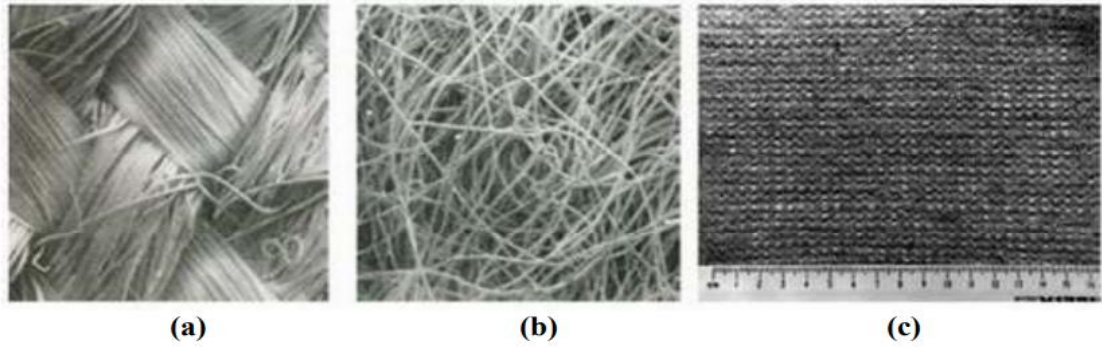


Figure 2.4 Comparative microstructure of geotextiles: (a) woven geotextile, (b) nonwoven geotextile, and (c) knitted geotextile (Zumrawi & Abdalgadir 2019)

The production of geotextiles fundamentally follows a two-stage process. In the first stage, polymeric raw materials are transformed into linear elements such as filaments, staple fibers, or slit films through melting, extrusion, and drawing. This stage is critical, as it determines the intrinsic material properties of the fibers, including tensile strength, stiffness, and durability, through molecular orientation (Giroud & Carroll 1983; Shukla 2016). In the second stage, these linear elements are assembled into planar structures using various textile or non-textile fabrication techniques, depending on the desired product characteristics (Rawal et al. 2010).

Woven geotextiles are produced by interlacing two orthogonal sets of yarns, known as warp (longitudinal) and weft (transverse), using conventional weaving techniques adapted from the textile industry. The yarns may consist of monofilament, multifilament, or slit-film fibers, depending on the intended application (Shukla 2016). Common weaving patterns including plain and twill weaves influence the pore size, fabric density, and mechanical behavior. As a result, woven geotextiles generally exhibit high tensile strength, low elongation, and controlled pore size, making them suitable for reinforcement, stabilization, and separation applications (Muniyappa et al. 2026; Shukla 2016). Figure 2.5 shows the sequence from polymer extrusion to woven fabric formation, distinguishing the filament and slit-film routes, which differ in the mechanical anisotropy and filtration behavior of the finished product.

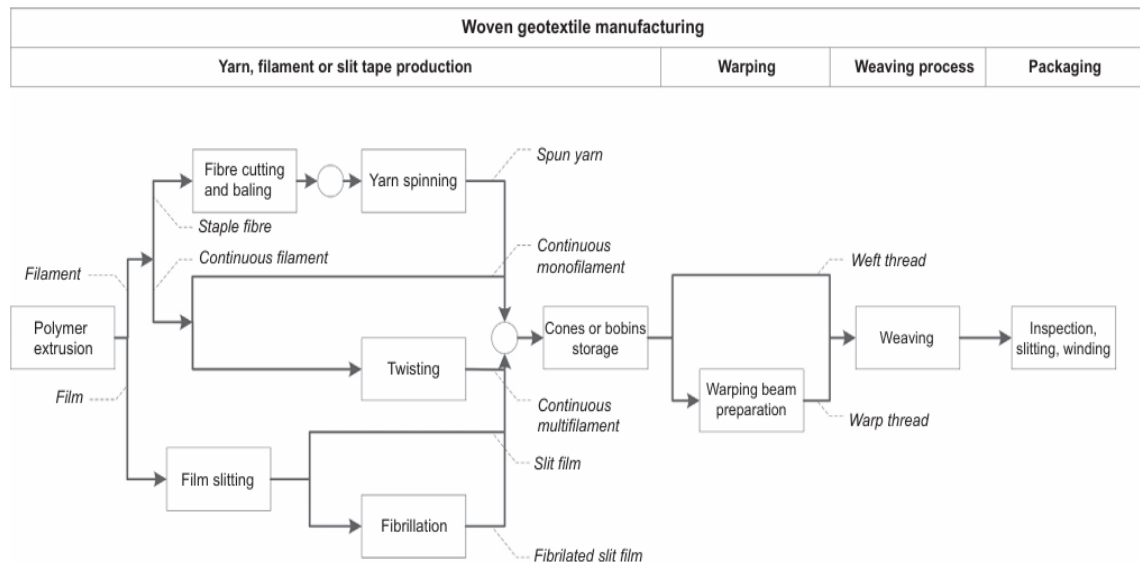


Figure 2.5 Woven geotextile manufacturing process flowchart (adapted from Bérubé & Saunier 2016)

Knitted geotextiles are formed by interloping yarns or filaments, producing flexible and extensible structures. Compared with woven products they exhibit higher extensibility and lower dimensional stability, which limits their use to specialized applications such as filtration and reinforcement under low loads (IGS 2021; Shukla 2016).

Nonwoven geotextiles are a major category, used principally for filtration, drainage, separation, and protection (Giroud 2005; Shukla 2016). Unlike woven and knitted geotextiles, nonwoven products are manufactured without yarn formation. Instead, fibers are directly assembled into a random, three-dimensional network, resulting in a structure characterized by high porosity and permeability (Bérubé & Saunier 2016). Production follows one of two routes, based on staple fibers or on continuous filaments, and the general sequence of fiber preparation, web formation, bonding, and finishing is illustrated in Figure 2.6.

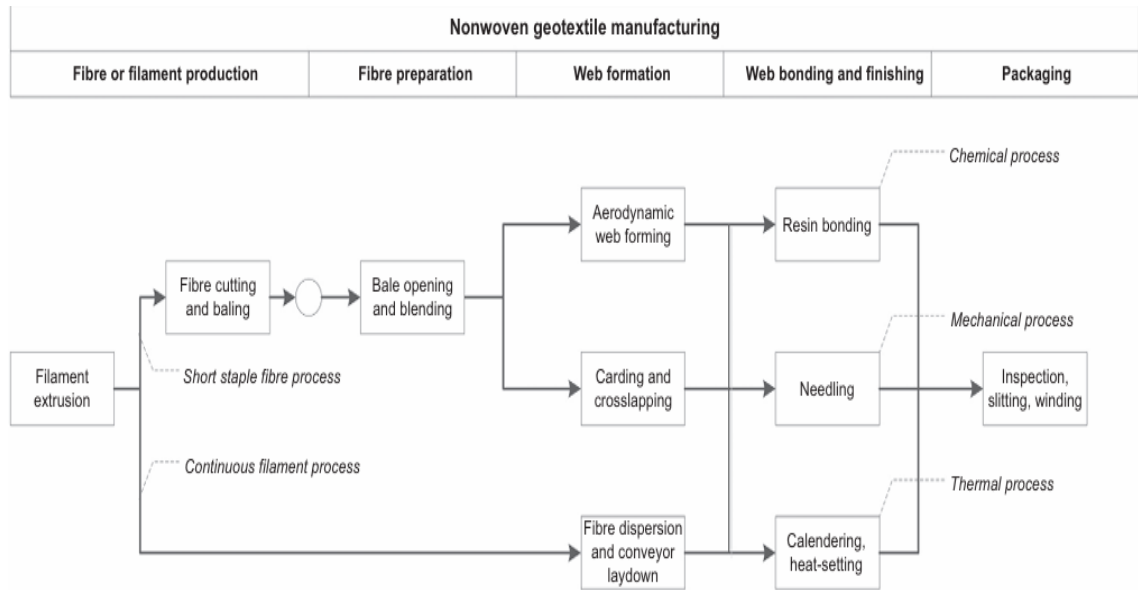


Figure 2.6 Nonwoven geotextile manufacturing process flowchart (adapted from Bérubé & Saunier 2016)

In staple fiber nonwoven production, fibers are first opened and blended to achieve a homogeneous mixture, followed by web formation through carding or air-laying techniques. The resulting fiber web is then consolidated using mechanical, thermal, or chemical bonding methods. Mechanical bonding through needle punching is the most commonly used technique, in which barbed needles repeatedly penetrate the fiber web, entangling fibers to form a cohesive structure with high permeability and flexibility (Rawal et al. 2010; Shukla 2016). This process is illustrated in Figure 2.7.

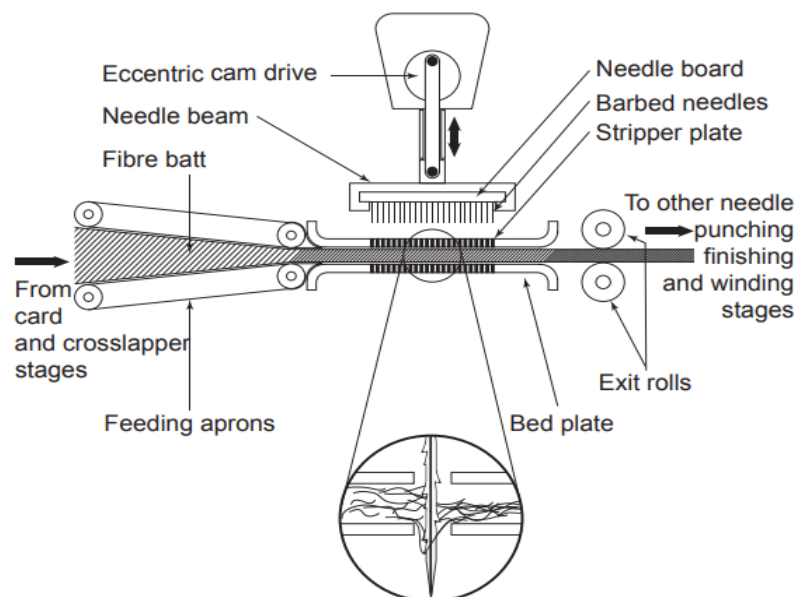


Figure 2.7 Schematic representation of the needle punching process used in nonwoven geotextile production (adapted from Bérubé & Saunier 2016)

Thermal bonding involves the application of heat, typically through heated rollers, to partially melt fiber surfaces and create bonding points, resulting in smoother and stronger

fabrics with reduced permeability, while chemical bonding with resins is used occasionally, mainly for natural-fiber products (Shukla 2016; Giroud 2005).

In continuous filament nonwoven production, polymer pellets are melted and extruded through spinnerets to form continuous filaments, which are subsequently cooled, drawn, and deposited onto a moving conveyor to form a web. The web is then bonded using thermal or mechanical methods to produce a cohesive fabric. This integrated process enables high production efficiency and is particularly suited to the manufacture of light-weight to medium-weight geotextiles (Rawal et al. 2010; Shukla 2016).

Following bonding, all nonwoven geotextiles undergo finishing processes such as heat setting, surface treatment, trimming, and roll winding (IGS 2021). These processes enhance dimensional stability and allow modification of surface and mechanical properties, including friction, permeability, and durability. The selected bonding and finishing techniques ultimately govern the final performance characteristics of the geotextile. For instance, needle-punched products typically exhibit higher elongation and permeability, whereas thermally bonded geotextiles provide higher strength and smoother surfaces (Shukla 2016).

2.3.2 Production Methods of Geotextile-Related Products

The manufacturing of geotextile-related products is predominantly based on extrusion-driven processes, often combined with stretching, bonding, or assembly, although yarn-based routes adapted from textile manufacturing are also widely used. These processes are closely linked to the structural configuration of the product and directly influence mechanical performance, hydraulic behavior, and long-term durability in geotechnical applications (IGS 2021; Shukla 2016).

Among geotextile-related products, geogrids represent a principal category for soil reinforcement applications. They consist of interconnected tensile elements forming apertures that enable mechanical interlocking with soil or aggregate, thereby improving load transfer and stability (Al-Barqawi et al. 2021). In the extrusion-based process, polymer sheets are perforated and subsequently stretched in one or more directions. This stretching forms the grid apertures and induces molecular orientation, which increases tensile strength and stiffness (Shukla 2016). As illustrated in Figure 2.8, the number and direction of the stretching stages determine whether the resulting geogrid exhibits uniaxial, biaxial, or triaxial mechanical behavior.

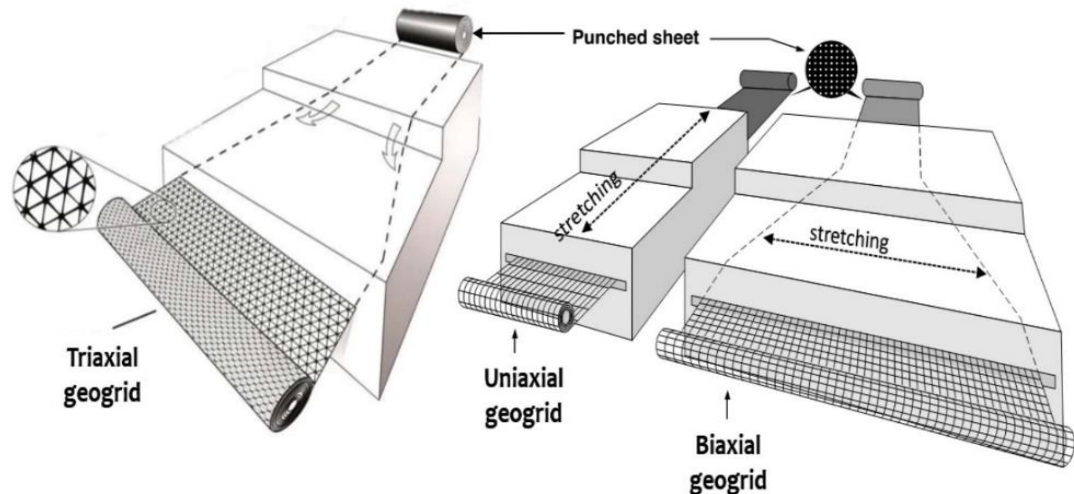


Figure 2.8 Extrusion process of geogrids (IGS 2021)

Geogrids are also fabricated from high-strength polymer yarns through weaving or knitting. These structures are often coated with protective materials such as PVC or bitumen to improve durability and junction integrity (Al-Barqawi et al. 2021). Coating introduces another material into the product, which is relevant to the emission analysis in Chapter 5, since products combining more than one material do not normalize per unit mass as consistently as single-polymer products. Bonded geogrids, illustrated in Figure 2.9, are produced by arranging extruded polymer strips in orthogonal configurations and joining them at intersection points using thermal or mechanical bonding techniques.

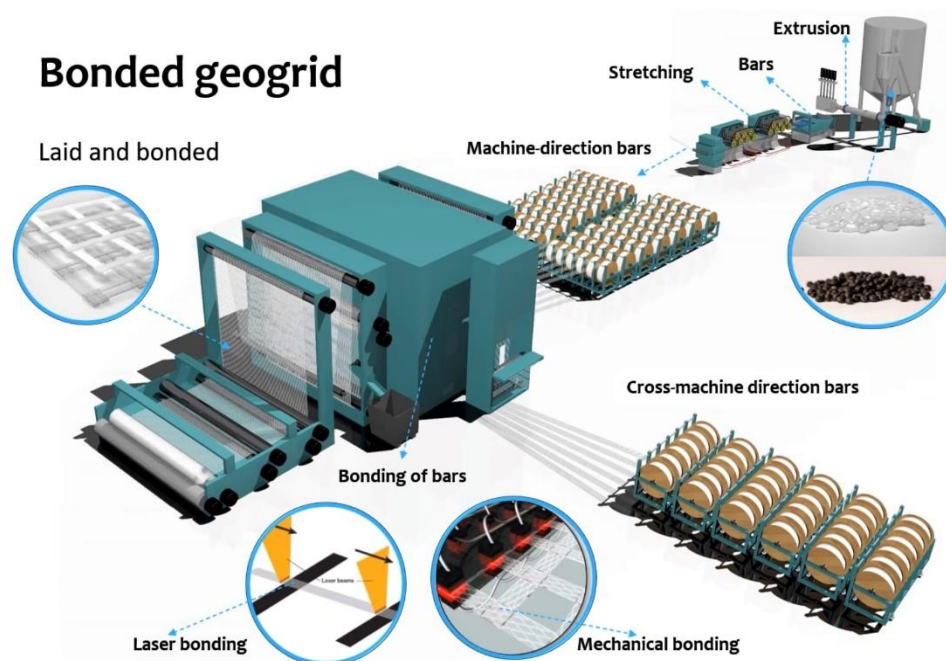


Figure 2.9 Bonded geogrid manufacturing process (IGS 2021)

Geonets are characterized by a network of intersecting ribs that create continuous flow channels. Their production is typically carried out through an extrusion process, in which molten polymer is passed through a specialized die to form a net-like tubular structure. This structure is then stretched, cooled, and slit to produce a flat sheet with controlled aperture geometry and thickness (Shukla 2016). The resulting configuration allows efficient in-plane fluid flow, and in many cases geonets are combined with geotextiles to form drainage composites (IGS 2021). The process is illustrated in Figure 2.10. A similar combination is used for reinforcement, where a nonwoven geotextile is welded between the bars of a laid geogrid so that the grid provides tensile reinforcement while the nonwoven performs separation and filtration within a single installed layer (Naue 2020).

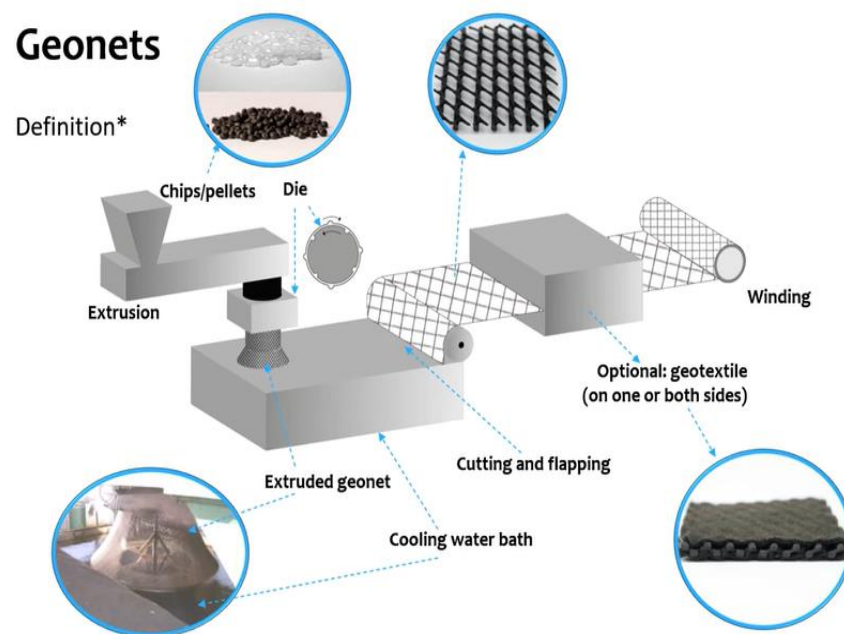


Figure 2.10 Geonet manufacturing process (IGS 2021)

Other geotextile-related products are produced by variations of the same extrusion process. Geomats are open three-dimensional structures used for erosion control, geocells are expandable honeycomb structures that confine infill material, geostrips are narrow tensile reinforcement elements, and geospacers are drainage cores that maintain a void under load (Shukla 2016; IGS 2021).

2.3.3 Production Methods of Geosynthetic Barriers

Geosynthetic barriers represent the impermeable class of geosynthetics and are specifically designed to restrict or prevent fluid or gas migration within engineering systems. In contrast to permeable materials such as geotextiles and geotextile-related products, their

primary function is to provide hydraulic containment in applications including landfill liners, hydraulic structures, and environmental protection systems (Shukla 2016; IGS 2021). Depending on the material responsible for the barrier function, geosynthetic barriers are generally categorized into polymeric, bituminous, and clay-based barriers (IGS 2021).

Polymeric geosynthetic barriers, commonly referred to as geomembranes, are factory-manufactured sheets in which the barrier function is primarily achieved through the intrinsic properties of the polymer. These materials are typically produced from thermoplastics such as HDPE, LLDPE, and PVC, and from elastomers such as EPDM, selected for their low permeability, chemical resistance, long-term durability, and weldability, which allows adjacent sheets to be joined into a continuous barrier on site (Scheirs 2009; Shukla 2016). The production of geomembranes is predominantly based on extrusion processes, in which polymer resins are blended with additives such as antioxidants, stabilizers, and carbon black to enhance resistance to environmental degradation (Müller 2007).

The resulting mixture is melted and forced through a die to form a continuous sheet. In flat-die extrusion, the molten polymer is shaped directly into a planar sheet and subsequently cooled using rollers to achieve uniform thickness. In contrast, blown film extrusion produces a tubular film that is expanded using internal air pressure and stretched in both longitudinal and transverse directions before being flattened into a sheet. As illustrated in Figures 2.11 and 2.12, these two processes differ fundamentally in terms of molecular orientation and thickness control, which in turn influence the mechanical properties and dimensional stability of the final product.

Geomembrane

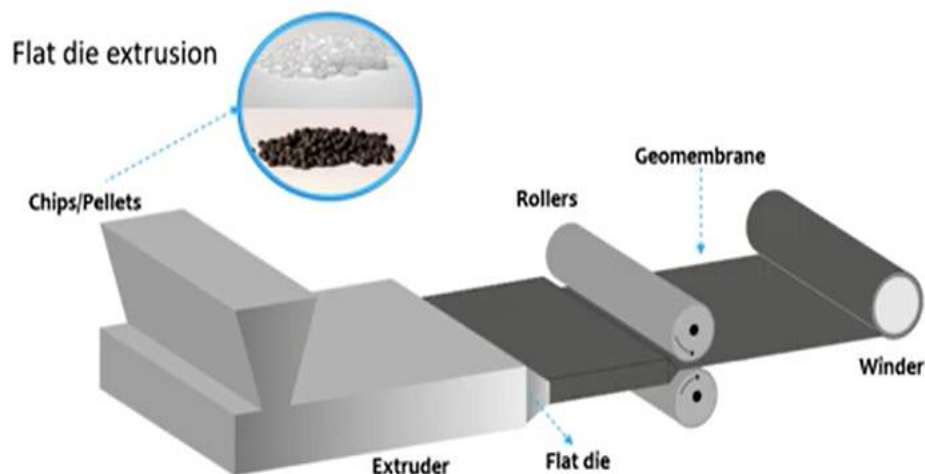


Figure 2.11 Flat-die extrusion process for geomembrane production (adapted from IGS 2021)

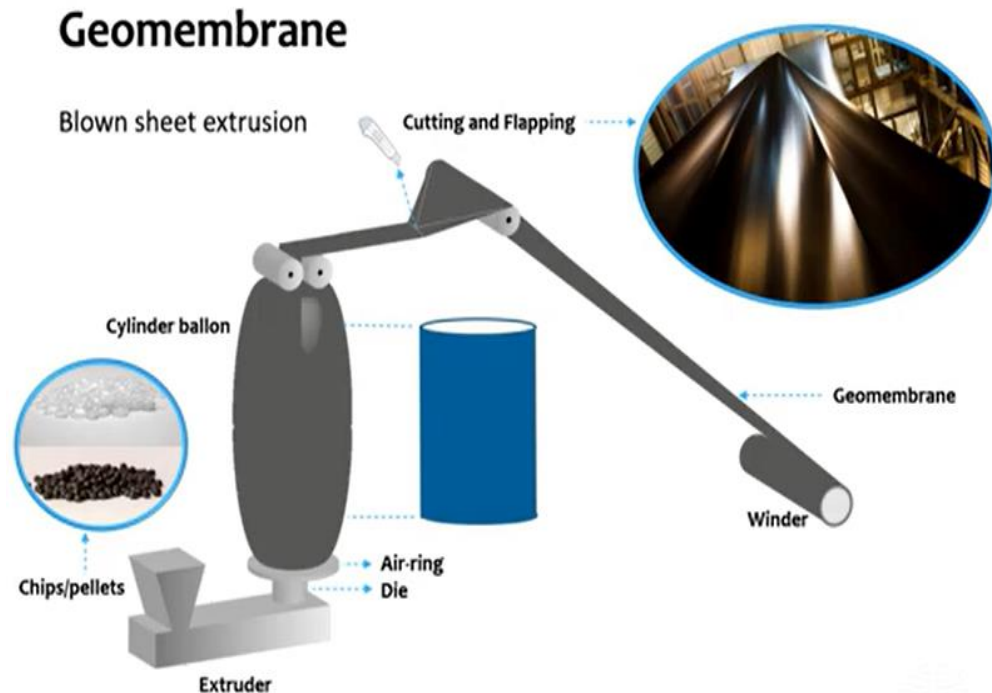


Figure 2.12 Blown film extrusion process for geomembrane production (adapted from IGS 2021)

In addition to extrusion, calendering is widely used, particularly for PVC, where a heated polymer compound is passed through rollers to produce sheets with uniform thickness (Shukla 2016). Elastomeric membranes such as EPDM are also produced by calendering, after which the sheet is vulcanized to form a cross-linked structure, a chemistry that differs fundamentally from that of the extruded thermoplastic membranes (Scheirs 2009). Alternative methods, such as spread coating, involve applying polymeric or bituminous compounds onto a supporting substrate to produce reinforced barrier systems. Surface properties may also be modified during production; for example, textured geomembranes are manufactured to enhance interface friction and improve stability in applications involving slopes or layered systems (Scheirs 2009).

Bituminous geosynthetic barriers represent another class of impermeable systems, in which the barrier function is provided by bitumen in combination with reinforcing geotextiles. These materials are typically produced by coating or impregnating geotextiles with bituminous compounds, resulting in flexible sheets suitable for applications such as canal lining, waterproofing, and containment systems (Shukla 2016). The interaction between bitumen and the textile determines both mechanical performance and impermeability.

Clay-based geosynthetic barriers, commonly referred to as GCLs, rely on the swelling behavior of bentonite clay to achieve very low permeability. These systems are manufactured by placing a thin, uniform layer of bentonite, typically sodium bentonite, between geotextiles, and less commonly by bonding it to a geomembrane (Shukla 2016). The production process generally involves unrolling a carrier geotextile, distributing bentonite evenly across its surface, and placing a second geotextile layer on top. The composite structure is then bonded using mechanical methods such as needle punching or stitch bonding, or through adhesive techniques, to ensure internal stability and confinement of the clay layer. As illustrated in Figure 2.13, this bonding prevents displacement of the clay layer during handling and installation (Shukla 2016; IGS 2021).

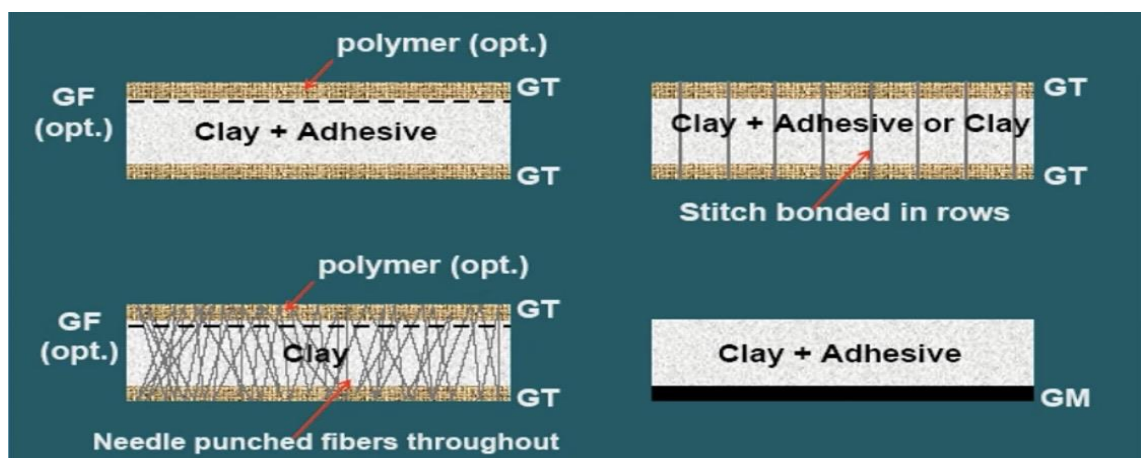


Figure 2.13 Manufacturing process of GCLs (adapted from IGS 2021)

Upon hydration, the bentonite undergoes volumetric expansion and forms a dense, low-permeability barrier that restricts fluid migration. This swelling also allows the liner to seal small punctures and overlaps arising during installation, a self-sealing capacity that distinguishes clay-based barriers from polymeric ones (Egloffstein 2001; Shukla 2016).

2.3.4 Production Methods of Geocomposites

Geocomposites are manufactured by combining two or more geosynthetic components to achieve multiple functions within a single product. Production therefore consists of an assembly step applied to components made by the processes described above, rather than a distinct forming process of its own. Drainage composites, for example, consist of an extruded geonet or geospacer core bonded to one or two geotextile layers, and paving interlayers combine a reinforcing grid with a nonwoven carrier (Shukla 2016). The components are joined by thermal lamination, needle punching, stitching, or adhesive bonding, and the joining method governs the shear and peel strength of the interface between layers (IGS 2021). Combining components in this way allows hydraulic and mechanical

functions to be integrated in a single product, making geocomposites adaptable to complex engineering requirements, but it also means that a geocomposite contains more than one polymer, which is relevant to the analysis in Chapter 5.

The choice of joining method is not merely a matter of assembly. Thermal lamination introduces an additional heating stage, needle punching and stitching are mechanical and require no added material, and adhesive bonding introduces a further material into the product (IGS 2021). A geocomposite therefore carries the production burden of each of its components together with that of the process used to unite them, so its emissions cannot be attributed to a single polymer or a single forming process. This is examined in Chapter 5, where the relationship between product mass and emissions is found to hold closely for single-material products but to break down for composites.

2.4 Environmental Role of Geosynthetics in Infrastructure Construction

Geosynthetics represent an important class of products with the potential to reduce environmental impacts in infrastructure construction. Their use can decrease the demand for natural aggregates, limit excavation and transportation activities, and enable more efficient construction processes, thereby lowering overall emissions (Dixon et al. 2017). These benefits are particularly evident in applications such as road construction, retaining structures, and landfill systems, where geosynthetics often demonstrate a lower carbon footprint than conventional alternatives (Ehrenberg 2024; Damians et al. 2016). Such advantages are not universal, however, and depend on project-specific conditions, including material availability and transport distances (Raja et al. 2015).

The size of the saving depends on the emission factor assigned to the geosynthetic itself. In published comparisons the geosynthetic contributes only a small share of the total, so the outcome is governed by the quantity of aggregate displaced and the distance it would otherwise be hauled. In a working platform example, replacing half the aggregate thickness with a reinforcing geotextile reduced embodied carbon by 43%, and in a landfill capping example the soil solution emitted 47% more than the geosynthetic solution at a 20 km haul distance (Dixon et al. 2016). A comparative assessment of an inland waterway found greenhouse gas emissions more than 25% lower with a nonwoven filter than with two 20 cm gravel and sand layers, a saving that persisted even at a 20 km haul distance for the mineral material (Ehrenberg 2024). Reliable emission factors for geosynthetics are what allow savings of this kind to be demonstrated rather than assumed.

Beyond emission reduction, geosynthetics also contribute to broader environmental objectives, including the protection of soil and water resources, mitigation of natural hazards, and support for circular economy practices (IGS 2021; Palmeira 2025). Realizing these benefits in practice requires that the environmental performance of individual products can be quantified and compared reliably, since uncertainties in emission data and differences in methodological choices influence the results obtained (Dixon et al. 2016). The methods developed for this purpose, and the conditions under which their results can be compared between products, are the subject of the following chapter.

3 LIFE CYCLE ASSESSMENT AND ENVIRONMENTAL PRODUCT DECLARATIONS

Chapter 2 established that whether a geosynthetic solution reduces emissions depends on the emission factor assigned to the product itself. This chapter introduces the methods by which such factors are produced. The carbon footprint has become the standard indicator for this purpose, quantifying the emissions associated with material production, transportation, construction, and end-of-life stages (Dixon et al. 2016; Dixon et al. 2017).

The chapter presents the principles of LCA, the modular structure of life cycle stages and system boundaries and identifies global warming potential (GWP) as the indicator used in this work. It describes EPDs and the PCRs that govern them, the process by which declarations are developed and verified, and the factors that limit their comparability. Comparability is the central concern here, since the values analyzed in this thesis are drawn from declarations issued under different rules, background databases, and declared units. Finally, the chapter introduces national emission databases and the Finnish CO2data database, for which the representative values are intended.

3.1 Principles of LCA

LCA is a standardized methodology for evaluating the environmental impacts of a product, process, or system across its entire life cycle, from raw material extraction to end-of-life management. The methodology is formally defined in ISO 14040:2006 (*Environmental management – Life cycle assessment – Principles and framework*) and ISO 14044:2006 (*Environmental management – Life cycle assessment – Requirements and guidelines*), which establish its principles, framework, and procedural requirements. By adopting a life cycle perspective, LCA enables the identification of environmental trade-offs between different stages and helps avoid the unintended shifting of environmental burdens from one phase to another (ISO 14040:2006). According to these standards, LCA is structured into four interconnected and iterative phases, as illustrated in Figure 3.1.

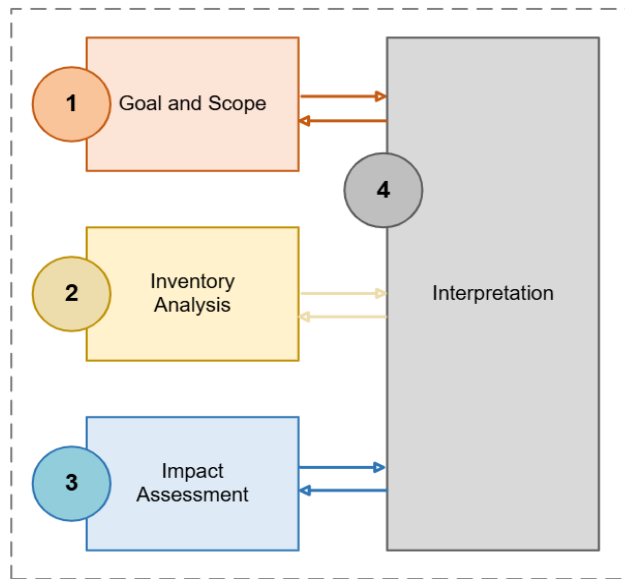


Figure 3.1 Life cycle assessment framework (adapted from ISO 14040:2006 and ISO 14044:2006)

The first phase, goal and scope definition, establishes the purpose of the study, the system boundaries, the functional unit, and the level of detail required. In infrastructure-related studies, the functional unit ensures comparability between materials or systems providing the same technical function, such as a defined area of geosynthetic providing a specific reinforcement function (ISO 14040:2006).

Once the scope is fixed, the life cycle inventory (LCI) phase collects and quantifies all relevant input and output flows within the defined system boundary, including raw material extraction, energy consumption, transportation, and emissions to air, water, and soil. The quality of this inventory data is critical, as it directly influences the reliability of the final results (ISO 14040:2006).

These inventory flows are then translated into potential environmental impacts in the life cycle impact assessment (LCIA) phase, using characterization models that group emissions into categories such as GWP, acidification, eutrophication, and resource depletion (ISO 14044:2006; Hauschild et al. 2018). For construction materials and geosynthetics, GWP, expressed as kg CO₂eq, is the most relevant of these categories because of its direct relation to climate change mitigation objectives. Its characterization factors are derived from the assessment reports of the Intergovernmental Panel on Climate Change (IPCC 2014), and the set in force when a declaration is prepared determines the values reported, a point returned to in Section 4.2.

The final phase, interpretation, draws conclusions from the impact results in relation to the defined goal and scope, identifying the most significant environmental aspects and testing their robustness through sensitivity analysis and data quality evaluation. Because

new insights at this stage may require earlier assumptions or system boundaries to be revised, the four phases are applied iteratively rather than in a single pass (ISO 14044:2006).

In the case of geosynthetics, the reliability of this process is limited by the availability of product-specific data. Life cycle assessment relies on background databases that supply environmental data for materials, energy production, transport, waste treatment, and industrial processes. *Ecoinvent* is the most widely used of these, providing unit process inventory data organized so that different modeling choices can be applied consistently across the whole database (Wernet et al. 2016). The Inventory of Carbon and Energy (ICE), developed at the University of Bath, is narrower in scope and lists embodied energy and carbon coefficients for around 200 construction materials, drawn from the published literature rather than from primary measurement (Hammond & Jones 2008). Geosynthetic products have no dedicated entries in either, so generic polymer values are applied in their place. Polypropylene, for example, is represented in the ICE and *ecoinvent* databases by three alternative entries, 1.98 kg CO₂eq/kg for granules, 3.43 for orientated film, and 4.49 for injection molding, none of which corresponds to a finished geosynthetic product (Dixon et al. 2016). Variations in polymer type and manufacturing process compound this, introducing uncertainty and reducing the comparability of LCA results (Reddy & Janga 2025). Environmental product declarations are intended to close this gap by reporting results for specific products rather than for generic materials.

3.2 Life Cycle Stages and System Boundaries

The definition of system boundaries and life cycle stages is a fundamental step in any LCA, since it determines which processes enter the analysis and therefore governs the scope, consistency, and comparability of the results. System boundaries are established during the goal and scope definition phase in accordance with ISO 14040:2006 and ISO 14044:2006, and their selection is consequential: boundaries drawn too narrowly may omit significant environmental impacts, while boundaries drawn too broadly increase complexity and data uncertainty.

Different boundary approaches are used depending on the objective of the assessment. A **cradle-to-gate** boundary covers processes from raw material extraction up to the factory gate; **cradle to site** extends this to include transport to the construction site; **cradle to end of construction** adds the installation processes; and **cradle to grave** covers the entire life cycle through to end-of-life disposal and potential recycling (Dixon et al. 2016). This flexibility allows an assessment to be matched to its purpose, but it also introduces

variability, since two studies of the same product drawn to different boundaries are not directly comparable (Ng 2022).

In the construction sector, these boundaries are formalized through a modular framework defined in EN 15804:2012+A2:2019 (*Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*) and ISO 21930:2017 (*Sustainability in buildings and civil engineering works – Core rules for environmental product declaration of construction products and services*), which provides the structure used in EPDs. The life cycle is divided into the product stage (A1–A3), covering raw material supply, transport to the manufacturer, and manufacturing; the construction stage (A4–A5), covering transport to site and installation; the use stage (B1–B7), covering use, maintenance, repair, replacement, refurbishment, and operational energy and water use; and the end-of-life stage (C1–C4), covering deconstruction, transport, waste processing, and disposal (ISO 21930:2017). An additional module D accounts for benefits and loads beyond the system boundary, such as reuse, recycling, and energy recovery. These stages and the common boundary approaches are illustrated in Figure 3.2.

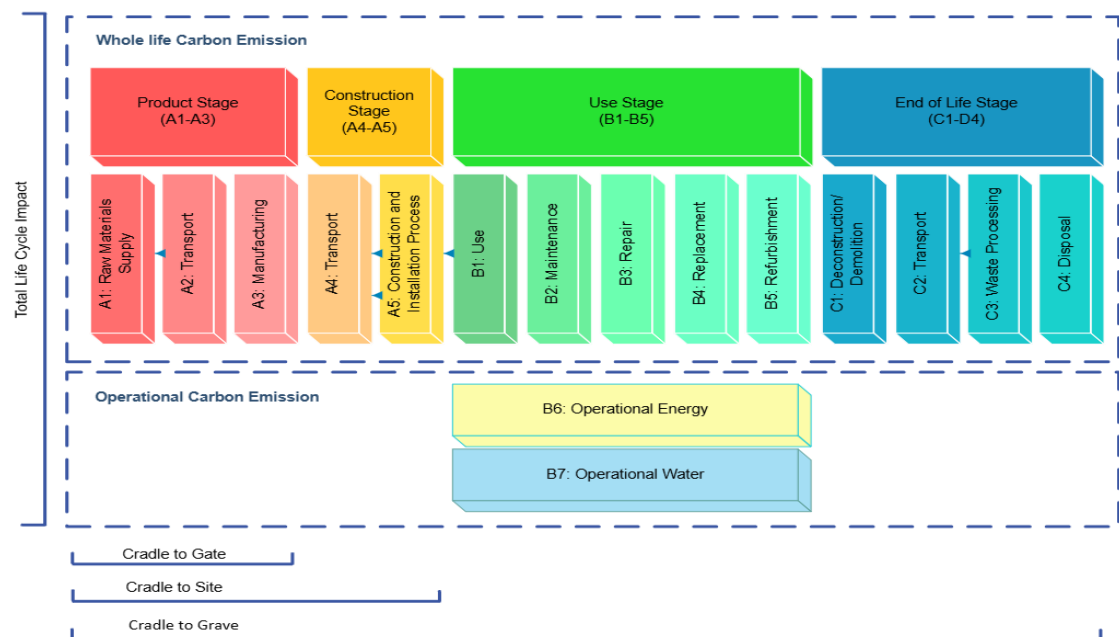


Figure 3.2 System boundaries and life cycle stages in construction-related LCA (adapted from Sartori et al. 2021)

The product stage, modules A1 to A3, is the boundary adopted throughout this thesis. This choice reflects both practice and data comparability. Modules A1 to A3 are declared consistently across products, manufacturers, and programs, and are therefore the only basis on which a large set of declarations can be compared (Passer et al. 2015). Where later modules are declared, they rest on assumptions specific to each declaration: end-

of-life results in particular depend on the disposal route assumed, and a single declaration may report two alternative scenarios yielding different totals. The product stage is also the stage most directly attributable to the product itself, since the later stages depend on how and where it is installed and used. The implications of restricting the analysis to this stage are considered further in Chapter 6.

The choice of boundaries has a strong effect on the reported result and can reverse a comparison entirely. For example, in a landfill capping study, a geosynthetic solution showed embodied carbon roughly five times that of the compacted clay alternative at the cradle-to-gate boundary, but once transport and construction emissions were included the clay solution emitted 47% more, because placing a one-meter clay layer required a thousand vehicle movements and extensive compaction (Dixon et al. 2016). This sensitivity is one of the central difficulties in using LCA results for comparison, and it is the reason transparent reporting and standardized boundaries are emphasized in both the standards and the literature (Hasselsteen et al. 2025; Reddy & Janga 2025).

3.3 Environmental Indicators and the Focus on Global Warming Potential

The LCIA phase translates inventory data into a set of impact category indicators using established characterization methods (ISO 14044:2006). The characterization method determines the factors used to convert inventory flows, such as kilograms of CO₂, methane, and nitrous oxide, into aggregated scores expressed in a common unit for each category, for example kg CO₂eq for GWP (Hauschild et al. 2018). Because different methods apply different factors, they may produce different numerical results from the same inventory data, even when the underlying physical emissions are identical.

Several internationally recognized characterization methods have been developed to standardize these calculations, among them CML, developed at the Institute of Environmental Sciences at Leiden University (Guinée et al. 2002), ReCiPe, and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI). Two are directly relevant to the declarations examined in this thesis. The CML method was the basis for the core indicators in construction product EPDs under EN 15804:2012+A1:2013. The Environmental Footprint (EF) characterization factors, developed by the European Commission Joint Research Centre within the Product Environmental Footprint (PEF) initiative, were subsequently adopted under the revised EN 15804:2012+A2:2019, which requires a transition from CML to EF characterization (Zampori & Pant 2019). For GWP the two methods differ less than for most other impact categories, since both derive their 100-year factors from the assessment reports of the

IPCC, and since fossil carbon dioxide, which dominates the emission profile of polymer products, carries a characterization factor of one under either method. The distinction between the two methods is nonetheless the basis of the first comparability criterion applied in Section 4.2.

Among the impact categories, GWP is the most widely applied in the construction sector because of its direct relevance to climate change mitigation. It quantifies the contribution of GHG emissions and expresses them in carbon dioxide equivalents, aggregating gases such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) into a single value according to their radiative forcing over a specified time horizon, commonly 100 years (IPCC 2014). Under EN 15804:2012+A2:2019, GWP is reported as four separate indicators: GWP-fossil, GWP-biogenic, GWP from land use and land use change (GWP-luluc), and GWP-total, which is their sum (Ramesh & Lee 2025).

GWP is one of several indicators defined in the EPD framework. EN 15804:2012+A2:2019 requires 13 core impact indicators to be declared. The 4 GWP indicators are among them, together with categories such as acidification potential, eutrophication potential, ozone depletion, and resource depletion (Ramesh & Lee 2025). A full environmental assessment therefore considers impacts well beyond climate change, and focusing on a single indicator does not capture the complete environmental profile of a product (Çelekli & Zariç 2023).

This thesis nonetheless focuses on GWP-total, for three reasons. First, it is the indicator on which the Finnish CO₂data database is built, so it is the quantity for which representative factors are required in this context. Second, it is the indicator declared most consistently across the collected declarations, whereas the other categories are reported unevenly and under characterization methods that changed between the two versions of the standard, which would compromise comparison. Third, it is the indicator addressed directly by the climate policy objectives that motivate the work. The focus on GWP-total is therefore a deliberate scope decision rather than a claim that other impact categories are unimportant, and the exclusion of those categories is noted among the limitations in Chapter 6.

3.4 Environmental Product Declarations (EPDs)

The ISO 14020 family of standards defines three types of environmental communication tool: Type I ecolabels, which are third-party certified labels awarded to products meeting predefined multi-criteria requirements (ISO 14024); Type II self-declared environmental claims made by manufacturers (ISO 14021); and Type III environmental declarations,

which present quantified data derived from life cycle assessment (ISO 14025). EPDs are Type III declarations, and unlike the pass-or-fail nature of Type I labels they present quantified environmental data across multiple impact categories without judging a product as good or bad, allowing purchasers to make their own comparisons (ISO 14025:2006).

An EPD is based on an LCA and reports quantified results for the impact categories defined by its governing PCR, which fixes the system boundaries, functional unit, and methodological requirements for a given product category, so that declarations for products in the same category are prepared on a consistent basis (ISO 14025:2006). The credibility of an EPD rests on verification, which confirms that the underlying assessment complies with the applicable standards and PCRs before the declaration is published. ISO 14025:2006 requires independent third-party verification for declarations communicated to consumers but permits internal verification for business-to-business declarations, so the level of independence varies between declarations and is recorded in the screening described in Section 4.2. Published declarations are registered by a program operator and remain valid for a limited period, commonly five years, after which they must be reviewed and reissued.

EPDs are primarily intended for business-to-business communication, such as the exchange of environmental data between manufacturers, specifiers, and public procurement bodies, rather than for direct communication to consumers (ISO 14025:2006). This orientation makes them well suited to the construction sector, where environmental data are used by designers and procurement authorities rather than end consumers, and it is the reason they form the data source for national infrastructure emission databases. Numerous EPD programs now operate internationally, among them the International EPD System, which supports a large number of PCRs across many sectors (Hunsager et al. 2014). In Finland, Rakennustieto is the Finnish EPD program, issuing third-party verified declarations in accordance with EN 15804:2012+A2:2019. Its program is approved into the ECO Platform, the umbrella organization for European EPD program holders, and it holds a mutual recognition agreement with other Nordic publishers, among them EPD International, EPD Norway, and EPD Denmark, which allows a declaration to be published in the systems of more than one operator and permits the use of product category rules developed under another program, an arrangement intended to make the information in declarations more comparable (Rakennustieto 2026).

Despite their advantages, EPDs also present challenges. Their development is resource-intensive, requiring a detailed LCA and adherence to the relevant PCR. More significantly

for the present work, inconsistencies between PCRs developed by different program operators for similar products limit the comparability of the resulting declarations (Subramanian et al. 2012; Hunsager et al. 2014). This limitation is central to the thesis and is examined in detail in Sections 3.5 and 3.7.

3.5 Product Category Rules and Their Impact on EPDs

PCRs are standardized methodological frameworks that define how the environmental impacts of products in a given category are assessed and reported across the life cycle. They are a mandatory component of Type III EPDs under ISO 14025:2006, ensuring that environmental information is transparent, consistent, and comparable within a defined product category.

General LCA standards such as ISO 14044:2006 provide overarching principles but do not include the product-specific detail needed for consistent application across similar products. PCRs address this gap by specifying the key methodological requirements for a category, including the system boundaries, functional or declared unit, allocation procedures, data quality criteria, and impact assessment methods (ISO 14025:2006). By fixing these choices, a PCR ensures that differences between the declarations of two products in the same category reflect genuine differences between the products rather than differences in method.

To ensure credibility, a PCR must be developed by or under the authority of a program operator in accordance with ISO 14025:2006. The process requires the involvement of relevant stakeholders, including industry representatives, LCA experts, and public institutions, and must include a transparent public consultation phase (ISO 14025:2006). This participatory development is intended to produce rules that are balanced and widely accepted within a sector.

A clearly defined product category is essential to this process. Categories are based on functional equivalence, so that products fulfilling the same function are assessed under the same PCR even when their production processes differ (ISO 14025:2006). Classification systems such as the United Nations Central Product Classification may support consistency and reduce the duplication of overlapping PCRs.

Despite these mechanisms, the global expansion of EPD programs has led to the development of multiple PCRs for similar product categories by different program operators. Because these PCRs may differ in methodological choices such as data sources, allocation rules, or system boundaries, declarations prepared under different PCRs are not necessarily comparable, even when each complies with ISO 14025:2006. Geosynthetics

illustrate this directly. The declarations collected for this thesis were prepared under PCRs issued by several different program operators: some specific to geosynthetic products, others covering construction products generally, and others applying only the core rules of EN 15804 with no sector-specific PCR named. Two documents govern most of the collected declarations. PCR 2019:14 of the International EPD System covers construction products generally and aims to be the main route by which such declarations are developed and registered in that system, while Kiwa-Ecobility Experts has issued a Part B PCR specific to geosynthetic products, covering geogrids, geotextiles, geomembranes, and geocomposites (Kiwa-Ecobility Experts 2023). Several of the manufacturers represented in the dataset have published under the latter. No complementary PCR for geosynthetics exists within the International EPD System, although 35 such documents had been adopted for other construction product categories at the time of writing. Work is under way within CEN technical committee CEN/TC 189 on a European standard for the environmental performance of geosynthetics, intended for adoption as a complementary PCR to PCR 2019:14, which as of July 2026 remained at a preliminary stage with publication estimated for 2026 to 2027 (EPD International 2026). Until it is available, the lack of harmonization remains a recognized limitation of the EPD system and directly constrains the comparability of the declarations analyzed in this thesis, a point developed further in Section 3.7.

3.6 Development and Verification of EPDs

The development of an EPD is a structured process based on LCA and governed by a hierarchy of standards, program rules, and product-specific requirements. Rather than a simple reporting exercise, it involves a sequence of analytical and procedural steps intended to ensure that the environmental information is robust, transparent, and verifiable (ISO 14025:2006; Del Borghi 2013). The process is illustrated as a five-step workflow in Figure 3.3.

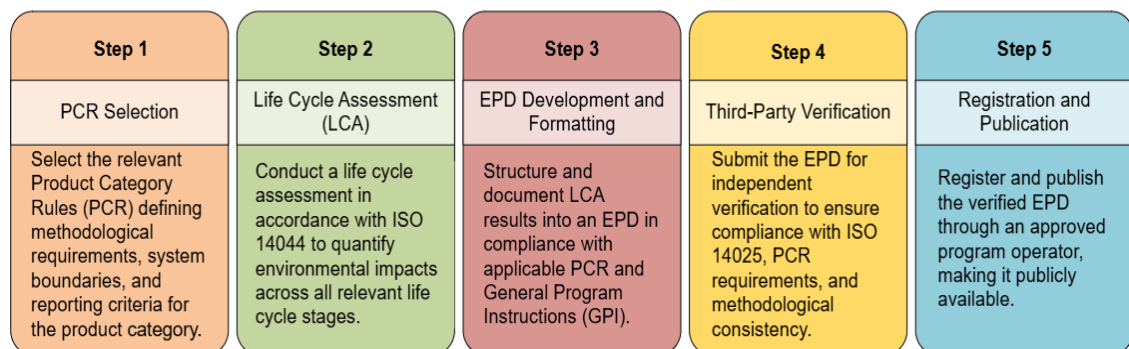


Figure 3.3 Standardized workflow for the development of an EPD (compiled from ISO 14025:2006 and ISO 14044:2006)

At its core, the process applies the four phases of LCA defined in ISO 14040:2006: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. These phases are iterative, requiring assumptions, system boundaries, and data to be refined as the study progresses (Guinée et al. 2002).

The specification of the functional or declared unit and the system boundaries is a decisive step, since these determine what the declaration covers and therefore what it can validly be compared against. The unit must reflect the product in a measurable and application-relevant way, and the system boundaries must include the life cycle stages required by the governing PCR (ISO 14025:2006). For construction products, EN 15804:2012+A2:2019 provides the modular structure within which these boundaries are defined.

Data collection requires a balance between primary and secondary sources. High-quality primary data are expected for processes under the direct control of the manufacturer, while secondary data from background databases are used for upstream processes such as raw material production. The reliability of the result depends strongly on the temporal, geographical, and technological representativeness of this data, and where data limitations require assumptions or proxies, these must be documented transparently (ISO 14025:2006; ISO 14044:2006).

A defining feature of an EPD is that its published results are a selected extract from a more extensive background LCA report, which is not itself made public. The background report contains the full inventory results, the data records used, the allocation decisions, and additional contribution and sensitivity analyses, and it is this document that a verifier examines to confirm that the declaration is plausible and compliant (Ramesh & Lee 2025). This distinction matters for anyone working from published declarations, since much of the information underlying a reported value is not visible in the declaration itself, and it is the reason the screening described in Section 4.2 can assess only what each declaration states.

Verification is the final safeguard of credibility. Under ISO 14025:2006 an EPD must be verified before publication, the verifier reviewing the LCA model, data sources, assumptions, and calculations for both technical correctness and compliance with the applicable standards and PCR (ISO 14025:2006; Del Borghi 2013). As noted in Section 3.4, this verification may be internal or independent depending on the intended audience, and the declarations analyzed in this thesis differ in this respect. Verification is nonetheless what distinguishes a Type III declaration from an unverified environmental claim, and it is the

basis on which the declarations are treated as reliable within the limits of their stated methodology.

3.7 Factors Affecting the Comparability of EPDs

Although EPDs are designed to standardize environmental reporting, declarations for similar products are frequently not directly comparable. Where the methodological choices embedded in two declarations differ, the difference in their reported results may reflect the method of assessment rather than any real difference between the products (Gelowitz & McArthur 2017). The factors described below determine when such a comparison is valid, and they form the basis of the screening criteria applied in Chapter 4.

Governing PCR is the most fundamental of these. A PCR fixes the choices that would otherwise be made independently in each assessment: the declared or functional unit, the life cycle modules that must be reported, the cut-off rules governing which flows may be omitted, the allocation procedure for multi-output processes, the requirements on data quality and background databases, and the impact categories to be declared (ISO 14025:2006). Not every choice is settled at this level, however, and where a PCR leaves a parameter open the manufacturer defines it for each declaration, so two products assessed under the same PCR may still differ in the assumptions behind their reported values. As described in Section 3.5, different program operators may in addition issue different PCRs for the same product category, so declarations prepared under different PCRs cannot be assumed comparable even when each is individually valid. A shared PCR is not sufficient either: in a study of 50 construction product EPDs, 61% of comparisons between declarations written to the same PCR were found to be invalid, and 38% of the declarations were missing information required by ISO 14025:2006 (Gelowitz & McArthur 2017).

How the calculation was carried out matters as much as the rules under which it was done. Declarations prepared under EN 15804:2012+A1:2013 use the CML characterization method, while those under EN 15804:2012+A2:2019 use the EF factors; for GWP the difference is limited, since both derive their 100-year factors from the IPCC and fossil carbon dioxide carries a factor of one under either, but the two remain formally different bases. The background database is a larger source of divergence. Declarations calculated with *ecoinvent*, GaBi, or national datasets, or with different versions of the same database, may report different results for reasons unrelated to the product, and older datasets rest on a different supply chain structure from current ones (Ramesh & Lee 2025). EN 15804:2012+A2:2019 accordingly limits specific data to five years and generic

data to ten. The manufacturing location compounds this, since national grids differ substantially in carbon intensity, making the same product emission-intensive depending on where it is produced.

A further group of factors concerns what the declared value describes. The declared unit may be expressed per unit area, per unit mass, or per unit length, and values on different bases cannot be compared until they are converted, which requires the mass per unit area of the product and is not always possible from the declaration alone. A declaration may also cover a product family rather than an individual product, using a mass-weighted average, a worst-case reference product, or a scaling function, in which case the declared value represents the family rather than any grade within it. For geosynthetics, where a single family may span an order of magnitude in mass per unit area, both are significant.

Finally, much of what would be needed to judge comparability is not published. A declaration reports a selected set of results extracted from a background LCA report that remains confidential, so the assumptions, allocation choices, and data records behind a reported figure are not visible (Ramesh & Lee 2025). Declarations also differ in the details they report, some declaring modules A1, A2, and A3 separately and others only the aggregated total. Comparability therefore cannot always be fully assessed from the declaration alone, which is itself a limitation of any analysis built on published EPDs.

Beyond these methodological factors, a further limitation applies specifically to products such as geosynthetics. An EPD reports the impacts of a product in isolation, whereas the environmental benefit of a geosynthetic often arises at the level of the structure in which it is used, for example by reducing the quantity of aggregate required or extending the service life of a road. Such system-level effects fall outside the product-level boundary of an EPD and are therefore not reflected in the declared values (Koerner 2012; Heerten 2012).

Taken together, these factors mean that published EPDs cannot be pooled or compared without prior screening. What such screening requires, and how it was carried out for the declarations analyzed here, is set out in Chapter 4.

3.8 National Emission Databases and the Finnish CO₂data Service

The comparability limitations described in the previous section explain why individual EPDs are difficult to use directly in project-level carbon assessment. A designer wishing to estimate the emissions of a construction project cannot simply collect declarations

from each supplier, because the values are prepared on differing methodological bases and are not directly comparable. National emission databases address this problem by compiling published environmental data into a consistent set of representative emission factors that can be applied uniformly across projects.

In Finland, this function is provided by the CO2data service, maintained by the Finnish Environment Institute (Syke). The service comprises two databases, one for building construction and one for infrastructure construction, both freely available and provided in a machine-readable format for integration into emission calculation tools (Syke 2025). The infrastructure database is the relevant one for the present work, since geosynthetics are used predominantly in infrastructure applications. It provides the emission data required by the low-carbon infrastructure assessment method published by the Finnish Transport Infrastructure Agency (FTIA) in 2023, within which the assessment of a project's climate impact is currently voluntary (Syke 2025).

The way the database is populated is directly relevant to this thesis. Rather than listing individual product-specific declarations, the database compiles average data for the most common and typical construction products, derived from public sources such as EPDs that are analyzed, compared, and assessed in collaboration with infrastructure construction experts (Syke 2025). The methodology gives preference to declarations prepared under the latest version of EN 15804, and European data are used where market-specific Finnish data are unavailable. Geosynthetics are represented by nine generic entries covering filter geotextiles, geogrids, a drainage mat, and a GCL, which leaves several product types without a value and none of the entries derived from the product-specific declarations now available. The gap this work addresses is therefore not the absence of geosynthetics from the database but the absence of representative values for them.

This context defines the requirements that the emission factors derived in this thesis must meet. The values must be expressed in a form consistent with the database, as GWP-total for the product stage per square meter of product and must be representative of the products used on the Finnish market rather than of any single manufacturer. These requirements shape the methodology described in the following chapter.

4 MATERIALS AND METHODS

This chapter describes the material studied and the methods applied. The material consists of published EPDs for geosynthetic products available on the European market, together with expert interviews with manufacturers and an EPD program operator. The methods comprise the collection of the declarations, a comparability screening, extraction and harmonization of product-stage GWP-total values, a two-stage grouping of products, statistical and regression analysis, a calculation of transport emissions from each manufacturing site to Finland based on route-specific distances and transport modes, and thematic analysis of the interviews. Each stage is described below in the order in which it was carried out, with the reasons for the choices made.

4.1 Research Design and Data Collection

The study is a documentary analysis of published declarations, supplemented by expert interviews. This design follows directly from the objective. The aim is not to produce new life cycle assessments but to determine what emission factors can defensibly be derived from declarations that already exist, and under what conditions those declarations may be compared. A documentary approach is therefore the appropriate primary method, since the declarations themselves are the object of study. Expert interviews were added as a secondary method to test whether the patterns identified in the documents correspond to the practices and constraints experienced by those who prepare declarations and by those who publish them, which strengthens the interpretation of the documentary evidence through methodological triangulation (Bryman 2016).

The overall workflow is presented in Figure 4.1. Two features of it require comment. First, the grouping of products was carried out in two stages. Products were initially compared within their conventional product categories, and only after this preliminary analysis had shown that carbon intensity follows polymer and structural function rather than commercial category were they regrouped across category boundaries. The initial grouping is therefore a step that produces the evidence on which the final grouping rests. Second, the interviews were conducted after the main quantitative analysis, so that the interview themes could be informed by both the standing themes of the study and the questions the data had raised, rather than being shaped in advance.

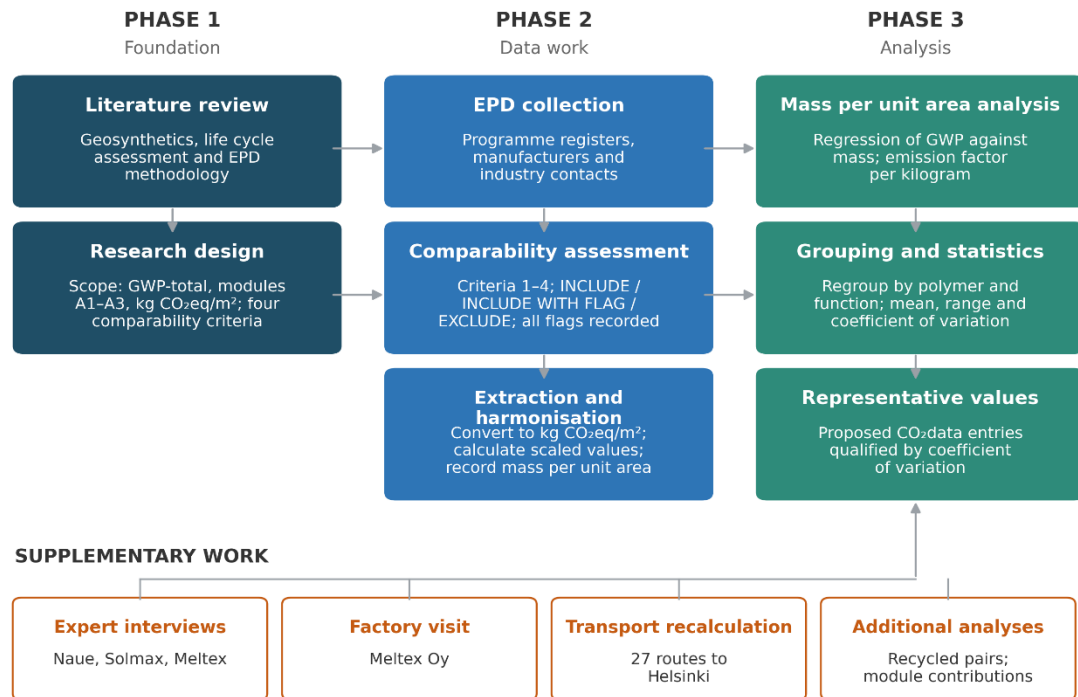


Figure 4.1 Workflow of the study, organized in three phases, with the supplementary work carried out alongside the main analysis

Declarations were collected from the public registers of EPD program operators, from manufacturer publications, and through contacts provided by the commissioning parties. The dataset was assembled to cover the geosynthetic product types used in Finnish infrastructure construction. The program operator, product category rules, and background database of every declaration collected are recorded in Table A.1 of Appendix A, and the operators are identified in the legend to that table.

A declaration had to concern a geosynthetic product intended for use in the ground, that is installed in soil or earthworks such as roads, embankments, drainage structures, landfills and ponds, which excluded products declared for building envelope or roofing use. It had to be prepared in accordance with EN 15804, in either its A1 or A2 amendment, which is the framework within which construction product declarations are comparable in principle (EN 15804:2012+A2:2019). And it had to declare a GWP result for modules A1 to A3. Declarations were collected irrespective of program, background database, and validity status, because establishing how such differences affect comparability is the purpose of the screening described in Section 4.2 rather than a reason to exclude material in advance.

The collection yielded 72 declarations from 38 manufacturers published under 11 programs, spanning geotextiles, geogrids, geocomposites, geomembranes, and GCLs. The dataset is a convenience sample of what was publicly available during the collection

period rather than a systematic sample of the market. This is a deliberate consequence of the method, since the aim is to represent the declared portion of the market that a national database can actually draw on, and its implications are considered in Section 6.3.

4.2 Comparability Assessment

A systematic comparability assessment was conducted for all collected EPDs prior to any statistical analysis. This step is necessary because EPDs prepared under different programs, standards, background databases, and methodological assumptions cannot be directly compared without first evaluating and documenting the sources of potential incomparability, as established in Section 3.7. Without this framework, differences in GWP-total values between products could be misattributed to differences in environmental performance when they are in fact caused by differences in database age, electricity emission factor, characterization method, or scaling approach. Separating these confounding factors from genuine product-level differences is the central analytical contribution of the screening, and it is structured around four criteria applied consistently to each EPD.

The first criterion concerned the EPD standard and characterization method. As explained in Section 3.3, declarations prepared under EN 15804:2012+A2:2019 use the EF characterization method, while those under the earlier EN 15804:2012+A1:2013 use CML. Declarations following EN 15804:2012+A2:2019 were therefore adopted as the reference, and those following EN 15804:2012+A1:2013 were retained but assigned a comparability flag. Because fossil carbon dioxide dominates the emission profile of polymer products and carries the same characterization factor under both methods, the resulting difference in GWP-total is small, and the flag therefore does not justify exclusion but is documented.

Background data formed the second criterion. The background database sets the emission factors for upstream processes such as electricity and polymer feedstock, and these have fallen as the European energy mix has decarbonized. Declarations using *ecoinvent* version 3.6 or later, or equivalent recent GaBi datasets, were treated as current. Declarations using the UVEK dataset based on *ecoinvent* 2.2 (2010), or earlier GaBi versions, were assigned an old-database flag, since their data lies outside the five-year limit for specific data and ten-year limit for generic data set by EN 15804:2012+A2:2019 (Ramesh & Lee 2025). The resulting difference is documented rather than corrected, as explained in Section 3.7.

Whether a declaration reported its modules separately formed the third criterion. Every EPD is required to declare at least the aggregated A1 to A3 GWP-total value, which is the primary metric for the representative value calculations. The stage-level analysis, which examines the separate contributions of A1, A2, and A3, additionally requires each module to be reported individually. Declarations reporting only an aggregated A1 to A3 total were therefore retained in the total-value comparison but excluded from the stage-level analysis, a distinction that applies to those declarations following a more condensed reporting convention.

The fourth criterion concerned the scaling method and representativeness of family declarations. Several EPDs cover a product family rather than a single product, using a mass-weighted average of several grades, a declared worst-case reference product where within-family variation exceeds the permitted threshold, or an explicit linear scaling function. Declarations using a worst-case reference product were flagged, because the declared value represents the highest-emitting product in the family rather than a typical one and may overstate the emission factor. Where a declaration provided fixed and scalable components per declared unit, the value for each declared variant was calculated from the stated coefficients as described in Section 4.3, and each variant with a distinct mass per unit area was treated as a separate product entry, so that the family is represented by its actual range rather than by a single grade. All values obtained in this way are identified in the master screening table as calculated rather than declared.

Following assessment against these four criteria, each EPD was assigned one of three statuses, abbreviated in the tables as IN, IN-F and EX. INCLUDE (IN) was assigned to declarations meeting all four criteria without qualification, whose values could be used directly. INCLUDE WITH FLAG (IN-F) was assigned to declarations carrying at least one documented issue that does not justify exclusion but must be acknowledged when interpreting results. EXCLUDE (EX) was assigned to declarations that could not enter the quantitative analysis at all, on four grounds: products falling outside the ground engineering scope of the study, declared values physically implausible for the polymer concerned, values so far outside the distribution of comparable products as to indicate a different product or a non-comparable system boundary, and family averages whose constituent products are already represented individually in the dataset. Four product entries received this status. The full assessment, with the result and written justification for each entry, is recorded in the master comparability screening table, which is the primary methodological link between the data collection and the statistical analysis.

4.3 Data Extraction and Unit Harmonization

The indicator extracted from each declaration was GWP-total for modules A1 to A3, expressed in kilograms of carbon dioxide equivalent per square meter (kg CO₂eq/m²). This scope was adopted for the reasons set out in Sections 3.2 and 3.3: it is the only life cycle stage declared consistently across the whole dataset, it corresponds to the information a designer needs at the point of product specification, and it is the basis on which the CO2data database expresses construction product emission factors (Syke 2025). Where a declaration reported results per kilogram or per ton rather than per square meter, the values were converted using the declared mass per unit area. The choice of reference unit is not neutral. Because emissions per square meter depend on mass per unit area while emissions per kilogram do not, two products can rank differently depending on which basis is used: a heavier product may have the higher per-square-meter footprint yet the lower per-kilogram intensity. Converting a per-kilogram declaration to a per-square-meter value also transfers any uncertainty in the mass per unit area into the result, including the typical production tolerance of around ten per cent as well as the larger uncertainty where the mass was estimated rather than declared. These effects are examined in Section 5.3, where the two bases are compared directly. Alongside the emission values, the mass per unit area, the individual module values where declared, the manufacturing site, the background database, the standard version, the program operator, and the validity period were recorded for each product.

Two situations required a defined extraction procedure rather than direct transcription. The first arose where a declaration presented its results in a fixed and scalable format, in which the impact per square meter is given as a constant term plus a mass-proportional term. For these, the value of each declared variant was calculated as

$$GWP = GWP_{fixed} + GWP_{scalable} \times m, \quad (1)$$

where GWP denotes the global warming potential of the product variant in kg CO₂eq/m², GWP_{fixed} the fixed component declared per square meter in kg CO₂eq/m², $GWP_{scalable}$ the mass-proportional component declared per kilogram in kg CO₂eq/kg, and m the mass per unit area of the variant in kg/m². Values obtained from equation (1) are identified in the master table as calculated rather than declared.

The second situation arose where a declaration covered a range of mass per unit area without stating a reference mass. In these cases, a representative mass per unit area from within the stated range was assigned so that the product could still enter the mass-based and transport analyses, and every such entry was flagged as estimated. Because these estimates were assigned without reference to the emission value, they introduce

uncertainty into individual results but should not introduce systematic bias into the group statistics. Products for which no mass per unit area could be established at all were retained in the per-square-meter analyses but excluded from the regression analysis of Section 4.5 and the transport recalculation of Section 4.6.

All extracted data were held in a single spreadsheet workbook, so that any reported value can be traced back to the declaration it came from and to the calculation by which it was derived. This traceability is the basis on which the results in Chapter 5 can be reproduced.

4.4 Grouping of Products

To propose a representative value, products first have to be gathered into groups that a database user would treat as alternatives for the same job. This grouping was done in two stages.

In the first stage, products were compared within their conventional commercial categories, grouped by polymer type and product structure. This was a preliminary screen, and its purpose was to find out whether products that are sold together as the same kind of product also behave alike in their declared emissions.

In the second stage, products were regrouped across the commercial category boundaries, on the rule that a group must be uniform in both polymer and structural function. The rule follows from the material-level evidence set out in Section 2.2, where carbon intensity per kilogram differs far more between polymers than between product types (Tenhunen-Lunkka et al. 2022; Dixon et al. 2016). It places, for example, PP woven geotextiles, PP geogrids, and PP reinforcement geocomposites together, because all three are planar PP reinforcement elements that a designer might weigh against one another for the same purpose, even though they sit in three different commercial categories.

Three further rules governed the boundaries of each group. Products made from recycled feedstock were kept apart from otherwise identical virgin products, since the two follow different production routes and an average would describe neither. Products carrying an extra material system, such as a coating or a laminated membrane layer, were kept apart from products without one. And a product whose mass per unit area fell far outside the range of a group was not forced into it, because emissions depend strongly on mass, as established in Section 2.2, so such a product would inflate the spread of the group without pointing to any real difference in the material.

The groups formed in this way are designated G1 to G9 and are reported in Chapter 5. Products that could not be placed in any group under these rules were kept as individual

values, each with their technical reason recorded rather than being absorbed into the nearest group. A smaller number of entries were set aside from the quantitative analysis altogether, on the grounds defined in Section 4.2. Two of those grounds, an extreme departure from the distribution of comparable products and a value too low to be physically plausible for the polymer concerned, could only be applied once the analysis had been carried out, so those exclusions were made at this stage rather than during the initial screening.

4.5 Statistical and Regression Analysis

Two types of analysis were applied to the extracted data. The first describes how much the products within each group vary, and the second explains where that variation comes from. For each group, the arithmetic mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV) were calculated. The CV was chosen as the main measure of spread because it is dimensionless, which allows groups with very different absolute emissions to be compared on the same footing. It is defined as

$$CV = \left(\frac{SD}{\bar{x}}\right) \times 100\%, \quad (2)$$

where SD denotes the sample standard deviation of the group in kg CO₂eq/m², and $\bar{x}$ the arithmetic mean of the group in kg CO₂eq/m². The mean was left unweighted. Weighting by market share would in principle give a more representative figure, but reliable sales volumes for individual geosynthetic products in Finland are not publicly available, and weighting by any proxy that is available would rest on an assumption weaker than the one it replaced.

Because reporting a mean alone can conceal a skewed distribution, the mean and median of each group were compared, following the benchmarking approach described for national EPD datasets by Ramesh and Lee (2025). Where the two diverge, the distribution is skewed and the mean is pulled toward the extreme values, which is itself useful information about how well a single figure represents the group.

Each group was then placed in one of three reliability levels according to its CV, so that a database user can see immediately how much confidence a single representative value carries. A CV below 15% was taken to mean that a single value represents the group well; between 15 and 40%, that a single value should be reported together with its range; and above 40%, that a single per-square-meter value is not adequate for the group. These thresholds are pragmatic rather than drawn from an established convention, and the underlying coefficients are reported in every case, so a reader preferring different thresholds can apply them.

The second analysis tested where the variation within a group comes from. The preliminary screen had suggested that the widest spread in emissions were also those spanning the widest range of product mass, so the relationship between declared emissions per square meter and mass per unit area was examined within each group by ordinary least squares linear regression of the form

$$y = ax + b, \quad (3)$$

where y denotes the A1 to A3 GWP-total in kg CO₂eq/m², x the mass per unit area in kg/m², a the slope in kg CO₂eq/kg, and b the intercept in kg CO₂eq/m². Because x is expressed in kilograms per square meter, the slope a reads directly as a mass-based emission factor for the material, while the intercept b captures the part of the footprint that does not scale with mass. The coefficient of determination, R^2 , was used to judge how fully mass accounts for the variation in each group.

The regression was run on subgroups defined more narrowly than the representative-value groups of Section 4.4, separating products by structure as well as by polymer, because the relationship being tested is between mass and emissions within a single material and a single construction type rather than across different ones. Products for which no mass per unit area could be established were excluded, as were groups left with fewer than three entries. Where a declaration reported its results in the fixed and scalable format of equation (1), the derived variants were retained, since they represent genuine products in the declared range. Comparing the slopes between subgroups then shows the effect of polymer choice, and the quality of the fit shows whether the mass-based approach works for a given subgroup.

A fit of $R^2 \geq 0.80$ was taken to indicate that a subgroup's emissions can be predicted from its mass, while a weaker fit signals a multi-material product for which mass alone is not sufficient. The threshold was set after the regressions had been run and reflects a clear separation in the results reported in Section 5.3: every single-polymer subgroup falls at or above 0.84 and every multi-material subgroup at or below 0.78, with no subgroup near the boundary.

4.6 Calculation of Transport Emissions to the Finnish Market

Module A4 as it appears in the declarations cannot be compared across the dataset. The transport scenario in an EPD is set either by the governing product category rules or by the manufacturer's own distribution assumptions, and several declarations omit the module entirely, so a declared A4 value describes whatever route its author assumed rather

than delivery to any particular market. This was confirmed in the expert interviews reported in Section 5.10, where scenarios were described as either prescribed by the applicable rules or estimated from the cheapest realistic freight option. Because the aim here is a set of factors for the Finnish market, transport was calculated for every product on a single common basis.

The manufacturing site named in each declaration was taken as the origin and the port of Helsinki as the destination, adopted as a single reference point of delivery so that all products are compared over routes ending at the same location. Each route was built as a road leg from the plant to the nearest suitable port followed by a sea leg to Finland, or as a road-only leg for products manufactured within the country. Road distances were obtained from route planning between the manufacturing site and the port of departure, and sea distances from a port-to-port distance service. In total, 27 routes were required to cover all the manufacturing sites in the dataset, and these are listed in Table C.1 of Appendix C. The resulting transport emission for each product is given in Table C.2.

The transport emission for each product was calculated as

$$A4 = m \times (d_{road} \times EF_{road} + d_{sea} \times EF_{sea}), \quad (4)$$

where $A4$ denotes the transport emission in kg CO₂eq/m², m the mass per unit area in t/m², d_{road} and d_{sea} the road and sea distances of the route in km, and EF_{road} and EF_{sea} the corresponding freight emission factors in kg CO₂eq per tonne-kilometer. Mass per unit area, recorded in g/m² during extraction, was converted to t/m² for this calculation.

The freight factors were taken from the GHG conversion factors published by the UK Department for Energy Security and Net Zero (DESNZ 2026). Road freight is represented by the average non-refrigerated heavy goods vehicle at average laden weight, and sea freight by the average container ship. Both are expressed on a well-to-wheel basis, which includes the emissions of producing the fuel as well as those released in transit and are therefore consistent with the product-stage values against which the results are compared. Each factor combines two parts that the DESNZ dataset reports separately. The first is the emissions released while the goods are actually being moved, that is, the burning of fuel by the truck or ship during the journey. The second is the upstream emissions of producing and delivering that fuel before it is burned, covering its extraction, refining, and distribution. Adding the two gives the full emissions per unit of freight, 0.12715 kg CO₂eq per tonne-kilometer for road and 0.01977 for sea. The average across all heavy goods vehicle classes was adopted in preference to a specific vehicle class, since the declarations do not state the vehicle by which their products are

transported. The scenario assumes full vehicle utilization with no empty return journeys counted, and treats loading as limited by mass rather than by volume.

The calculation was carried out for the 61 products with an available mass per unit area. The result was expressed both in absolute terms and as a percentage of the product's own A1 to A3 value, so that the significance of transport could be compared across products with very different product-stage footprints.

4.7 Expert Interviews

Three semi-structured expert interviews were conducted in June 2026 both to test the documentary findings against practitioner experience and to learn how the experts work with EPDs in practice. A semi-structured form was chosen because the subject required the same set of themes to be covered in every interview while still allowing each conversation to follow the particular expertise of the person being interviewed, both the standing themes of the study and the questions the data had raised, which a fully structured instrument would not permit (Bryman 2016).

The interviewees were selected to cover different positions in the chain through which a declaration comes into existence. The first, by video conference on 16 June 2026, was a joint discussion with Patrick Kollmeier, quality assurance at Naue GmbH & Co. KG, and Onur Üzümlü, LCA practitioner at Kiwa, an accredited EPD program operator. The second, by video conference on 22 June 2026, was with Darryl Kofi Safo, sustainability analyst at Solmax. The third, in person at the manufacturing site on 23 June 2026, was with Johannes Hakala, environmental specialist at Meltex Oy, together with Jarkko Aho-nen, purchaser of the same company. The participants and interviews are listed in Table D.1 of Appendix D.

An interview plan of 14 questions was prepared, covering the scaling of results within product families, the comparability of declarations across programs and product category rules, transport scenarios, the availability and quality of upstream data, the verification process, and the sources of uncertainty in declared results. The full guide is reproduced in Appendix D. Two interviews were held by video conference and one in person at the manufacturing site, all in English. Invitations were issued by electronic mail together with a description of the study, and each participant received a privacy notice prepared in accordance with the data protection practice of Tampere University before the interview took place.

The material was analyzed thematically. For each theme in the guide, the relevant statements were identified and compared across the three interviews to establish where the

accounts agreed and where they differed. The findings are attributed collectively to the interviews in Section 5.10.

5 RESULTS

This chapter presents the results of the comparability screening of EPDs, the analysis of variation between declarations, and the representative emission factors derived from them. All emission factors are expressed as GWP-total in kg CO₂eq/m² for the product stage, modules A1 to A3, unless otherwise stated.

The 72 declarations yielded 84 individual product entries, because several manufacturers declare an entire product family in a single EPD, and each declared variant with a distinct mass per unit area and a calculable result was treated as a separate entry. Of these, 64 were consolidated into 9 product groups, 16 were reported as individual values with documented reasons for separate treatment, and 4 were excluded from the quantitative statistics. The full dataset is provided in Table A.1 of Appendix A, and the written justification for every flagged and excluded entry in Table B.1 of Appendix B.

Section 5.1 reports the outcome of the comparability screening and Section 5.2 the preliminary comparison within conventional product categories. Sections 5.3 and 5.4 present the relationship between emissions and product mass and the representative values derived from it. Section 5.5 covers the products reported individually, Section 5.6 the representative values by NorGeoSpec profile, and Section 5.7 the effect of recycled raw materials. Section 5.8 presents the distribution of emissions between the individual product-stage modules, Section 5.9 reports the recalculated transport to the Finnish market, and Section 5.10 the expert interviews.

5.1 Comparability Assessment

Before any quantitative comparison was made, every declaration was evaluated against the four comparability criteria defined in Chapter 4: the applied standard version and characterization method, the background database, the availability of stage-level data, and the scaling method used for product families. This screening matters because EN 15804:2012+A2:2019 itself cautions that EPDs are only comparable when their methodological basis is equivalent, a condition that cannot be assumed for a dataset drawn from 11 different EPD programs.

The outcome is summarized in Table 5.1. Almost every entry yielded a usable GWP-total result for modules A1 to A3, but 50 of the 84 carried at least one documented methodological flag and 4 could not enter the quantitative analysis. The written justification for every flagged and excluded entry is recorded in Table B.1 of Appendix B.

Table 5.1 Results of the comparability screening across the five product categories, where *IN* denotes entries included without reservation, *IN-F* entries included with a flag noting a comparability limitation, and *EX* entries excluded from the quantitative analysis

Product category	Entries	IN	IN-F	EX
Geotextiles	30	7	23	0
Geomembranes	9	4	1	2
Geosynthetic barriers	7	3	3	1
Geogrids	18	9	8	1
Geocomposites	20	4	15	0
Total	84	27	50	4

The flags fall into four recurring types, presented here in descending order of their effect on comparability. The first concerns the age of the background data. Ten entries rest on data that predates the currency limits of EN 15804:2012+A2:2019, which require specific data to be no older than five years and generic data no older than ten (Ramesh & Lee 2025). Seven use the UVEK dataset based on *ecoinvent* version 2.2 from 2010, with feedstock data from 2005 to 2007 (Frischknecht et al. 2005), and three, covered by a single declaration, use GaBi 6 from 2016. All ten come from one manufacturer and span all five product categories, so the flag reflects one company's declaration practice rather than a property of any product type. Because these versions rest on a Europe-centred supply chain structure with far fewer regionalized datasets, the affected values differ systematically from those calculated on current versions. Comparing matched datasets between *ecoinvent* 2.2 and a current version, Steubing et al. (2016) found global warming results a median of 6% higher in the newer version, with a median deviation of 13% at the level of individual datasets. The direction of the effect for any individual product cannot be determined from the declarations themselves, since no product appears under both an old and a current database, so it is carried through this work as a qualitative caveat rather than a numerical correction.

A second group of entries is flagged for the version of the standard under which they were prepared. Seventeen entries are published under EN 15804:2012+A1:2013, or under product category rules aligned to it, and therefore use the CML method rather than the EF characterization factors of the current standard. For GWP-total of polymer products the difference between the two is limited, since both derive their 100-year factors from the IPCC assessment reports and fossil carbon dioxide carries a factor of one under

either method, so the affected values were retained without adjustment. The flag is documented nonetheless, since the same difference would not be negligible for other impact categories.

The third arises from how manufacturers declare product families. Declarations following the Kiwa-Ecobility Experts program instructions present results in a fixed-plus-scalable structure, in which the impact per square meter is the sum of a constant and a mass-proportional term. Where no pre-combined result table was provided, the value for each declared variant was calculated from this structure as described in Section 4.3, which applied to three entries. Because the fixed and scalable components stand side by side in the result tables and can be misread as complete product values, this format requires particular care, and all values derived are identified as calculated in Appendix A.

The remaining flag records incomplete reporting. Of the 80 entries retained in the analysis, 55 report modules A1, A2 and A3 separately; the remainder declare only an aggregated total and are therefore usable for the representative value analysis but excluded from the stage-level analysis of Section 5.8. A second group states no mass per unit area, which does not affect the per-square-meter results but excludes those products from the mass-based analysis of Section 5.3 and the transport recalculation of Section 5.8, both of which require mass as an input. This gap between what EPDs declare and what a database-oriented comparison needs recurs throughout the chapter and is taken up in the Discussion.

The screening therefore points to a clear conclusion. The obstacle to building a national database from published EPDs is not a shortage of data, since almost every entry yielded a usable product-stage result. The obstacle is the unevenness of the conditions under which those results were produced, and it is this unevenness that the rest of the chapter works to resolve.

5.2 Preliminary Grouping Within Product Categories

Before the products could be given representative values, they had to be gathered into groups whose members are genuinely comparable. As a first step, the products were grouped as they are conventionally classified, within their commercial product categories and by polymer type and structure. This preliminary grouping was not intended to produce final values. Its purpose was to test whether the conventional commercial category is itself an adequate basis for grouping, that is, whether products sold under the same commercial description behave alike in their declared emissions. This was not expected to hold across all categories, since products of a single polymer and structure should

behave more predictably than multi-material geocomposites or geomembranes made from different raw materials, even where a wide range of mass per unit area still spreads their per-square-meter values.

The preliminary statistics reveal a sharp divide. Two product types produce highly consistent results across manufacturers and programs. Polyolefin geomembranes vary by only 7.03% (n=4) and standard geosynthetic clay liners by 5.71% (n=3), although each rests on a small number of declarations that does not cover every producer on the market. At the other extreme, every geotextile subgroup exceeds 49% variation despite being restricted to a single polymer and structure, and the geogrid and geocomposite subgroups fall between the two, at roughly 30 to 46%.

The pattern behind this divide is what directs the rest of the analysis. The consistent groups are precisely those supplied within a narrow range of mass per unit area, while the variable groups are those sold across a wide range of mass per unit area. This suggests that within a single polymer and structure much of the dispersion is driven not by disagreement between manufacturers about the carbon intensity of the material, but by how much material each product contains. Grouping by broad category alone is therefore not sufficient, and product mass must be examined directly alongside polymer and structure. Production method also varies within a group and contributes to the residual spread, a factor returned to in Section 5.3.

5.3 Mass Per Unit Area Analysis and Mass-Based Emission Factors

The preliminary grouping in Section 5.2 showed that the subgroups with the widest spread are precisely those spanning the widest range of mass per unit area, which points to product mass per unit area, rather than any difference in production technology, as the dominant driver of per-square-meter variation. To test this directly, the relationship between declared A1 to A3 GWP-total per square meter and product mass per unit area was quantified by linear regression within each subgroup. Products whose declarations state no mass per unit area were left out of the fits, and entries whose mass per unit area rests on a mid-range estimate rather than a declared value were kept but noted, since their position on the mass axis is approximate. Mass per unit area is expressed in kilograms per square meter, so the regression slope carries the unit kg CO₂eq/kg of product and can be read directly as a mass-based emission factor. The fitted regressions are shown in Figure 5.1 for the eight subgroups that share a common scale, and in Figure 5.2 for the recycled PE ground reinforcement grids, whose mass and emission ranges are far higher than the rest and which are therefore plotted separately.

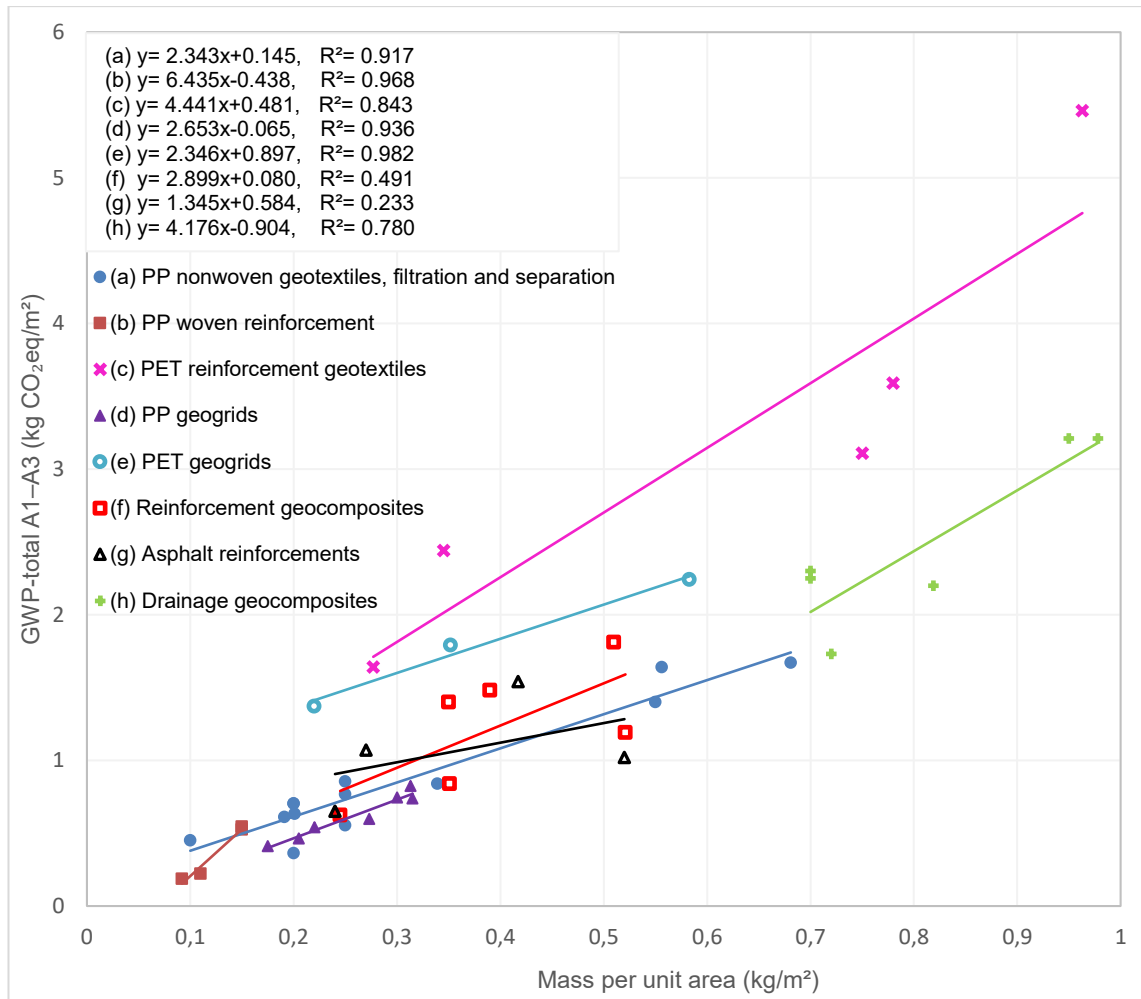


Figure 5.1 Linear regression of A1 to A3 GWP-total per square meter against product mass per unit area within each subgroup

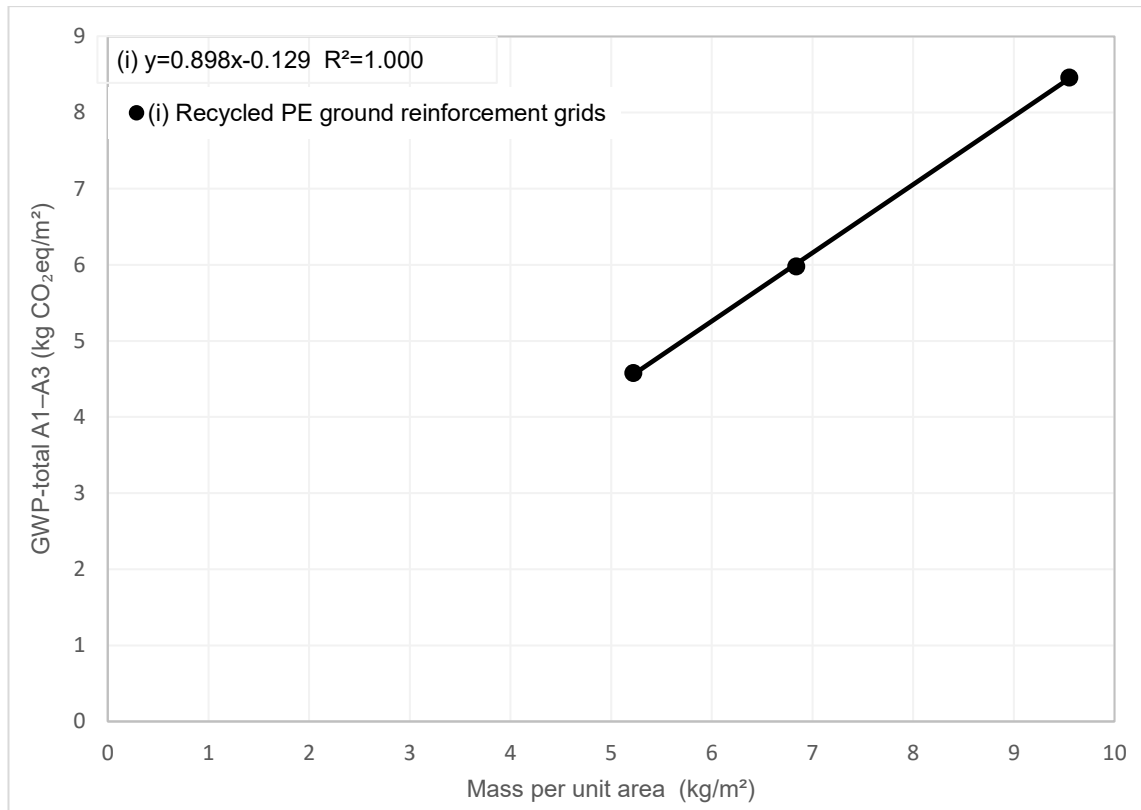


Figure 5.2 Linear regression of A1 to A3 GWP-total per square meter against product mass per unit area for recycled PE ground reinforcement grids

Three findings follow from these regressions. First, for single-polymer products the linear relationship is strong to very strong, with R^2 between 0.84 and 1.00 across the nonwoven, woven, geogrid subgroups and the recycled PE ground grid of Figure 5.2. Within these groups a product's per-square-meter value is, to close approximation, its mass multiplied by a polymer-specific carbon intensity. The wide coefficients of variation in Section 5.2 therefore reflect the range of mass per unit areas a single product family is sold across, not disagreement between manufacturers about the material's carbon intensity. These subgroups are better represented by a mass-based emission factor applied to the specified mass per unit area than by any single per-square-meter value.

Second, the regression slopes reveal a clear hierarchy of carbon intensity between polymers. Recycled PE carries the lowest mass-based factor at 0.90 kg CO₂eq/kg, PP products fall between 2.3 and 2.7 across the nonwoven and geogrid subgroups covering both product forms, and virgin PET geotextiles reach 4.44, roughly 1.9 times the PP level. Because raw material supply dominates the product-stage footprint, as Section 5.8 shows, polymer choice is the single largest lever on the carbon footprint of these products. The PP woven subgroup is the one case where the slope cannot be read as a mass-based factor. Its products span only 92 to 150 g/m², and the fitted line carries an

intercept of $-0.44 \text{ kg CO}_2\text{eq/m}^2$, larger in magnitude than any declared value in the subgroup, so the slope of 6.43 reflects the narrow mass range rather than a transferable per-kilogram intensity; the declared values themselves imply 2.0 to 3.6 $\text{kg CO}_2\text{eq/kg}$, consistent with the other PP subgroups. A few other subgroups also show a small negative intercept in Figure 5.1. In each of these the line crosses zero below the lightest real product, so it never predicts a negative footprint for any product in the range, and the slope can still be used as a mass-based factor. The PP woven subgroup is the only exception, as explained above. The PET geogrid subgroup is revealing in a different way. Its slope of 2.35 is close to the PP level, but it carries the largest positive intercept in the dataset, $0.89 \text{ kg CO}_2\text{eq/m}^2$, a mass-independent burden consistent with the polymer coating on these grids. This is why the consolidated PET group in Section 5.4 remains so dispersed, since PET geotextiles and PET geogrids differ by almost a factor of two in mass-based intensity despite sharing a polymer. Third, the linear relationship breaks down for geocomposites. The asphalt reinforcement and reinforcement composite fits reach R^2 of only 0.23 and 0.49, and the drainage composites, though better behaved at $R^2 = 0.78$, remain well below the single-polymer groups. This is the expected consequence of multi-material structure. In a product that combines a carrier grid or core with bitumen or acrylic coatings, glass fiber, sand, or a second polymer, total mass is no longer a reliable proxy for material composition, so two composites of equal mass per unit area can carry substantially different footprints. For these product types a mass-based factor is not an appropriate database format, and representative values must instead be defined by structure type, as done in Section 5.4.

5.4 Consolidated Representative Values

The preliminary screen of Section 5.2 grouped products by their commercial category, and Section 5.3 showed why that fails, since carbon intensity follows the polymer and the product form rather than the commercial category. The products were therefore regrouped across category boundaries, on the rule that a group must be uniform in both polymer and structural function. This places, for example, PP woven geotextiles, PP geogrids, and PP reinforcement geocomposites together in a single group, because all three are planar PP reinforcement elements that a designer could weigh against one another for the same purpose, even though they are not technically equivalent in performance, and it separates products that share a commercial category but differ in polymer or structure. The regrouping yields nine product groups, G1 to G9, covering 64 of the 84 product entries. Of the remaining 20, 16 are reported individually in Section 5.5 and 4 were excluded from the quantitative statistics.

The proposed representative values are given in Table 5.2 and illustrated in Figure 5.3. The reliability tier assigned to each group follows the thresholds defined in Section 4.5. Below 15% variation a single value represents the group well, between 15 and 40% it should be reported with its range, and above 40% a single per-square-meter value is not adequate.

Table 5.2 Proposed representative A1 to A3 emission factors for the geosynthetic product groups, where n is the number of product entries in each group. Mean, median, SD and representative value in kg CO₂eq/m²

Group	Group name	n	Mean	Median	SD	CV	Representative value
G1	Polyolefin geomembranes (HDPE, LLDPE, PP)	4	3.65	3.54	0.26	7.03%	3.65
G2	GCL (bentonite with PP geotextiles)	3	4.08	4.15	0.23	5.71%	4.08
G3	PP nonwoven geotextiles, filtration and separation	15	0.82	0.70	0.42	50.86%	0.82
G4a	PP geogrid, reinforcement	7	0.62	0.60	0.16	25.27%	0.62
G4b	PP woven geotextile, reinforcement	3	0.64	0.54	0.19	28.98%	0.64
G4c	PP reinforcement geocomposite, grid plus nonwoven	6	1.22	1.29	0.44	35.66%	1.22
G5a	PET woven and knitted geotextile, reinforcement	6	2.96	2.77	1.46	49.27%	2.96
G5b	PET geogrid, reinforcement	4	1.58	1.58	0.57	36.09%	1.58
G6	Asphalt reinforcement, asphalt interlayer geocomposite	5	1.02	1.02	0.34	33.15%	1.02
G7	Drainage geocomposite	6	2.59	2.28	0.78	30.01%	2.59
G8	PVA-based reinforcement	2	3.89	3.89	0.09	2.37%	3.89
G9	Recycled PE 3D ground reinforcement grid	3	6.34	5.98	1.96	30.99%	6.34

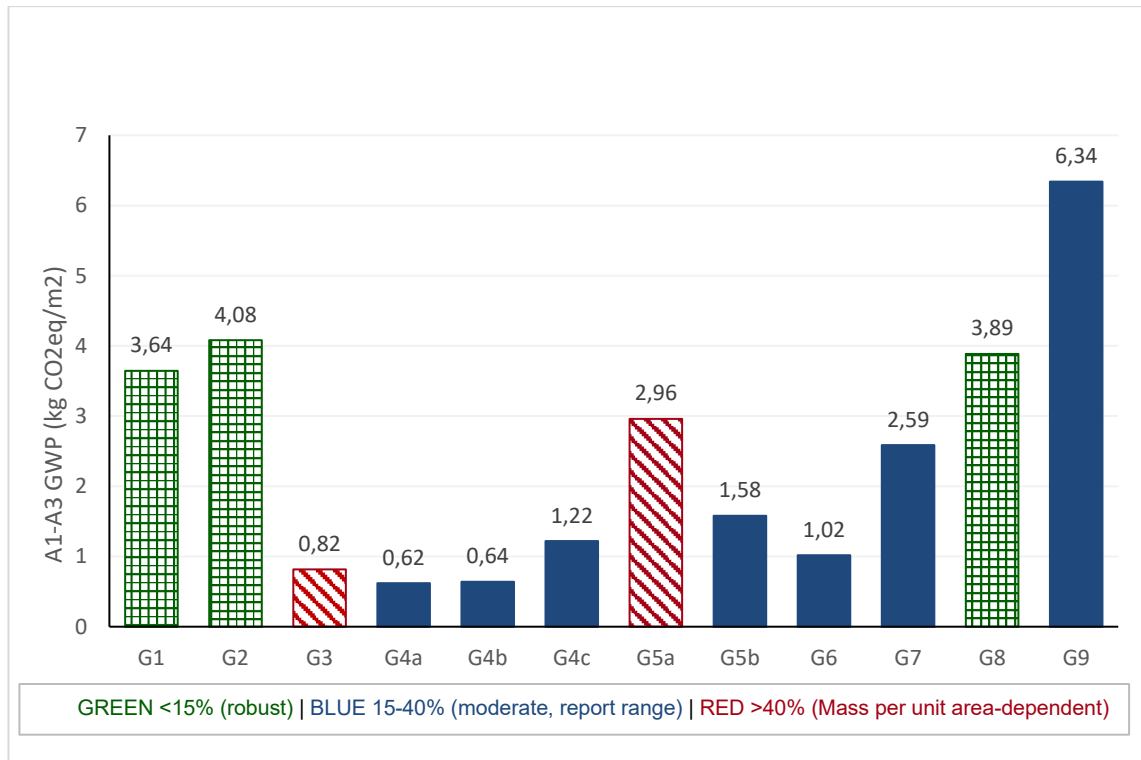


Figure 5.3 Representative A1 to A3 emission factors for geosynthetic product groups. Each bar is the group mean, shaded by reliability tier defined by the coefficient of variation: green below 15%, blue 15 to 40%, and red above 40%

Three groups qualify as green in Figure 5.3. Polyolefin geomembranes, at 7.03% variation, and GCLs, at 5.71%, achieve this despite drawing on products from several manufacturers published under different EPD programs, which is a meaningful result, since for these product types the declared values converge closely enough that a single representative figure is defensible for database use. This holds only for the products examined here, since the geomembrane and GCL declarations available do not cover every producer on the market. The consistency has a physical explanation, since both are supplied within a narrow band of mass per unit area, so the mass per unit area effect that dominates elsewhere has little room to operate. The third green group, PVA-based reinforcement, has an even lower CV at 2.37%, but it rests on only two products, so its apparent precision reflects the small sample rather than demonstrated market-wide agreement and should be treated as indicative until more declarations become available.

Seven groups fall in the blue class in Figure 5.3, with coefficients of variation between 25 and 37%, namely the PP geogrid, PP woven geotextile, PP reinforcement geocomposite, PET geogrid, asphalt interlayer, drainage, and recycled PE ground grid groups. For these a mean alone would conceal a real spread, so the recommended database format is the representative value reported together with its range.

The remaining two groups are red in Figure 5.3, with coefficients of variation near 50%, namely the PP nonwoven geotextiles and the PET woven and knitted geotextiles. As Section 5.3 established, this dispersion is not evidence of unreliable declarations. Within these groups the relationship between mass and emissions is strongly linear, and the spread arises because each group spans a wide commercial mass per unit area range. The appropriate response is therefore not to reject these groups but to change the format in which their values are expressed, replacing a single per-square-meter figure with the mass-based emission factor, applied to the mass per unit area of the product specified.

The distribution of products across these classes shows how consequential the choice of format is. Of the 64 grouped products, 9 (14.1%) fall into green groups where a single per-square-meter value is robust, 34 (53.1%) into blue groups, and 21 (32.8%) into red groups where a single per-square-meter value would misrepresent most of the products. For the red groups, a mass-based factor combined with the specified mass per unit area is required instead. The PET woven and knitted geotextile group (G5a) retains the highest dispersion in the dataset even after separation from the PET geogrids, at 49.27%. This is only partly a matter of mass per unit area, since PET geotextiles and PET geogrids differ by nearly a factor of two in mass-based intensity because the two forms are made by different processes. Separating the two forms, as done here, removes the structural part of the spread; the residual dispersion within the woven group reflects its wide range of mass per unit area and is best handled with a mass-based factor.

5.5 Products Reported Outside the Group Structure

Sixteen of the products considered could not be placed in any of the groups without breaking the polymer or structure rule on which the grouping rests. Each EPD carries a valid declared value and is reported individually in Table 5.3, with the justification for its separate treatment. This preserves the information these declarations hold while keeping products of a different polymer or structure out of the group statistics.

Table 5.3 *Products reported as individual values, with technical grounds for separate treatment*

Product	A1–A3 (kg CO ₂ eq/m ²)	Grounds for separate treatment
Fortrac T eco	0.67	Made from recycled rather than virgin PET, giving a value 62.8% below its virgin equivalent at comparable mass per unit area. Pooling recycled and virgin routes would distort the virgin average.

Product	A1–A3 (kg CO ₂ eq/m ²)	Grounds for separate treatment
HaTelit C 40/17 eco	0.83	Same geometry and mass per unit area as the virgin product but reinforced with recycled AR glass, giving a value 22.7% lower. A feedstock variant rather than a distinct product type.
Fortrac MDT	1.79	Hybrid multi-fiber structure, predominantly PP with PVA. A blended-fiber product sits between the single-polymer groups and would bias the mean of any group it joined.
MIRAGRID PEC	1.27	A PET geogrid bonded to a PP nonwoven, so it differs in polymer from the PP reinforcement geocomposites. Its mass per unit area is not stated in the declaration, so it cannot be placed in a mass-based group and is reported individually.
BTT Terralys	0.19	Ultra-light woven PP at 92 g/m ² , for separation rather than reinforcement. Its mass regime is far below the reinforcement products.
BTT Terralys GCL	0.22	Ultra-light woven PP carrier fabric at 110 g/m ² , used as a component layer within GCL assemblies rather than as a standalone product.
BTT Coated Terralys	0.35	Woven PP with an added polymer coating, which introduces a second material system and an extra process step, so emissions per unit mass are not comparable with uncoated wovens.
BTT Terrabarrier	0.77	HDPE tape woven with a barrier coating, differing from the PP wovens in both polymer and structure.
THRACE WMM	0.52	Woven from HDPE tape rather than PP fiber, so it does not belong in the single-polymer PP groups.
ElastoSeal	3.65	EPDM synthetic rubber membrane made by vulcanized rubber compounding rather than thermoplastic extrusion. Same function as the polyolefin geomembranes but a different production system.
Firestone PondEasy	2.41	EPDM pond lining membrane, an in-scope ground application reported separately from the thermoplastic groups. Declared

Product	A1–A3 (kg CO ₂ eq/m ²)	Grounds for separate treatment
		under an older PCR (EN 15804+A1) and background database (<i>ecoinvent</i> 3.2, 2017), so it is flagged rather than pooled.
Firestone GeoSmart	4.17	EPDM agricultural lining membrane, an in-scope ground application. Same older PCR and background database as PondEasy and reported individually for the same reason.
BENTOLINER laminated	6.43	GCL with a factory-laminated PE geomembrane, 58% above the GCL mean because it contains an additional functional layer.
EUROBENT SandMat	1.07	Sand-filled mat in which the fill mass is dominated by natural sand with near-zero embodied carbon, giving a value far below bentonite-based products of similar structure.
EUROBENT TILTEX	4.13	Cement-sand mat containing hydraulic cement, whose clinker production adds a mineral-binder emission profile absent from every polymer- or bentonite-based product in the dataset.
EUROBENT GCL	1.37	Bentonite geosynthetic clay liner whose declaration draws on mixed background data and the CML method, so it is not directly comparable with the other GCLs and is reported individually rather than pooled into the GCL group.

A further four entries were excluded from the quantitative analysis. Two Firestone EPDM membranes, Gisolene and Gisolene F, are specified for roofing and building applications rather than ground engineering and so lie outside the scope of this work. The paving product GEOTER FPET was excluded as a statistical outlier, exceeding its group mean by more than a factor of four. The bare EnkaGrid MAX value of 0.0756 kg CO₂eq/m² was excluded as physically implausible, since it implies a mass-based intensity several times below that of virgin PP established in Section 5.3 and below the footprint of the raw polymer itself, pointing to a probable unit error in the declaration.

Three points stand out from Table 5.3. First, the reasons for separate treatment fall into a few recurring types, namely a different feedstock route, a different polymer, an added coating or laminated layer, or a mass regime far outside the group. These are the same factors identified in Section 5.3 as the drivers of variation, which supports the consistency of the grouping rules.

Second, separation was decided on compositional grounds rather than on the values themselves, and two products demonstrate this clearly. ElastoSeal, an EPDM membrane produced by a completely different chemistry from the extruded thermoplastic membranes, returns 3.65 kg CO₂eq/m² against a polyolefin geomembrane mean of 3.64. EUROBENT TILTEX, a cement-sand mat, returns 4.13 against a GCL mean of 4.08. Both were removed from their nearest group because their material systems differ, and in both cases the resulting value coincides almost exactly with the group they were removed from. Product level agreement of this kind does not establish that the production systems are equivalent, and the separation remains justified, but it shows that the grouping rules were applied on physical grounds and not fitted to produce tidy statistics.

Third, several of these products are the only representative of their type in the dataset, so for certain product types on the Finnish market no group-based representative value can currently be derived from published declarations. This gap is taken up in Chapter 7.

5.6 Representative values for NorGeoSpec filter geotextile classes

NorGeoSpec is a Nordic system for the specification and quality control of geosynthetics, established in 2002 by the road authorities of Finland, Sweden and Norway and administered with third-party quality control and auditing (NorGeoSpec 2012). For separation and filtration in roads and other trafficked areas it defines five specification profiles, N1 to N5, distinguished by required values for tensile strength, tensile strain, strain energy index, static puncture, dynamic perforation resistance, characteristic opening size and permeability. A designer selects a profile based on the subsoil conditions and the grain size of the fill rather than specifying each property individually, which is why the system is widely used in the Nordic countries and applied by the Finnish Transport Infrastructure Agency (NorGeoSpec 2012). Expressing the results of this work in the same terms is therefore necessary.

The profiles are defined by mechanical and hydraulic performance, not by mass, so a single product is certified in a different profile at a different mass per unit area: typically, the heavier the fabric, the higher the profile it satisfies. A declaration, by contrast, reports one product-stage emission value per kilogram, which does not itself vary with profile. The emission per square meter for a given profile therefore follows from the per-kilogram value of the product and the mass per unit area at which that product is certified in the profile, as in equation (1) of Section 4.6. For each certified product the declared mean mass per unit area and its tolerances in each profile are presented in its NorGeoSpec certificate, where they appear as the mass per unit area determined according to EN ISO

9864. The corresponding emission per square meter was obtained by multiplying the product's per-kilogram value by that given mass. Table 5.4 lists the declared masses and the per-kilogram value for each of the twelve certified filter geotextiles for which declaration data were available.

Table 5.4 Declared mean mass per unit area (g/m^2) by NorGeoSpec profile, from each product's certificate (EN ISO 9864), and the product-stage emission per kilogram from its declaration.

Product	N1	N2	N3	N4	N5	A1–A3 GWP
	mass per unit area (g/m^2)					kg CO ₂ eq/kg
Meltex MXF	87	133	183	240	325	1.83
Ahlsell Hipertex	90	135	190	260	340	2.51
Tessilbrenta Hipertex	90	135	190	260	340	3.08
Drefon ST	90	125	175	235	310	3.23
Edilfloor Geodren	90	135	190	250	340	3.25
Geo&Tex GEO PP	90	135	190	250	340	3.45
DuPont Typar	110	150	220	–	–	4.51
Bontec TS (BontexGeo NV)	85	135	195	260	345	2.25
Thrace	83	123	170	230	310	3.51
BTT Terralys	–	–	130	–	–	2.08
Fibertex F	100	130	190	255	–	2.87
BG-Text (Byggros)	85	135	195	260	345	2.05

The resulting emissions per square meter are shown in Figure 5.4 for every product across the profiles in which it is certified, with the value currently published in the database marked for each profile. Two features are visible. The emission per square meter rises steadily from N1 to N5 for every product, but this rise reflects mainly the increasing mass required by the higher profiles, since the per-kilogram intensity of a given product is nearly constant across profiles. The products also spread over a wide band within each profile, because their per-kilogram intensities differ by more than a factor of two, from 1.83 to 4.51 kg CO₂eq/kg, following the same pattern established in Section 5.3.

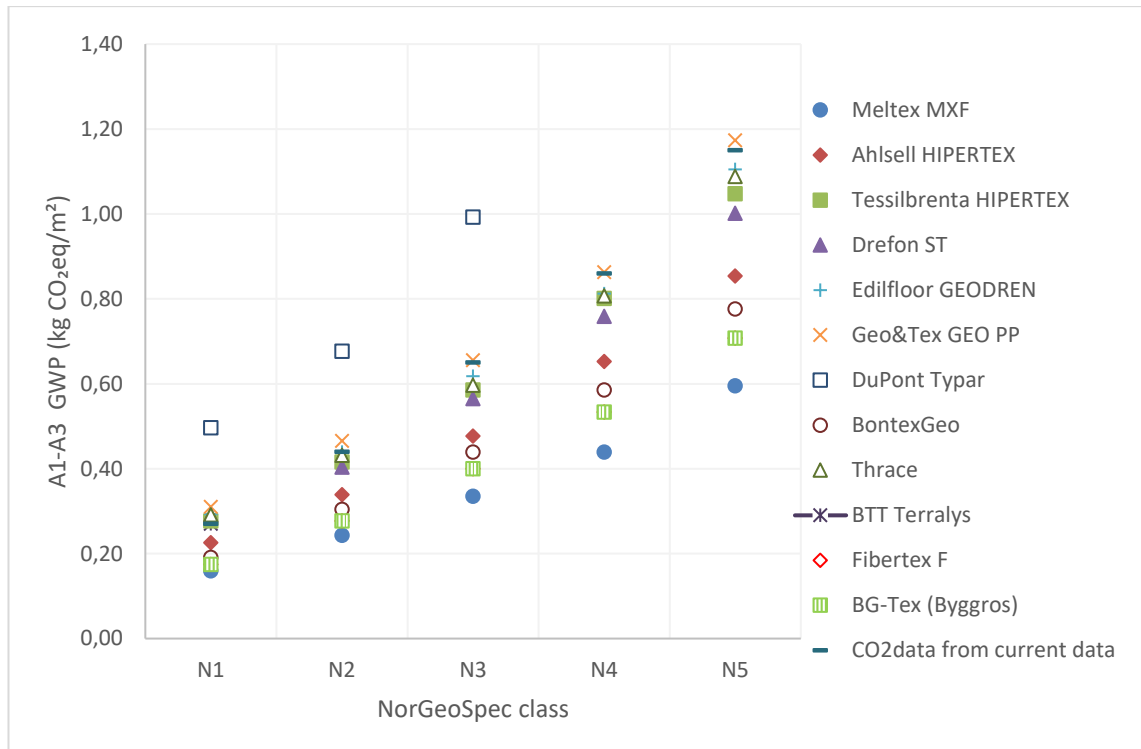


Figure 5.4 A1 to A3 GWP per square meter for the NorGeoSpec-certified filter and separation geotextiles, shown by specification profile

Averaging across the certified products gives a representative value for each profile, shown in Table 5.5 against the value currently in the database. The two agree closely at N1, but the representative values derived here fall below the current database values from N2 upward, by about 10 per cent at N2 and roughly 17 to 19 per cent at N3, N4 and N5. The current CO2data database figures are built from a single per-kilogram intensity applied to reference masses, whereas the values here rest on the actual per-kilogram intensities and certified masses of the products on the market. The difference at the higher profiles suggests that the current values published in the CO2data database may overstate the product-stage footprint of the heavier separation classes. Expressed by profile in this way, the representative values in Table 5.5 are the form in which the filter geotextile results of this work can be entered directly into the database, which is the practical purpose the analysis was intended to serve.

Table 5.5 Representative A1 to A3 GWP per square meter by NorGeoSpec profile, derived from the certified filter geotextiles, compared with the value currently published in the CO2data database

NorGeoSpec profile	N1	N2	N3	N4	N5
Representative value in this study (kg CO ₂ eq/m ²)	0.27	0.40	0.54	0.70	0.93
Coefficient of variation	33.7%	29.5%	34.4%	20.1%	21.7%
Current database value (kg CO ₂ eq/m ²)	0.27	0.44	0.65	0.86	1.15

5.7 Effect of Recycled Raw Materials

The dataset contains two matched product pairs in which a manufacturer declares the same product in both a virgin and a recycled version. In each pair the geometry, production site, and declaration methodology are identical, so the pairs isolate the effect of recycled feedstock cleanly. Both recycled products were kept out of the group statistics so that the virgin averages remain representative of virgin production.

The first pair compares Fortrac T, a virgin PET reinforcement geogrid at 352 g/m², with Fortrac T eco, the same geogrid made from 100% recycled PET at 370 g/m². The recycled version declares 0.669 kg CO₂eq/m² against 1.799 for the virgin product, a reduction of 62.8% in total A1 to A3 emissions, achieved despite the recycled variant being marginally the heavier of the two. The reduction concentrates where the mechanism predicts, with module A1 falling by 41.7% and module A3 by 92.1%. The second pair compares HaTelit C, an asphalt reinforcement made with virgin alkali-resistant glass, with HaTelit C eco, made with recycled glass at the same mass per unit area of 270 g/m². Here the total reduction is 22.7%, from 1.073 to 0.829 kg CO₂eq/m², with module A1 falling by 30.6% while module A3 rises by 15.7% (Figure 5.5).

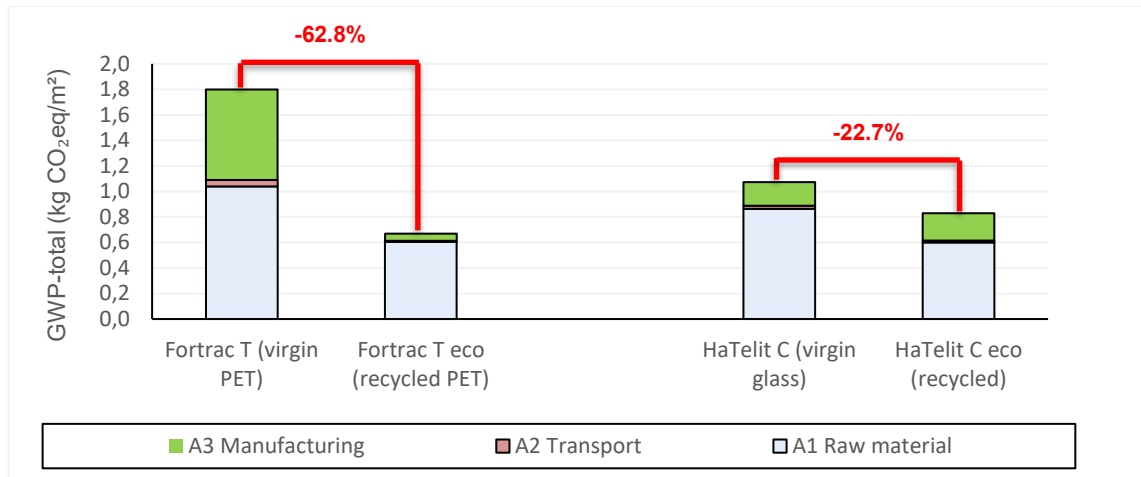


Figure 5.5 Effect of recycled raw material on A1 to A3 GWP-total for two product pairs. Each bar shows the contribution of modules A1, A2, and A3 for the virgin and recycled version of the same product, with the percentage reduction in the total indicated

The reduction in production-stage emissions is substantial but strongly material-dependent. The underlying mechanism is the displacement of virgin polymer production, which for European plastics carries between 1.91 and 5.70 kg CO₂eq/kg depending on the polymer, against approximately 0.321 kg CO₂eq/kg for the mechanical recycling route (Tenhunen-Lunkka et al. 2022). The gap between a 62.8% and a 22.7% reduction therefore reflects how much of each product's footprint sits in the material being replaced. PET fiber production is carbon-intensive, so substituting it displaces a large share, whereas alkali-resistant glass makes up 54% of the HaTelit mass and the remainder lies in the bitumen coating and carrier, which are unchanged between versions. This tracks the finding in Section 5.8 that raw material supply dominates the product stage.

Second, the rise in module A3 for the recycled glass product shows that processing recycled material can require more manufacturing energy than virgin material. The increase is small in absolute terms, 0.029 kg CO₂eq/m² against a fall of 0.264 in module A1, so the net effect remains strongly favorable, but it means recycled content should be assessed on the full A1 to A3 balance rather than on the raw material stage alone.

Third, the results support keeping virgin and recycled variants as separate database entries. Averaging the Fortrac pair would describe neither product, overstating the recycled version by nearly a factor of two and understating the virgin one by a third. This is the treatment adopted in Section 5.5. These two pairs demonstrate the effect and its order of magnitude but are too few to establish a general reduction factor for recycled content in geosynthetics. A lower carbon footprint is also not the only consideration in using partially recycled feedstock, since recycled polymers can vary in quality and their effect on long-term mechanical performance and durability requires verification. Studies

of recycled-plastic geogrids report a trade-off between stiffness and ductility, together with a need for further work on long-term and degradation behavior (Vicuña et al. 2024).

A product-level comparison against the representative values was also applied to the other geosynthetic families in the dataset. To keep the main text concise, these figures are collected in Appendix E, each showing the individual products of one family against the representative value derived for it, and, where the CO2data database currently holds a value for that product type, that value is shown for comparison. No such value exists for geomembranes, and for some barrier types few manufacturers have yet published declarations, so those figures cover the products for which data could be obtained.

5.8 Stage-Level Analysis

The preceding sections treated the product stage as a single value. Because several findings depend on where within modules A1 to A3 the emissions arise, the 55 product entries that report the three modules separately were examined individually. The remaining entries declare only an aggregated total and are absent from this analysis, as noted in Section 5.1.

Across these 55 products, module A1, raw material supply, accounts for a mean of 82.3% and a median of 85% of the product-stage GWP-total, ranging from 51% to 98.1% (Figure 5.6). This dominance is not a tendency in a few products but a structural feature of the whole dataset, holding across every polymer, product form, manufacturer, and EPD program. Module A2, transport of raw materials to the plant, contributes about 3% on average and never more than 10%, and module A3, manufacturing, accounts for the remaining 15% on average. This is the quantitative basis for earlier findings. It is why mass-based factors predict single-polymer products so well, since the footprint is largely the polymer itself, and why the recycled-content substitutions of Section 5.7 achieve reductions of the magnitude observed.

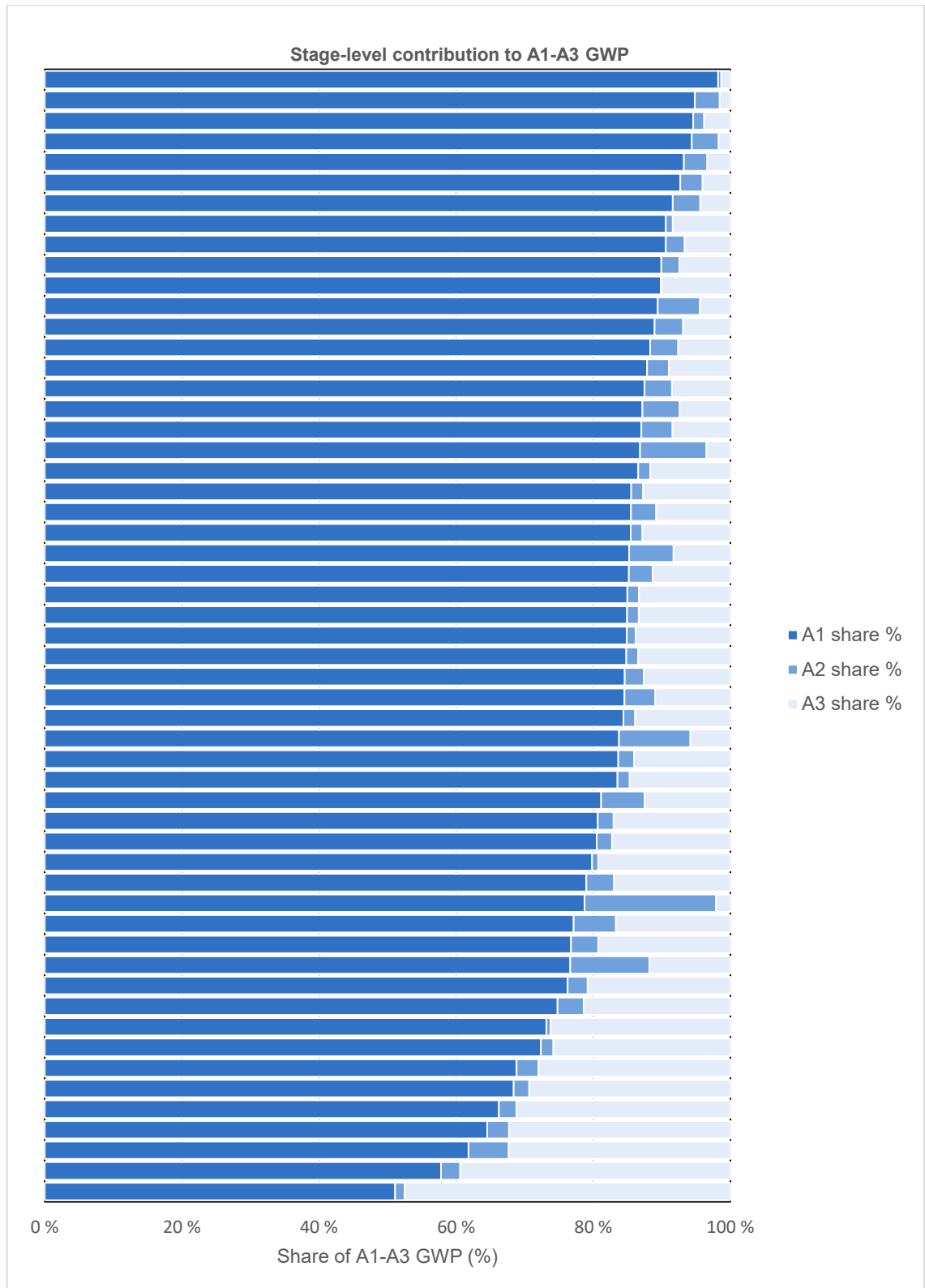


Figure 5.6 Contribution of modules A1, A2, and A3 to product-stage GWP-total for the 55 products with separately declared modules, ordered by the share of module A1

Although module A3 is the smaller contributor, its magnitude varies considerably between manufacturers, and the electricity mix at the production site is a principal reason.

The clearest instance is the comparison in Table 5.6 between two PP nonwoven geotextiles, one made in Finland and one in Greece, both declared per kilogram so that product mass does not enter the comparison (Table 5.6). The Finnish product, on an electricity mix dominated by nuclear, hydro, and wind, declares a manufacturing value of 0.08 kg CO₂eq/kg. The Greek product, on a grid dominated by gas and lignite, declares 1.03, thirteen times higher. Manufacturing accordingly accounts for 4.4% of the product-stage total for the Finnish product and 29.4% for the Greek one.

Table 5.6 *Controlled comparison of two PP nonwoven geotextiles of the same structure manufactured on national electricity grids of differing carbon intensity. Module values in kg CO₂eq/kg of product*

Product	Coun-try	Electricity mix		A1	A2	A3	A1–A3	A3 share
Meltex	Finland	Low-carbon (nuclear, hydro, wind)	(nu-	1.66	0.07	0.08	1.83	4.4%
THRACE NW	Greece	Fossil-heavy (gas, lignite)	(gas,	2.40	0.08	1.03	3.51	29.4%

Note: The ratio of module A3 between the Greek and Finnish product is 13.

This comparison should be read with care, since the two declarations differ not only in grid but also in background database, standard version, and reference year, so the difference cannot be attributed to the electricity mix alone. Its direction and scale are nonetheless consistent with the published carbon intensities of the two grids, and no other single factor plausibly accounts for a difference of this size. A related effect comes from database vintage. The ten entries identified in Section 5.1 as resting on superseded background data differ systematically from values calculated on current versions, in a direction that cannot be determined from the dataset. Both the location of manufacture and the age of the underlying data are thus real variables behind a published figure, neither of them visible in a headline per-square-meter value.

5.9 Transport to the Finnish Market

Every declaration prepares module A4 for its own market or for the scenario prescribed by its product category rules, and neither necessarily corresponds to delivery to Finland; several declarations omit the module entirely. Because the aim is a set of factors for the Finnish market, transport was calculated for all 61 products with a declared or estimated mass per unit area on a single common basis, from the manufacturing site named in

each declaration to Helsinki, as described in Section 4.6. The calculated value is expressed as a percentage of the product's own A1 to A3 total, so that the significance of transport can be compared across products of very different product-stage footprints.

Across the 61 products, transport to Helsinki amounts to a mean of 4.72% and a median of 3.77% of the product-stage total, ranging from 0.95% to 11.85% (Figure 5.7). Transport is therefore consistently a secondary contributor, never approaching the scale of module A1, but it is not uniformly negligible: 26 products fall below 3% and 27 exceed 5%. The gap between the mean and the median indicates a right-skewed distribution, in which a minority of heavy or distant products pull the mean above the typical value.

These transport figures assume mass-limited loading, in which a vehicle reaches its weight capacity before its volume. For very light, bulky products whose loading is instead limited by volume, a mass-based calculation understates transport, so the values here are best read as an indication of the typical scale of module A4 rather than an exact figure for every product.

Overall, module A4 does not change the broad ranking of product groups established on modules A1 to A3, since transport remains a small share of the product-stage footprint across the dataset. Its influence is confined to cases where two products are already close on the product stage, where the shorter route can decide the lower-carbon option, and domestic manufacture carries the smallest transport burden for this reason.

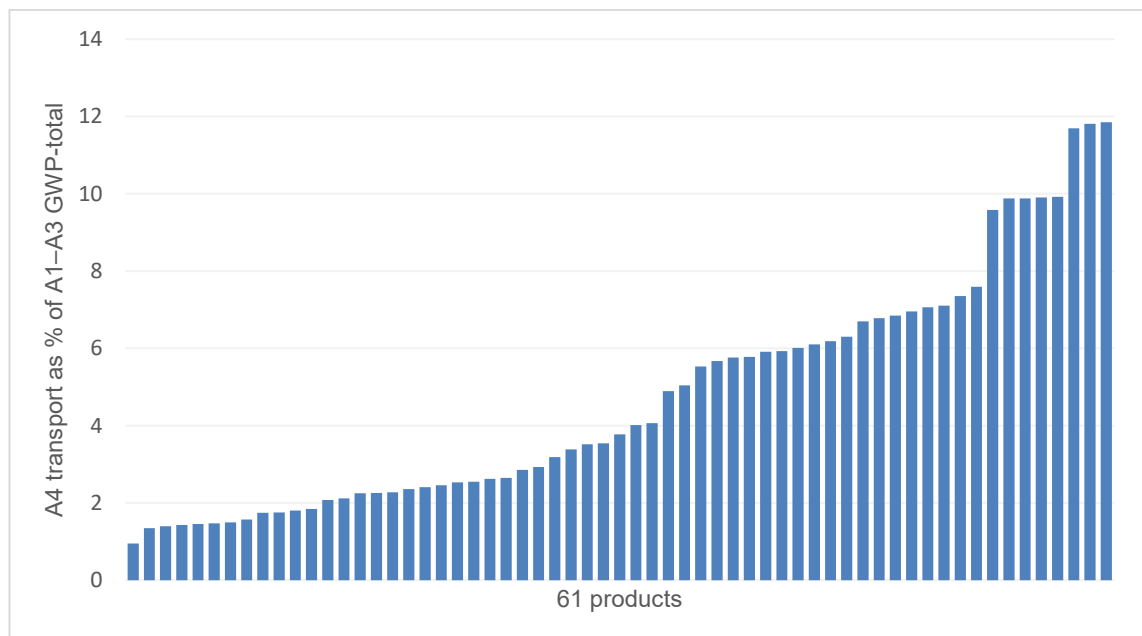


Figure 5.7 Distribution of calculated module A4 transport emissions to Helsinki, expressed as a percentage of each product's A1 to A3 GWP-total, for the 61 products with an available mass per unit area, sorted in ascending order

To make the effect of manufacturing location explicit, transport to Helsinki was calculated for a single representative filter geotextile of 200 g/m², holding the product constant and varying only the country of manufacture along the routes used in this study (Figure 5.8). On this common basis, domestic manufacture in Finland carries the smallest transport burden, at 0.007 kg CO₂eq/m². Manufacture elsewhere in the immediate region is only slightly higher, 0.011 for Germany and 0.013 for Latvia, while southern-European origins rise several-fold, to 0.030 for France, 0.035 for Italy, and 0.069 for Greece. Because the product and its mass were assumed identical in every case, the differences arise solely from route length and mode, which isolates the contribution of manufacturing location to the delivered footprint.

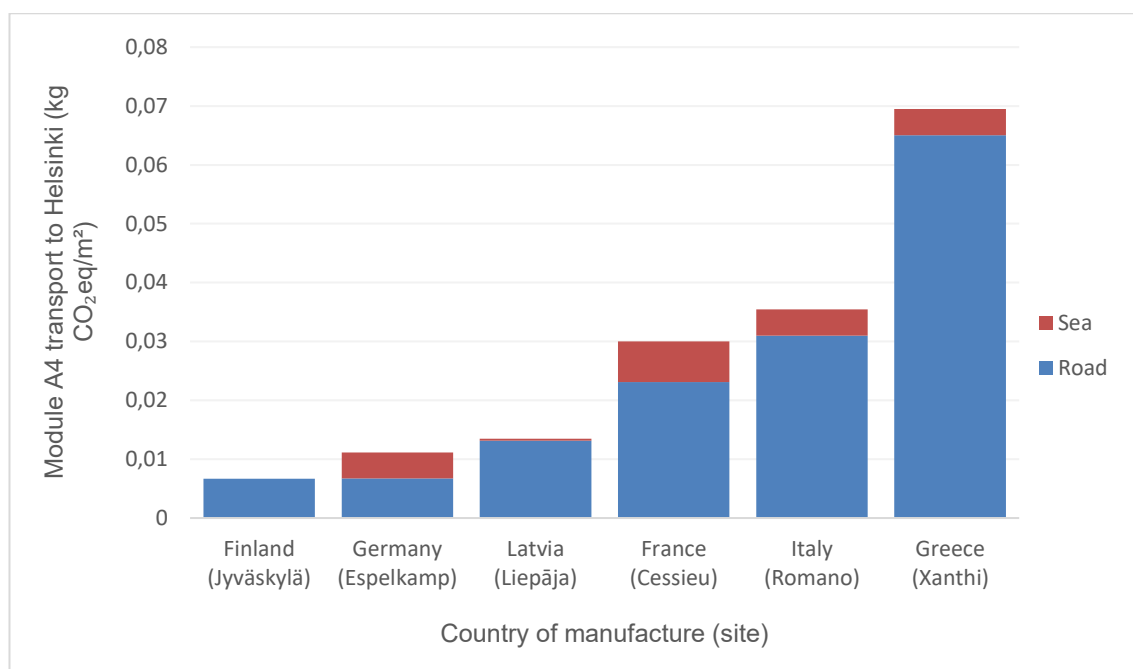


Figure 5.8 Module A4 transport emissions to Helsinki for a representative 200 g/m² filter geotextile, by country of manufacture, calculated on the route distances used in this study under a mass-limited loading assumption

5.10 Expert Interview

The interviews first establish how far the EPD process has matured for geosynthetics, since this shapes how the declarations should be read. Across all three, environmental declaration emerged as a recent and still-developing practice rather than an established routine. The Finnish manufacturer had produced its first declaration in 2024 and had nine in total, none yet through an update cycle, with data still gathered manually and no automation in place. The global manufacturer had issued its first declarations for the European market only in the previous year and had not yet defined how updates would be handled. The quality specialist at the German manufacturer described the work as still new and not part of daily responsibilities. All parties expected the practice to expand

quickly, driven by stricter transparency requirements and by forthcoming regulation that will attach emission reporting to construction product CE marking, moving EPDs from a largely voluntary exercise toward a market and legal expectation.

On comparability, the manufacturer with the widest international portfolio described heterogeneity between programs and product category rules as the principal obstacle, noting that products in the same market may be declared under construction product rules or under technical textile rules, and that declarations prepared on different bases will not yield comparable results. This echoes the screening results of Section 5.1. The Finnish producer, by contrast, had not examined the product category rules of competing declarations, which is itself informative: the incomparability documented in this thesis is not necessarily visible to the practitioners who publish into it. One interviewee observed that the geosynthetic figures previously held in CO2data derived from a generic European PP granulate value of roughly 2.1 kg CO₂eq/kg applied directly to finished fabric and identified this as the reason work of the present kind is needed. That figure is close to the generic PP granulate value carried in the background databases discussed in Section 3.1.

On scaling within product families, all three interviews independently identified a variation of about 10% in results as the operative threshold, although they applied it to different decisions. For the manufacturer and the program operator it is the limit within which a scaled value may stand in for an individually calculated one, and for the Finnish producer it is the point beyond which an existing declaration ceases to be compliant. Two of the three confirmed that mass per unit area is the variable used to scale within a family, one describing the conversion factor as simply the unit weight applied to the reference product's results. The same interviewee reported that this factor had been validated against full life cycle assessments carried out for every product in the family, with the scaled and calculated values agreeing to be within 10%. Another gave intra-family variability of 1% to 4% for nonwoven fabrics while noting that composites behave far less predictably. Both statements correspond directly to the regression results, where single-polymer products follow mass closely and geocomposites do not.

The program operator described how such scaling is verified in practice. The linear relationship is not tested on one or two results but applied across every declared impact category and module, amounting in a recent case to 592 individual values, so that a systematic error in the underlying equation becomes visible as a pattern in the residuals rather than remaining hidden in a single figure. Verification itself was described as an accredited process with strict separation of roles, in which no member of the team that

performed a calculation may verify it, and which proceeds through at least two rounds of written questions before publication.

The influence of the manufacturing electricity mix, examined in Section 5.8, was raised independently in two interviews. One manufacturer publishes separate declarations for the same product made in Germany and in Egypt specifically because the energy mixes differ. The Finnish producer confirmed that its own facility runs on 100% renewable electricity, which is the direct explanation for the low manufacturing-stage value observed for that product in Table 5.6.

On transport, the interviews clarified why declared A4 values are so heterogeneous. Transport scenarios are either prescribed by the governing product category rules, one interviewee citing the Dutch national database as an example of a fixed scenario or estimated from the cheapest realistic freight option in the absence of such a rule, and in neither case do they describe delivery to a specific national market. This confirms the premise of Section 5.9 that published A4 figures cannot be compared directly and must be calculated on a common basis for market-specific use. The Finnish producer raised a further point not visible in any declaration, namely that transported volume rather than mass can govern freight for these products, since fabric rolls of differing density occupy different amounts of a vehicle for the same delivered mass.

The most consistent theme across all interviews was the difficulty of obtaining reliable upstream data. Every interviewee identified the availability of supplier data for raw materials as the single greatest obstacle to producing a declaration, and one noted that the absence of supplier-specific declarations forces reliance on generic database values, which reduces the specificity of the result. The verification process, by contrast, was described as substantive rather than formal. One interviewee recounted a case in which the verifier identified an omission relating to Finnish electricity transmission and transformation losses, which was corrected before publication and has been included in every subsequent declaration. This supports the assumption underlying this work, that published and verified declarations may be treated as reliable within the limits of their stated methodology, and that the flags identified in Section 5.1 concern comparability between declarations rather than the correctness of any individual one.

Taken across all themes, the interviews support the principal conclusions drawn from the data. The dominance of raw material supply, the use of mass per unit area as the scaling variable, the weaker predictability of composites, the effect of the electricity mix, the incomparability of declared transport scenarios, and the methodological heterogeneity between programs were each described by practitioners without reference to the results of

this analysis, which were not shared with them. This convergence between what the declarations show and what those who produce them report adds confidence to the conclusions of this chapter.

6 DISCUSSION

This chapter interprets the results presented in Chapter 5 and considers what they mean for the use of published EPDs as a basis for national emission factors. Section 6.1 examines how reliable the proposed representative values are and what form they should take, comparing the derived factors against independently measured values reported in the literature. Section 6.2 distinguishes the two kinds of variation found between declarations and explains why screening cannot be avoided. Section 6.3 tests how far the conclusions depend on the main assumptions made in Chapter 4.

6.1 Reliability and Form of the Representative Values

The main research question posed in Chapter 1 concerns which emission factors for geosynthetic products are representative for the Finnish market. Answering it required first settling a prior question, namely whether a single figure can represent a class of these products at all. The results show that it can for some classes and cannot for others, and that the difference is systematic rather than arbitrary. For polyolefin geomembranes, where HDPE and LLDPE products vary by only 7.03%, and for GCLs, which vary by 5.71%, the small spread across several manufacturers and programs makes a single value defensible, though each of these groups rests on only a few declarations (four and three respectively), so the low variation is indicative rather than firmly established and would benefit from confirmation as more declarations become available. For more than half of the grouped products a single per-square-meter value is not adequate, because within those groups the relationship between mass and emissions is strongly linear and the spread simply reflects the range of mass per unit areas over which a product family is sold.

This distinction is the principal contribution of the work, and its consequence is a change of format rather than a rejection of data. For the mass per unit area-driven groups, a mass-based factor applied to the specified mass per unit area represents the products far better than any single value, since the regressions for single-polymer groups reach R^2 between 0.84 and 1.00 and mass therefore predicts emissions almost completely.

Because this study derives factors from published declarations rather than from measurement, external validation is the evidence it most needs. The closest available comparison is Raja et al. (2015), who measured embodied carbon directly at two geotextile

manufacturers by metering the electricity consumed on the production lines, and reported 2.35 kg CO₂eq/kg for nonwoven geotextiles, 2.36 for woven geogrids and 2.97 for extruded geogrids. The factor obtained here for PP nonwovens, 2.34, is the marginal rate at which emissions rise with product mass, while the measured figure is an average over finished products; the two nevertheless agree to within half a percent, which indicates that the mass-proportional component dominates and that any fixed component is small. The PP geogrid factor of 2.65 falls between their woven and extruded values. The two results were reached by wholly independent routes, one from metered manufacturing energy and one from regression on published declarations.

A second comparison can be made against European polymer production data. Tenhunen-Lunkka et al. (2022) report cradle-to-gate emissions of 1.91 kg CO₂eq/kg for PP resin and 2.94 for PET resin and give the conversion of resin into a finished product as adding between 0.294 and 1.14 depending on the process. The finished-product factors obtained here sit above the resin figures, as expected, with increments of 0.43 kg CO₂eq/kg for PP nonwovens and 0.74 for PP geogrids, both within the published conversion range. The ratio between the two polymers is also preserved, PET exceeding PP by a factor of 1.5 in the resin data and by 1.7 to 1.9 in the factors derived here. Those factors obtained from declared per-square-meter values and product mass per unit areas reproduce the level, the increment and the polymer ordering of independent production data indicates that the mass-based approach recovers the real material intensity of the products rather than an artifact of the declarations.

The interviews reinforce the same conclusion from practice. Mass per unit area was described as the variable manufacturers themselves use to scale results within a product family, validated internally against full life cycle assessments to within about 10%, while composites were described as far less predictable. This matches the results exactly, since the mass-based approach fails for geocomposites, whose fits fall to R² of 0.23 to 0.78, because in a multi-material product total mass is no longer a proxy for composition. The overall picture is therefore not one format but three, each following the physical nature of the product class: a single value where the product is physically constrained to a narrow mass range, a mass-based factor where the footprint follows the polymer, and a value reported with its range where multi-material construction breaks the link between mass and impact.

Expressing the filter geotextile values by NorGeoSpec profile also exposes a difference from the figures currently in the national database. The values derived here agree with the database at the lighter profiles but fall below it by around fifteen to seventeen per

cent at the heavier ones. The likely reason is methodological: the current database figures apply a single per-kilogram intensity to reference masses, whereas the values here combine the actual per-kilogram intensities of the certified products with the masses at which they are certified in each profile. Because the products on the Nordic market vary in per-kilogram intensity by more than a factor of two, a single flat intensity cannot represent the heavier profiles well, and the profile-specific values proposed here are a more defensible basis for those classes. This does not overturn the database but suggests where its filter geotextile values could be refined.

6.2 Sources of Variation and the Need for Screening

The screening in Section 5.1 flagged 50 of the 84 product entries and set aside a further four, and the analysis that followed showed that the flagged issues fall into two quite different kinds. Distinguishing them is essential, because only one kind should influence a procurement decision.

The first kind is real variation between products. Product mass is the largest single driver, followed by polymer choice, and these are genuine physical differences that a database should preserve rather than average away. The stage-level analysis reinforced this, since module A1 accounts for a mean of 82.3% of the product-stage total, so the material a product is made from, and how much of it, governs the footprint almost entirely. This agrees closely with the published figure for the same product family, Dixon et al. (2016) reporting the raw polymer at approximately 80% of a geosynthetic's embodied carbon at the factory gate. Variation of this kind is informative and should be visible to a database user.

The second kind is methodological, and it is the reason screening is unavoidable. Two declarations of the same product can differ because they use different background databases, different versions of the standard, or different characterization methods, none of which reflects any difference in the product itself. This is a documented and widespread problem. Gelowitz and McArthur (2017), reviewing 50 construction product declarations, found that 38% were missing information required by ISO 14025:2006, and that 61% of comparisons between declarations written to the same product category rules were invalid; even among declarations prepared under rules aligned to EN 15804, only 33% of comparisons were valid. More recent work demonstrates the consequences experimentally: Konradsen et al. (2024) modelled the same window product ten times, each time following a different program operator's rule, and obtained results differing by more than 10% across all impact categories, concluding that numerous different but equally compliant declarations can be produced for one product. The heterogeneity

found in the present dataset, drawn from 11 programs, is therefore not unusual but characteristic of the published EPD landscape.

The database-vintage flag is the clearest case where a methodological difference masquerades as a product difference. Seven entries rest on UVEK data built on *ecoinvent* 2.2, with feedstock data from 2005 to 2007, and three further entries on GaBi 6 from 2016, all of them outside the currency limits set by EN 15804:2012+A2:2019 (Ramesh & Lee 2025). Comparing matched datasets between *ecoinvent* 2.2 and a current version, Steubing et al. (2016) found global warming results a median of 6% higher in the newer version, with a median deviation of 13% at the level of individual datasets, driven largely by the replacement of Europe-centered supply chains with regionally appropriate ones. The direction of the effect for any individual product therefore cannot be assumed. The manufacturing-location effect documented in Section 5.8, where two otherwise similar products differed by roughly a factor of thirteen in module A3, is a related case: real, but a property of where the product was made rather than of its design.

The practical consequence is that the comparability of two declarations cannot be assumed and must be established before their values are pooled. This is why the four-criterion screening preceded all quantitative analysis in this work, and why every representative value in Chapter 5 traces back to a screening record in which the relevant flags remain visible. Averaging unscreened declarations would blend genuine product differences with methodological artifacts, producing figures that represent neither the products nor the market reliably.

6.3 Limitations and Sensitivity of the Results

The reliability of the representative values depends on how far they would change if the main assumptions were altered. Rather than listing potential shortcomings, this section examines the four assumptions most likely to affect the results and asks how much the conclusions depend on each.

Estimated mass per unit areas are the first of these. Where a declaration stated a range without a reference mass, a representative value from within that range was assigned. Because these estimates were made without reference to the emission value, they should not bias a group mean in any direction, but they add scatter to the regressions. Their effect is bounded and visible in the fits, since the groups containing most of the estimates still reach R^2 of 0.916, 0.968 and 0.935.

A second assumption concerns the flagged old-database entries, which were kept with a documented flag rather than removed. Ten entries rest on background data outside

the currency limits of EN 15804:2012+A2:2019 and deleting them would have thinned the sample across six of the groups. Recomputing every affected group without them changes the representative values by between -20.8% and $+2.8\%$. Among the low-variation groups, where a single mean is the recommended database value, the shifts are -3.4% for polyolefin geomembranes and -0.8% for GCLs, so the recommendation for those groups does not depend on the retention decision. The largest effects fall on the PP planar reinforcement products in groups G4a, G4b and G4c. Removing the flagged entries lowers their means and dispersion, with three of the four removed entries being among the highest values, so their removal reduces both the mean and the spread irrespective of why they were flagged. Because these products are already reported as blue groups in Section 5.4, the retention decision does not change their recommended database format.

The freight emission factors used in the transport calculation form a third assumption. Because equation (4) is linear in these factors, the choice scales every transport result by the same proportion and cannot alter the ranking of products. Recomputing the full set on the two other defensible bases gives a mean transport share of 3.72% if large articulated vehicles are assumed rather than the fleet average, and 3.76% if only the fuel burned in transit is counted. The value adopted here, 4.72% , is the highest of the three, so the finding that transport is a minor contributor holds under every assumption tested and rests on the least favorable of them. A further simplification is that the calculation treats loading as limited by mass, whereas wound fabric rolls are of low density and a vehicle may reach its volume limit first, a point raised independently in the interviews. The reported transport shares are therefore likely to be slight underestimates for the lightest products.

The dataset itself carries the fourth assumption. It is a convenience sample of publicly available declarations rather than a systematic sample of the market (Bryman 2016), and with no reliable sales volumes to weight by, the group means are unweighted. The effect is contained by the structure of the results: for the low-variation groups the weighting is immaterial, and for the high-variation groups the recommended mass-based format side-steps weighting because the user supplies the product mass. The limitation therefore bears mainly on the blue groups, where a value reported with its range already signals the uncertainty attached to it.

Two further limitations bound the scope rather than the numerical stability of the results. The analysis covers only the product stage, so it speaks to emissions at the factory gate and not to the whole life cycle. And the comparison between geosynthetic and conven-

tional aggregate solutions could not be carried out quantitatively, since it requires a designed structure for each alternative, the material quantities that follow from it, and haulage distances specific to a site, none of which a product declaration contains (Dixon et al. 2016).

7 CONCLUSIONS

Geosynthetics are increasingly used in Finnish infrastructure to reduce the demand for natural aggregates and realizing that benefit in low-carbon design depends on reliable product-stage emission factors for the products actually used on the market. In Finland such factors are compiled in the national CO₂data database, but for geosynthetics they have rested on generic polymer values rather than product-specific declarations. This thesis set out to determine representative product-stage carbon emission factors for the geosynthetic products used on the Finnish market, and to establish the conditions under which the published declarations behind them can be compared.

The declarations needed for this purpose were collected from manufacturers and importing companies and, where necessary, located through public EPD databases, so the dataset covers the products that could be readily accessed rather than every product on the market. Sufficient published data exists to derive representative factors for many of the geosynthetic types used in Finland, but it cannot be used without a prior assessment of comparability. Almost every collected declaration yielded a usable product-stage value, yet 50 of the 84 product entries carried at least one methodological flag, such as an outdated background database or a different set of product category rules, and 4 could not enter the analysis at all, on grounds such as falling outside the ground-engineering scope of this work or lacking an isolable product-stage value. The obstacle is therefore not only the availability of data but the unevenness in how the declarations are prepared, and data availability is itself a real limitation, since declarations do not yet exist for every product type used in Finland and some producers have not published EPDs at all. The four-criterion screening developed here, covering the EPD standard and characterization method, the background database and its reference year, the completeness of module reporting, and the scaling method and representativeness of the declared value, separates genuine product differences from differences in how the declarations were prepared.

The variation between declared values proved to be driven overwhelmingly by how much material a product contains and which polymer it is made from. This is why product mass explained almost all the variation within single-polymer groups, and why material choice is the largest lever on the footprint, although manufacturing differences, including the electricity mix at the production site, also contribute and cannot be read directly from a declaration. The effect of recycled feedstock, though substantial, was shown to depend

on the share of the footprint held by the material replaced. Transport to the Finnish market adds a mean of 4.72% of the product-stage total and is therefore a secondary contributor, although its magnitude depends on both distance and mode, and where two products are already close on their product-stage values the country of manufacture can determine which is the lower-carbon choice for a Finnish project. Beyond product mass and polymer, the comparability of the declarations themselves, their category rules, background databases, and transport assumptions, is what governs whether two published figures can be set side by side at all.

For the same type of products, these findings allow a representative factor to be determined in the form the data supports. Where a product type is physically constrained to a narrow mass range, as with geomembranes and GCLs, a single representative value is defensible, although for these classes it rests on a limited number of products. Where the footprint follows the polymer, which covers about 60% of the products examined, a mass-based factor applied to the specified mass per unit area describes a product type better than any single per-square-meter value. The factors derived for this purpose are 2.34 kg CO₂eq/kg for PP nonwoven geotextiles, 2.65 for PP geogrids, 4.44 for PET reinforcement geotextiles, and 0.90 for recycled polyethylene ground reinforcement grids. When multi-material products such as geocomposites are considered, the link between mass and emissions is no longer clear, and a value specific to the product's structure and raw materials, or a typical range where no specific product has been chosen, is the appropriate form. Virgin and recycled variants, and the woven or knitted geotextile and the geogrid forms of PET reinforcement, should be kept as separate entries rather than averaged, and transport should be added separately rather than embedded in the product-stage factor.

For the filter and separation geotextiles that dominate Nordic road construction, these representative values were expressed in the form the Finnish national CO₂data database itself uses, as a value for each NorGeoSpec profile from N1 to N5. Because a higher profile is defined by greater strength, which correlates strongly with mass per unit area, products certified in higher profiles are typically heavier, so the emission per square meter rises across the profiles even though the per-kilogram intensity remains the same, and the profile-specific values derived here fall below the figures currently published for the heavier classes. Presenting the results by profile in this way allows them to be entered directly into the database and compared against the values it currently holds.

The declarations examined here represent a first generation of EPDs for geosynthetics, and the practice is still developing. Product category rules for geosynthetics remain het-

erogeneous, and greater harmonization would remove much of the incomparability documented in this work. As producers and verifiers carry the experience of these first declarations into later ones, and as background databases are updated and the sector's electricity supply shifts toward fossil-free sources, both the consistency and the level of declared emissions can be expected to change. The screening and grouping method developed here is transferable to that evolving evidence base and to other product groups and national databases. Further work should compare geosynthetic and conventional aggregate solutions quantitatively and extend the dataset as declarations become available for the product types that currently rest on a single declaration or none at all.

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APPENDIX A: MASTER DATASET OF ENVIRONMENTAL PRODUCT DECLARATIONS

This appendix presents the full dataset underlying Chapters 5 and 6. Each row is one product entry, defined as a single product covered by an environmental product declaration. Several manufacturers publish one declaration covering a product family, so the number of product entries exceeds the number of declarations reviewed. Descriptive fields are coded, and the codes are defined in the legend below the table. Values reported per square meter are as published or converted as described in Section 4.3. Entries marked n.s. were not stated in the declaration. The screening outcome follows the four criteria of Section 4.2 and the group assignment the grouping described in Section 4.4.

Table A.1 Master dataset of the reviewed environmental product declarations

No.	Product entry	Type	Polymer	Program	PCR	Database	Year	mass per unit area (g/m ²)	A1-A3 (kg CO ₂ eq /m ²)	Status	Group
1	Geotextiles for filtration and separation, Meltex	GTX	PP	EPD Hub	Hub core	ecoinvent 3.8	2023–2024	200	0.362	IN-F	G3
2	Secutex® — Naue GmbH & Co. KG	GTX	PET/PP	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	n.s.	0.839	IN-F	G3
3	Secutex® H — Naue GmbH & Co. KG	GTX	PP	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	681	1.667	IN-F	G3
4	BontexGeo NV Nonwoven	GTX	PP	EPD DK	EN core	ecoinvent 3.7 + GaBi	2020	250	0.552	IN-F	G3
5	Geotextile MIRAFI® Geolon® PET	GTX	PET	MRPI	EN core	ecoinvent 3.6	2023	n.s.	1.552	IN-F	G5a
6	Geotextile MIRAFI® Polyfelt® — Solmax	GTX	PP	MRPI	EN core	ecoinvent 3.6	2023	n.s.	0.547	IN-F	G3
7	Geotextile MIRAFI® HMi — Solmax	GTX	PP	MRPI	EN core	ecoinvent 3.6	2023	n.s.	0.857	IN	G4b
8	Geotextile MIRAFI® Bidim® — Solmax	GTX	PP	MRPI	EN core	ecoinvent 3.6	2023	n.s.	0.518	IN	G3
9	Drefon® ST (average product, 191 g/m ²) — Manifattura Fontana	GTX	PP	IES	2019:14	ecoinvent 3.8	2020	191	0.612	IN-F	G3
10	Drefon® S (average product, 556 g/m ²) — Manifattura Fontana	GTX	PP	IES	2019:14	ecoinvent 3.8	2020	556	1.638	IN-F	G3
11	Woven polyester high strength geotextile (GTX TeleVev & GTX TeleEnviro) - Tele Textile Latvia SIA	GTX	PET	IES	2019:14	ecoinvent 3.10	2022	345	2.439	IN-F	G5a

No.	Product entry	Type	Polymer	Program	PCR	Database	Year	mass per unit area (g/m ²)	A1-A3 (kg CO ₂ eq /m ²)	Status	Group
12	Ringtrac® — HUESKER	GTX	PET	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2024	n.s.	3.106	IN	G5a
13	Stabilenka® — HUESKER	GTX	PET	Kiwa BCS	PCR B TT	ecoinvent 3.5	2018	n.s.	3.591	IN-F	G5a
14	Stabilenka® Xtreme — HUESKER	GTX	PVA	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2024	n.s.	3.948	IN	G8
15	NOTEX® GX range — AFITEXINOV	GTX	PET	IES	2019:14	ecoinvent 3.10	2023	n.s.	1.640	IN	G5a
16	GEOTER® WPET range — AFITEXINOV	GTX	PET	IES	2019:14	ecoinvent 3.10	2023	n.s.	5.460	IN	G5a
17	THRACE NW/SNW/PNW	GTX	PP	IES	2012:01	ecoinvent 3.5 + GaBi	2019–2020	200	0.703	IN-F	G3
18	THRACE CNW/G_EX	GTX	PP	IES	2012:01	ecoinvent 3.5 + GaBi	2019–2020	200	0.703	IN-F	G3
19	THRACE WG/WGPB/TPG	GTX	PP	IES	2012:01	ecoinvent 3.5 + GaBi	2019–2020	150	0.544	IN-F	G4b
20	THRACE WMT/HF	GTX	HDPE	IES	2012:01	ecoinvent 3.5 + GaBi	2019–2020	150	0.526	IN-F	G4b
21	THRACE WMM	GTX	HDPE	IES	2012:01	GaBi/Sphera	2019–2020	150	0.525	IN-F	outside
22	Ahlsell Geotess Geotextile (90–700 g/m ²)	GTX	PP	IES	2019:14	GaBi/Sphera	2022	550	1.397	IN-F	G3
23	Edilfloor Geodren (avg product)	GTX	PP	IES	2019:14	ecoinvent 3.8	2020	201	0.632	IN	G3
24	Geo&Tex 2000 GEO PP/TEX PP (65-1550 g/m ²)	GTX	PP	IES	2019:14	ecoinvent+ EF (v n.s.)	2021	250	0.855	IN-F	G3
25	DuPont Tytar (100 g/m ² ref, scalable 30–400)	GTX	PP	IBU	IBU TT	GaBi/Sphera	2021	100	0.451	IN-F	G3
26	Tessilbrenta Hipertex/Hipertex Z (avg product)	GTX	PP	IES	2019:14	ecoinvent 3.8	2022	250	0.767	IN-F	G3
27	BTT Terralys (Group 1, woven PP, 92 g/m ² ref)	GTX	PP	IES	2019:14	GaBi/Sphera	2020	92	0.187	IN-F	outside
28	BTT Coated Terralys (Group 2, woven PP+coating, 167 g/m ² ref)	GTX	PP	IES	2019:14	GaBi/Sphera	2020	167	0.347	IN-F	outside
29	BTT Terralys GCL (Group 3, woven PP, 110 g/m ² ref)	GTX	PP	IES	2019:14	GaBi/Sphera	2020	110	0.223	IN-F	outside
30	BTT Terrabarrier (Group 4, woven HDPE+coating, 365 g/m ² ref)	GTX	HDPE	IES	2019:14	GaBi/Sphera	2020	365	0.773	IN-F	outside
31	Secugrid PP (Naue GmbH & Co. KG)	GGR	PP	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	313	0.825	IN-F	G4a
32	Secugrid PET (Naue GmbH & Co. KG)	GGR	PET	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	583	2.242	IN-F	G5b
33	EnkaGrid MAX (Freudenberg Performance Materials)	GGR	PP	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2022	1011	0.076	EX	excluded
34	MIRAGRID GX (Solmax)	GGR	PET	MRPI	EN core	ecoinvent 3.6	2024	n.s.	0.911	IN	G5b
35	Fortrac MDT (HUESKER Synthetic GmbH)	GGR	PVA	Kiwa BCS	PCR B TT	ecoinvent 3.5	2018	370	1.787	IN-F	outside
36	Fortrac T (HUESKER Synthetic GmbH)	GGR	PET	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2024	352	1.799	IN-F	G5b
37	Fortrac T eco (HUESKER Synthetic GmbH)	GGR	PET (rec.)	Kiwa-EE	Kiwa GS	ecoinvent 3.19	2024	370	0.669	IN-F	outside
38	NOTEX C range (AFITEXINOV)	GGR	PET	IES	2019:14	ecoinvent 3.10	2023	220	1.370	IN	G5b
39	NOTEX PVA C range (AFITEXINOV)	GGR	PVA	IES	2019:14	ecoinvent 3.10	2023	667	3.820	IN	G8
40	Tensar TX140 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	175	0.412	IN	G4a

No.	Product entry	Type	Polymer	Program	PCR	Database	Year	mass per unit area (g/m ²)	A1-A3 (kg CO ₂ eq /m ²)	Status	Group
41	Tensar TX150 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	205	0.464	IN	G4a
42	Tensar TX160 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	220	0.540	IN	G4a
43	Tensar TX170 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	273	0.598	IN	G4a
44	Tensar TX180 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	315	0.738	IN	G4a
45	Tensar TX190 (Tensar International)	GGR	PP	Kiwa-EE	PCR B GS	ecoinvent 3.6	2022	300	0.745	IN	G4a
46	ECORASTER E50 (Purus Plastics GmbH)	GGR	PE (rec.)	IES	2012:01	ILCD/ei	2016	9550	8.460	IN-F	G9
47	ECORASTER E40 (Purus Plastics GmbH)	GGR	PE (rec.)	IES	2012:01	ILCD/ei	2016	5220	4.580	IN-F	G9
48	ECORASTER S50 (Purus Plastics GmbH)	GGR	PE (rec.)	IES	2012:01	ILCD/ei	2016	6840	5.980	IN-F	G9
49	Geocomposite MIRAGRID PEC	GCO	PET/PP	MRPI	MRPI v4.0	ecoinvent 3.6	2024	n.s.	1.270	IN	outside
50	Combigrd 30/30 Q1 GRK 4 C	GCO	PP	Kiwa BCS	Kiwa GS	GaBi 6	2020	350	1.400	IN-F	G4c
51	Combigrd 40/40 Q1 GRK 4 C	GCO	PP	Kiwa BCS	Kiwa GS	GaBi 6	2020	390	1.480	IN-F	G4c
52	Combigrd 60/60 Q1 GRK 4 C	GCO	PP	Kiwa BCS	Kiwa GS	GaBi 6	2020	510	1.810	IN-F	G4c
53	EnkaGrid MAX C lightest grade (245 g/m ²)- EnkaGrid MAX 20C/M110PP	GCO	PP	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2026	245	0.622	IN-F	G4c
54	EnkaGrid MAX C (351 g/m ²)	GCO	PP	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2026	351	0.839	IN-F	G4c
55	EnkaGrid MAX C — EnkaGrid MAX 60PP/M160PP (heaviest grade)	GCO	PP	Kiwa-EE	Kiwa GS	ecoinvent 3.9.1	2026	521	1.187	IN-F	G4c
56	Asphalt reinforcement MIRAGRID PGM-G	GCO	Glass/PET	MRPI	EN core	ecoinvent 3.6	2024	n.s.	0.804	IN	G6
57	HaTelit C 40/17	GCO	Glass/PET	Kiwa-EE	PCR B TT	ecoinvent 3.5	2021	270	1.073	IN-F	G6
58	HaTelit C 40/17 eco	GCO	Glass(r)/PET	Kiwa-EE	PCR B TT	ecoinvent 3.5	2021	270	0.829	IN-F	outside
59	HaTelit XP 50	GCO	Glass/PET	Kiwa-EE	PCR B TT	ecoinvent3.5	2021	240	0.651	IN-F	G6
60	SamiGrid XP 50 S	GCO	PET	Kiwa	PCR B TT	ecoinvent 3.6	2022	520	1.023	IN-F	G6
61	NOTEX GLASS C range	GCO	Glass/PET	IES	2019:14	ecoinvent 3.10	2025	417	1.540	IN	G6
62	GEOTER FPET range	GCO	PET/PP	IES	2019:14	ecoinvent 3.10	2025	n.s.	4.280	EX	excluded
63	Secudrain	GCO	PP	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	819	2.202	IN-F	G7
64	FABRINET double-sided drainage geocomposite	GCO	HDPE/PP	MRPI	EN core	ecoinvent 3.6	2025	n.s.	3.832	IN	G7
65	EnkaDrain and Enka Break	GCO	PP	Kiwa-EE	Kiwa GS	ecoinvent 3.6	2022	978	3.208	IN-F	G7
66	Maccaferri MacDrain W 1071 (720 g/m ²)	GCO	PP	Kiwa-EE	PCR B GS	GaBi/Sphera	2022	720	1.730	IN-F	G7
67	TeMa Q-Drain C (average of product range, pyramidal/bicuspid core, thickness 15-20mm)	GCO	PP	IES	2019:14	ecoinvent 3.7.1	2020	n.s.	2.254	IN-F	G7
68	TeMa Q-Drain ZW (average of product range, wavy core, thickness 5-9mm)	GCO	PP	IES	2019:14	ecoinvent 3.7.1	2020	n.s.	2.296	IN-F	G7
69	Carbofol	GMB	HDPE	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	1703	4.025	IN-F	G1

No.	Product entry	Type	Polymer	Program	PCR	Database	Year	mass per unit area (g/m ²)	A1-A3 (kg CO ₂ eq /m ²)	Status	Group
70	GSE-HD	GMB	HDPE	MRPI	EN core	ecoinvent 3.6	2023	n.s.	3.513	IN	G1
71	GSE-LL	GMB	LLDPE	MRPI	EN core	ecoinvent 3.6	2023	n.s.	3.566	IN	G1
72	GSE-TP	GMB	PP	MRPI	EN core	ecoinvent 3.6	2023	n.s.	3.475	IN	G1
73	ElastoSeal	GMB	EPDM	IES	2019:14	ecoinvent 3.8	2021	n.s.	3.650	IN	outside
74	Firestone Gisolene (EPDM roofing membrane, 1.2mm)	GMB	EPDM	IES	2012:01	ecoinvent 3.2	2017	1230	4.14	EX	excluded
75	Firestone PondEasy (EPDM pond lining membrane, 0.8mm)	GMB	EPDM	IES	2012:01	ecoinvent 3.2	2017	765	2.41	IN-F	outside
76	Firestone GeoSmart (EPDM agricultural lining membrane, 1.2mm)	GMB	EPDM	IES	2012:01	ecoinvent 3.2	2017	1230	4.17	IN-F	outside
77	Firestone Gisolene F (EPDM facades membrane, 0.75mm)	GMB	EPDM	IES	2012:01	ecoinvent 3.2	2017	710	1.95	EX	excluded
78	Bentofix® — Naue	GBR-C	Bent. /PP	Naue	IES CP v2.3	ecoinvent 2.2 (UVEK)	2019	5093	4.15	IN-F	G2
79	BENTOLINER® laminated — Solmax	GBR-C	Bent. /PP	MRPI	EN core	ecoinvent 3.6	2023	5100	6.43	IN-F	outside
80	BENTOLINER® — Solmax	GBR-C	Bent. /PP	MRPI	EN core	ecoinvent 3.6	2023	4000	3.82	IN	G2
81	BENTOMAT® — CETCO	GBR-C	Bent. /PP	ITB	ITB-PCR A	ecoinvent 3.6	2017	n.s.	4.27	IN-F	G2
82	EUROBENT GCL / GCL CS	GBR-C	Bent. /PP	ITB	ITB-PCR A	ecoinvent 3.6	2022	n.s.	1.37	IN-F	outside
83	EUROBENT SandMat	GCO	Sand/PP	ITB	ITB-PCR A	ecoinvent 3.6	2022	n.s.	1.07	IN	outside
84	EUROBENT TILTEX / TILTEX PLUS	GCO	Cem. /PP	ITB	ITB-PCR A	ecoinvent 3.6	2022	n.s.	4.13	IN	outside

Legend

Type. GTX geotextile, GGR geogrid, GCO geocomposite, GMB geomembrane, GBR-C clay geosynthetic barrier; under ISO 10318 the suffix denotes the barrier material, -B bituminous, -C clay, -P polymeric.

Polymer. The dominant polymer or filler by mass. A solidus separates the two components of a composite product. Bent. bentonite, Cem. cement, (rec.) recycled feedstock. Other polymer abbreviations are given in the list of symbols and abbreviations.

EPD prog. IES International EPD System, MRPI Stichting MRPI, Kiwa-EE Kiwa-Ecobility Experts, Kiwa BCS Kiwa BCS Öko-Garantie, EPD Hub EPD Hub Limited, Kiwa Kiwa GmbH, Naue manufacturer-operated program, EPD DK EPD Danmark, IBU Institut Bauen und Umwelt, ITB Building Research Institute, Poland.

PCR. 2019:14 and 2012:01 construction products PCR of the International EPD System; IES CP v2.3 International EPD System PCR for construction products; Kiwa GS Kiwa-Ecobility Experts PCR for geosynthetic products; PCR B GS Part B PCR for geosynthetic products; PCR B TT Part B PCR for technical textiles; MRPI v4.0 MRPI PCR; IBU TT IBU PCR for technical textiles; ITB-PCR A ITB PCR Part A; Hub core EPD Hub core PCR; EN core the core PCR of EN 15804 alone, where no sector PCR was named.

Background database. EF Environmental Footprint database; (v n.s.) version not stated.

Screening outcome. IN (include) meets all four criteria of Section 4.2 without qualification; IN-F (include with flag) carries a documented comparability issue that does not justify exclusion, with the justification given in Appendix B; EX (exclude) could not enter the quantitative analysis.

Group. G1 to G9 the subgroups of Section 5.4; outside retained and reported individually in Section 5.5; excluded not used in any quantitative statistics.

n.s. Not stated in the declaration.

APPENDIX B: SCREENING JUSTIFICATIONS

This appendix records the written justification for every product entry assigned the status INCLUDE WITH FLAG (IN-F) or EXCLUDE (EX) in the comparability screening of Section 4.2. Entry numbers correspond to Appendix A. Entries assigned the status INCLUDE carried no documented issue and are therefore not listed.

Table B.1. Screening justification for each flagged and excluded product entry

No.	Product entry	Screening outcome	Justification
1	Geotextiles for filtration and separation, Meltex	IN-F	Mass per unit area estimated (200 g/m ²).
2	Secutex® — Naue GmbH & Co. KG	IN-F	Old background database: UVEK LCI based on Ecoinvent v2.2 (2010) and PlasticsEurope data from 2005–07. Values may differ from those calculated on current database versions.
3	Secutex® H — Naue GmbH & Co. KG	IN-F	Same database flags as Secutex. Internal verification only. Additionally heavier product (681 g/m ²) — mass per unit area drives higher absolute values per m ² .
4	BontexGeo NV Nonwoven	IN-F	Different program operator (EPD Danmark, not EPD International) with its own PCR approach - comparability with EPD International dataset entries requires documentation; A1-A3 declared as one combined module, no individual stage breakdown available; Mass per unit area not stated - 250 g/m ² applied as mid-range estimate - flagged as estimated, not a declared EPD value.
5	Geotextile MIRAFI® Geolon® PET	IN-F	Scaling EPD — reference product MIRAFI Geolon PET 100S selected as worst case because product group variance exceeds allotted percentage. Value may overstate typical product performance.
6	Geotextile MIRAFI® Polyfelt® — Solmax	IN-F	Scaling EPD — reference product MIRAFI Polyfelt TS selected as worst case. Same issue as Geolon PET. Two production sites (Austria, France) — geographic averaging not documented.
9	Drefon® ST (average product, 191 g/m ²) — Manifattura Fontana	IN-F	Background database version not declared. Electricity modelled using Italian residual mix (AIB 2020) — not declared as a factor value. A4 and A5 not declared — system boundaries narrower than other EPDs.
10	Drefon® S (average product, 556 g/m ²) — Manifattura Fontana	IN-F	Same flags as Drefon ST. Identical A3 value to Drefon ST — only A1 differs due to product density.
11	Woven polyester high strength geotextile (GTX TeleVev & GTX TeleEnviro) - Tele Textile Latvia SIA	IN-F	A1-A3 stage breakdown not separately declared (combined total only); PET reinforcement, high per-kg intensity; Latvian residual electricity 0.610 kg CO ₂ eq /kWh is very high.
13	Stabilenka® — HUESKER	IN-F	EN 15804+A1 (older standard); data year 2018; Ecoinvent v3.5/3.6; electricity not declared; scaling EPD.
17	THRACE NW/SNW/PNW	IN-F	EN 15804+A1 (older standard) GWP characterization factors differ from A2. Greek electricity grid mix used — higher carbon intensity than Western European averages. Cradle-to-gate only (A1–A3).
18	THRACE CNW/G_EX	IN-F	Same flags as THRACE NW/SNW/PNW. Greek electricity grid mix. Cradle-to-gate only.
19	THRACE WG/WGPB/TPG	IN-F	EN 15804+A1. Greek electricity grid mix. Cradle-to-gate only. GaBi database version not declared.
20	THRACE WMT/HF	IN-F	Same flags as WG/WGPB/TPG. Mixed raw material (PP + HDPE) unique within woven subgroup.
21	THRACE WMM	IN-F	Same flags as WG/WGPB/TPG. HDPE-dominant raw material (95%) fundamentally different polymer from all other products in table.
22	Ahlsell Geotess Geotextile (90–700 g/m ²)	IN-F	Multi-product average; per-kg unit requires mass per unit area for conversion.
24	Geo&Tex 2000 GEO PP/TEX PP (65–1550 g/m ²)	IN-F	Database version unconfirmed; A1-A3 combined; specific data share only 10%; no reference mass per unit area stated.

No.	Product entry	Screening outcome	Justification
25	DuPont Typar (100 g/m ² ref, scalable 30–400)	IN-F	Different program operator (IBU) and PCR (Technical Textiles 2013, not PCR 2019:14); A1-A3 combined.
26	Tessilbrenta Hipertex/Hipertex Z (avg product)	IN-F	A1-A3 combined; no reference mass per unit area stated.
27	BTT Terralys (Group 1, woven PP, 92 g/m ² ref)	IN-F	A1-A3 declared as one combined module, no individual stage breakdown.
28	BTT Coated Terralys (Group 2, woven PP+coating, 167 g/m ² ref)	IN-F	A1-A3 combined; C4-type composite structure (geotextile base + separate coating layer changes the emission profile)
29	BTT Terralys GCL (Group 3, woven PP, 110 g/m ² ref)	IN-F	A1-A3 declared as one combined module; NOTE: product name includes 'GCL' but this is a woven PP geotextile component, not a complete bentonite GCL assembly
30	BTT Terrabarrier (Group 4, woven HDPE+coating, 365 g/m ² ref)	IN-F	Included in geotextile master table per EPD self-classification (EPD declares 4 'woven geotextile' product groups including this one). However: base polymer is HDPE not PP (differs from Terralys/Terralys GCL/Coated Terralys which are PP-based); GWP (0.773 kg CO ₂ eq /m ²) is over 4x higher than Terralys at comparable production line, consistent with a barrier/containment function rather than separation/filtration.
31	Secugrid PP (Naue GmbH & Co. KG)	IN-F	Old background DB (Ecoinvent v2.2, 2010); internal verification only; German grid undeclared.
32	Secugrid PET (Naue GmbH & Co. KG)	IN-F	Old background DB (Ecoinvent v2.2, 2010); internal verification only; German grid undeclared; same EPD as Secugrid PP.
33	EnkaGrid MAX (Freudenberg Performance Materials)	EXCLUDE	A4 and A5 not declared; very heavy reference mass per unit area (1011 g/m ²); scaling EPD; A1-A3 per-kg value anomalously low
35	Fortrac MDT (HUESKER Synt-hetic GmbH)	IN-F	EN 15804+A1 (older CML characterization); 2018 data; scaling EPD; multi-fiber polymer mix (PVA+PP+PET) not comparable with PET-only subgroup.
36	Fortrac T (HUESKER Synthetic GmbH)	IN-F	Scaling EPD; high German residual grid factor (0.799 kg CO ₂ /kWh) drives high A3; virgin PET raw material.
37	Fortrac T eco (HUESKER Synt-hetic GmbH)	IN-F	Scaling EPD; 100% recycled PET raw material — A1 41.7% lower than the virgin equivalent at the same mass per unit area, and 62.8% lower in the A1–A3 total; report separately from virgin PET mean.
46	ECORASTER E50 (Purus Plastics GmbH)	IN-F	EN 15804+A1 (older standard); EPD validity expired 2023 (oldest in dataset); 2016 reference data; cradle-to-gate only (no downstream); different product type and function— not substitutable with soil reinforcement geogrids.
47	ECORASTER E40 (Purus Plastics GmbH)	IN-F	Same flags as ECORASTER E50.
48	ECORASTER S50 (Purus Plastics GmbH)	IN-F	Same flags as ECORASTER E50.
50	Combigrid 30/30 Q1 GRK 4 C	IN-F	EN 15804:2012+A1:2013 (older standard); stage breakdown not available (A1-A3 total only); internal verification; EPD validity expired Feb 2025.
51	Combigrid 40/40 Q1 GRK 4 C	IN-F	Same flags as Combigrid 30/30; EPD validity expired Feb 2025.
52	Combigrid 60/60 Q1 GRK 4 C	IN-F	Heaviest Combigrid variant; same flags as 30/30 and 40/40; EPD validity expired Feb 2025.
53	EnkaGrid MAX C lightest grade (245 g/m ²) - EnkaGrid MAX 20C/M110PP	IN-F	ANOMALOUS: negative A2 value (-0.0062) likely recycled content credit; A3=0 for second product variant; A1-A3 (0.622); Values calculated by applying EPD fixed+scalable decomposition, No pre-combined product table available in EPD. Calculation methodology follows Kiwa-EE GPI R.4.0 Annex B1.
54	EnkaGrid MAX C (351 g/m ²)	IN-F	ANOMALOUS: negative A2 value (-0.0062) likely recycled content credit; A3=0 for second product variant; A1-A3 (0.839); Values calculated by applying EPD fixed+scalable decomposition, No pre-combined product table available in EPD. Calculation methodology follows Kiwa-EE GPI R.4.0 Annex B1.
55	EnkaGrid MAX C — EnkaGrid MAX 60PP/M160PP (heaviest grade)	IN-F	ANOMALOUS: negative A2 value (-0.0062) likely recycled content credit; A3=0 for second product variant; A1-A3 (1.187); Values calculated by applying EPD fixed+scalable decomposition, No pre-combined product table available in EPD. Calculation methodology follows Kiwa-EE GPI R.4.0 Annex B1.
57	HaTelit C 40/17	IN-F	DB version not stated; A1-A3 calculated as sum of stages (1.073); bitumen coating drives A1.
58	HaTelit C 40/17 eco	IN-F	Recycled glass fiber — A1 reduced 30.6% vs virgin HaTelit C at same mass per unit area; A3 slightly higher (different process energy profile); report separately from virgin glass products; same DB flags as HaTelit C.
59	HaTelit XP 50	IN-F	No glass fiber — lower A1 than glass-containing products; same DB flags as other HaTelit products.

No.	Product entry	Screening outcome	Justification
60	SamiGrid XP 50 S	IN-F	Sand coating increases mass per unit area to 520 g/m ² vs 240-270 for other asphalt reinforcement; same DB flags.
62	GEOTER FPET range	EX	Extreme product range: A1-A3 from 1.96 to 16 kg CO ₂ /m ² across variants; 4.28 is production-weighted average for 2024 sales — very high uncertainty; mass per unit area not stated; dual-function product; excluded from representative value.
63	Secudrain	IN-F	Old background database (UVEK LCI / Ecoinvent v2.2, 2010) — same flag as all Naue EPDs; German grid undeclared; no D declared.
65	EnkaDrain and Enka Break	IN-F	Single EPD covering the entire EnkaDrain/EnkaBreak range (41 products) via a linear mass-scaling function; represented here as ONE product line at the reference weight 0.978 kg/m ² . A4/A5 not declared; D declared. A1 dominance 87.0% of A1-A3. Ecoinvent v3.6 (2019) acceptable but not the newest. GWP-biogenic small negative in scalable part.
66	Maccaferri MacDrain W 1071 (720 g/m ²)	IN-F	Different program operator (Kiwa-EE) and PCR (geosynthetics-specific PCR B, not PCR 2019:14); A1-A3 declared as one combined module, no individual stage breakdown; A1-A3 contribution clearly dominant per EPD's own interpretation chart (~96% of total impact for most categories, other modules ~4%).
67	TeMa Q-Drain C (average of product range, pyramidal/bicuspoid core, thickness 15-20mm)	IN-F	Ecoinvent 3.7.1 is older than the v3.8+ threshold but still reasonably current for 2020 reference year; mass per unit area not stated - per-m ² conversion requires an assumed reference mass per unit area; A1 dominance confirmed (92.9% of A1-A3).
68	TeMa Q-Drain ZW (average of product range, wavy core, thickness 5-9mm)	IN-F	Ecoinvent 3.7.1 is older than the v3.8+ threshold but still reasonably current for 2020 reference year; Mass per unit area not stated - per-m ² conversion requires an assumed reference mass per unit area; A1 dominance confirmed (93.3% of A1-A3); GWP-total essentially identical to Q-Drain C (within 1.9%) despite different core geometry.
69	Carbofol	IN-F	Old DB (Ecoinvent v2.2, 2010); internal verification; CB modelled as HDPE.
74	Firestone Gisolene (EPDM roofing membrane, 1.2mm)	EX	Roofing membrane (building envelope), outside the infrastructure ground-application scope of this work. Not used in any quantitative statistic.
75	Firestone PondEasy (EPDM pond lining membrane, 0.8mm)	IN-F	In-scope ground application (pond lining), reported individually in Section 5.5 as a single EPDM entry rather than pooled, since the dataset holds too few EPDM membranes to form a group. Flagged for an older PCR (EN 15804+A1, 2012, CML-IA characterization) and an older background database (ecoinvent 3.2, 2017) than used across the rest of the dataset. A1-A3 is declared (2.41 kg CO ₂ eq/m ²); only A4 cannot be isolated, as transport is bundled with C1-C4 downstream.
76	Firestone GeoSmart (EPDM agricultural lining membrane, 1.2mm)	IN-F	In-scope ground application (agricultural lining), reported individually in Section 5.5 for the same reason as PondEasy. Flagged for the same older PCR (EN 15804+A1) and background database (ecoinvent 3.2, 2017). A1-A3 is declared (4.17 kg CO ₂ eq/m ²); only A4 cannot be isolated.
77	Firestone Gisolene F (EPDM facades membrane, 0.75mm)	EX	Facade membrane (building envelope), outside the infrastructure ground-application scope of this work. Not used in any quantitative statistic.
78	Bentofix® — Naue	IN-F	Old background DB (Ecoinvent v2.2, 2010), Internal verification only, A3 may differ from values calculated on current database versions.
79	BENTOLINER® laminated — Solmax	IN-F	Contains HDPE geomembrane layer (21% PE by mass); Functionally different from GCL; Assigned to separate subgroup.
81	BENTOMAT® — CETCO	IN-F	Data year 2017 — older dataset, A4 and A5 not declared — narrower scope, High A2 (0.819) complex international bentonite supply chain.
82	EUROBENT GCL / GCL CS	IN-F	Mixed background data (multiple ecoinvent versions); CML method applied; not directly comparable with other GCLs; reported individually rather than pooled.

APPENDIX C: TRANSPORT ROUTES AND MODULE A4 RESULTS

This appendix documents the transport calculation reported in Section 5.9. Module A4 covers transport from the manufacturing site to the construction site, which is taken as Helsinki throughout as a single reference point of delivery. In total, 27 routes were defined, one for each manufacturing site in the dataset. Road distances were obtained from route planning between the manufacturing site and the port of departure, and sea distances between the port of departure and the port of Helsinki. Routes were defined for every manufacturing site, including sites whose products could not enter the calculation for want of a stated mass.

Emission factors were taken from the greenhouse gas conversion factors published by the UK Department for Energy Security and Net Zero (DESNZ 2026). Road freight is represented by the average non-refrigerated heavy goods vehicle at average laden weight and sea freight by the average container ship. Both are expressed on a well-to-wheel basis, obtained by summing the in-transit factor from the Freightling goods worksheet and the corresponding upstream fuel production factor from the WTT worksheet. This gives 0.12715 kg CO₂eq per tonne-kilometer for road and 0.01977 for sea. The scenario assumes full vehicle utilization with no empty return journeys, and transport limited by mass rather than by volume.

Module A4 could be calculated for 61 of the 80 product entries retained in the analysis. Sixteen entries could not be included because the declaration states no mass per unit area, and transport emissions are proportional to transported mass. One further entry has a declared mass but no route defined for its manufacturing site.

Table C.1. Transport routes from manufacturing site to Helsinki

Route	Manufacturing site and route	Company	Road (km)	Sea (km)	Total (km)	Product entries
1	Espelkamp (Germany) to Lubeck to Helsinki	Naue	264	1 125	1 389	Carbofol; Secugrid; Secudrain; Combigrid 30/30, 40/40, 60/60; Bentofix; Secutex; Secutex H
2	Cessieu (France) to Rotterdam to Helsinki	AFITEXINOV	909	1 746	2 655	NOTEX C, PVA C, GLASS C and GX ranges; GEOTER FPET and WPET
3	Arnhem (Netherlands) to Lubeck to Helsinki	Freudenberg	462	1 125	1 587	EnkaGrid MAX; EnkaGrid MAX C
4	Obernburg (Germany) to Lubeck to Helsinki	Freudenberg	581	1 125	1 706	EnkaDrain Building Drainage; EnkaDrain; Enka Break
5	Dulmen (Germany) to Lubeck to Helsinki	HUESKER	368	1 125	1 493	HaTelit C 40/17, eco and XP 50; SamiGrid XP 50 S; Fortrac MDT and T; Stabilenka
6	Gescher (Germany) to Lubeck to Helsinki	HUESKER	396	1 125	1 521	HaTelit C 40/17, eco and XP 50; SamiGrid XP 50 S; Fortrac MDT, T and eco; Ringtrac; Stabilenka; Stabilenka Xtreme
7	Linz (Austria) to Lubeck to Helsinki	Solmax (Mirafi)	918	1 125	2 043	MIRAGRID PEC, PGM-G and GX; MIRAFI Polyfelt; MIRAFI Bidim
8	Rechlin (Germany) to Rostock to Helsinki	Solmax (MRPI)	118	1 064	1 182	GSE HD, LL and TP; FABRINET; BENTOLINER standard and laminated
9	Jyväskylä (Finland) to Helsinki	Meltex	263	0	263	Geotextiles for filtration and separation
10	Blackburn (UK) to Dover to Calais to Lubeck to Helsinki	Tensar	1 127	1 167.4	2 294.4	Tensar TriAx TX140, TX150, TX160, TX170, TX180, TX190
11	Zelee (Belgium) to Lubeck to Helsinki	BontexGeo NV	676	1 125	1 801	BontexGeo
12	Hengelo (Netherlands) to Lubeck to Helsinki	Solmax	378	1 125	1 503	MIRAFI Geolon PET; MIRAFI HMI
13	Bezons (France) to Rotterdam to Helsinki	Solmax	450	1 746	2 196	MIRAFI Polyfelt; MIRAFI Bidim
14	Romano d'Ezzelino (Italy) to Lubeck to Helsinki	Manifattura Fontana S.p.A.	1 219	1 125	2 344	Drefon ST; Drefon S
15	Liepaja (Latvia) to Tallinn to Helsinki	Tele Textile	518	78	596	Woven polyester high-strength geotextile
16	Xanthi (Greece) to Lubeck to Helsinki	Thrace	2 557	1 125	3 682	Needle-punched nonwoven geotextiles; woven geotextiles
17	Varnamo (Sweden) to Stockholm to Helsinki	SealEco	392	396	788	ElastoSeal
18	Szczytno (Poland) to Tallinn to Helsinki	CETCO	865	78	943	BENTOMAT
19	Swidnica (Poland) to Tallinn to Helsinki	EUROBENT	1369	78	1 447	Bentonite GCL and GCL CS mats; sand mats; cement-sand mats
20	Pove del Grappa (Italy) to Lübeck to Helsinki	Ahlsell Geotess	1 217	1 125	2 342	Nonwoven polypropylene geotextiles
21	Valbrenta (Italy) to Rostock to Helsinki	Geo&Tex 2000	1 191	1 064	2 255	Nonwoven geotextiles
22	Luxembourg to Lubeck to Helsinki	DuPont Typar	698	1 125	1 823	Nonwoven geotextile
23	Pove del Grappa (Italy) to Lubeck to Helsinki	Tessilbrenta	1 217	1 125	2 342	Polypropylene nonwoven geotextile, needle punched
24	Comines-Warneton (Belgium) to Lubeck to Helsinki	BTT	770	1 125	1 895	Terralys; Coated Terralys; Terralys GCL; TerrabARRIER
25	Senica (Slovakia) to Lubeck to Helsinki	Maccaferri	978	1 125	2 103	MacDrain W and TerraDrain W range, geocomposite for planar drainage
26	Arzberg (Germany) to Lubeck to Helsinki	ECORASTER	640	1 125	1 765	ECORASTER S50, E40, E50
27	Vittorio Veneto (Italy) to Lubeck to Helsinki	TeMa	1 420	1 125	2 545	Q-Drain C; Q-Drain ZW

Table C.2 Module A4 results by product entry, in ascending order of A4 as a share of A1 to A3

Product entry	Manufacturing site	Road (km)	Sea (km)	Mass unit (g/m ²)	per area	A1-A3 CO ₂ eq /m2)	(kg A4 (kg CO ₂ eq /m2)	A4 as % of A1-A3
TeleTextile	Tele Textile, Liepaja LV	518	78	345		2.440	0.02325	0.95
Fortrac T	HUESKER, Dülmen DE	368	1 125	352		1.800	0.02430	1.35
Combigrid 30/30	Naue, Espelkamp DE	264	1 125	350		1.400	0.01953	1.40
Fortrac MDT	HUESKER, Dülmen DE	368	1 125	370		1.790	0.02554	1.43
Secugrid PET	Naue, Espelkamp DE	264	1 125	583		2.240	0.03254	1.45
Combigrid 40/40	Naue, Espelkamp DE	264	1 125	390		1.480	0.02177	1.47
Stabilenka	HUESKER, Dülmen DE	368	1 125	780		3.590	0.05385	1.50
Combigrid 60/60	Naue, Espelkamp DE	264	1 125	510		1.810	0.02846	1.57
HaTelit C 40/17	HUESKER, Dülmen DE	368	1 125	270		1.070	0.01864	1.74
Ringtrac	HUESKER, Gescher DE	396	1 125	750		3.110	0.05444	1.75
Stabilenka Xtreme	HUESKER, Gescher DE	396	1 125	980		3.950	0.07114	1.80
Meltex	Meltex, Jyväskylä FI	263	0	200		0.362	0.00669	1.85
Secudrain	Naue, Espelkamp DE	264	1 125	819		2.200	0.04571	2.08
Secugrid PP	Naue, Espelkamp DE	264	1 125	313		0.825	0.01747	2.12
HaTelit C 40/17 eco	HUESKER, Dülmen DE	368	1 125	270		0.829	0.01864	2.25
Secutex	Naue, Espelkamp DE	264	1 125	339		0.839	0.01892	2.25
Secutex H	Naue, Espelkamp DE	264	1 125	681		1.670	0.03801	2.28
Carbofol	Naue, Espelkamp DE	264	1 125	1 703		4.030	0.09504	2.36
NOTEX C	AFITEXINOV, Cessieu FR	909	1 746	220		1.370	0.03302	2.41
DuPont Typar	DuPont Typar, Luxembourg	698	1 125	100		0.451	0.01110	2.46
NOTEX GX	AFITEXINOV, Cessieu FR	909	1 746	277		1.640	0.04158	2.54
HaTelit XP 50	HUESKER, Dülmen DE	368	1 125	240		0.651	0.01657	2.54
NOTEX PVA C	AFITEXINOV, Cessieu FR	909	1 746	667		3.820	0.10012	2.62
GEOTER WPET	AFITEXINOV, Cessieu FR	909	1 746	963		5.460	0.14454	2.65
BENTOLINER laminated	Solmax/MRPI, Rechlin DE	118	1 064	5 100		6.430	0.18380	2.86
EnkaDrain/EnkaBreak	Freudenberg, Osnabrück DE	581	1 125	978		3.208	0.09400	2.93
EnkaGrid MAX C 245	Freudenberg, Arnhem NL	462	1 125	245		0.622	0.01984	3.19
EnkaGrid MAX C 351	Freudenberg, Arnhem NL	462	1 125	351		0.839	0.02843	3.39
SamiGrid XP 50 S	HUESKER, Dülmen DE	368	1 125	520		1.020	0.03590	3.52
EnkaGrid MAX C 521	Freudenberg, Arnhem NL	462	1 125	521		1.190	0.04219	3.55
BENTOLINER	Solmax/MRPI, Rechlin DE	118	1 064	4 000		3.820	0.14416	3.77
Fortrac T eco	HUESKER, Gescher DE	396	1 125	370		0.669	0.02686	4.01
NOTEX GLASS C	AFITEXINOV, Cessieu FR	909	1 746	417		1.540	0.06259	4.06
BontexGeo	BontexGeo NV, Zele BE	676	1 125	250		0.553	0.02705	4.89
Geo&Tex 2000	Geo&Tex 2000, Valbrenta IT	1 191	1 064	250		0.855	0.04312	5.04
Drefon ST	Manifattura Fontana, Romano IT	1 219	1 125	191		0.612	0.03385	5.53

Product entry	Manufacturing site	Road (km)	Sea (km)	Mass unit (g/m ²)	per area	A1-A3 CO ₂ eq /m2)	(kg A4 (kg CO ₂ eq /m2)	A4 as % of A1-A3
BTT Terrabarrier	BTT products, Comines-Warneton BE	770	1 125	365		0.773	0.04385	5.67
Tessilbrenta Hipertex	Tessilbrenta, Pove del Grappa IT	1 217	1 125	250		0.768	0.04425	5.76
BTT Coated Terralys	BTT products, Comines-Warneton BE	770	1 125	167		0.347	0.02006	5.78
BTT Terralys	BTT products, Comines-Warneton BE	770	1 125	92		0.187	0.01105	5.91
BTT Terralys GCL	BTT products, Comines-Warneton BE	770	1 125	110		0.223	0.01322	5.93
Drefon S	Manifattura Fontana, Romano IT	1 219	1 125	556		1.640	0.09854	6.01
MacDrain W	Maccaferri, Senica SK	978	1 125	720		1.730	0.10555	6.10
Q-Drain ZW	TeMa, Vittorio Veneto IT	1 420	1 125	700		2.296	0.14196	6.18
Q-Drain C	TeMa, Vittorio Veneto IT	1 420	1 125	700		2.254	0.14196	6.30
Tensar TX190	Tensar, Blackburn UK	1 127	1 167.4	300		0.745	0.04991	6.70
Tensar TX160	Tensar, Blackburn UK	1 127	1 167.4	220		0.540	0.03660	6.78
Bentofix	Naue, Espelkamp DE	264	1 125	5 093		4.150	0.28423	6.85
Ahlsell Geotess	Ahlsell Geotess, Norsborg SE	1 217	1 125	550		1.400	0.09734	6.95
Tensar TX140	Tensar, Blackburn UK	1 127	1 167.4	175		0.412	0.02912	7.07
Tensar TX180	Tensar, Blackburn UK	1 127	1 167.4	315		0.738	0.05241	7.10
Tensar TX150	Tensar, Blackburn UK	1 127	1 167.4	205		0.464	0.03411	7.35
Tensar TX170	Tensar, Blackburn UK	1 127	1 167.4	273		0.598	0.04542	7.60
THRACE WG	Thrace, Xanthi GR	2 557	1 125	150		0.544	0.05210	9.58
THRACE NW	Thrace, Xanthi GR	2 557	1 125	200		0.703	0.06947	9.88
THRACE CNW/G_EX	Thrace, Xanthi GR	2 557	1 125	200		0.703	0.06947	9.88
THRACE WMT	Thrace, Xanthi GR	2 557	1 125	150		0.526	0.05210	9.91
THRACE WMM	Thrace, Xanthi GR	2 557	1 125	150		0.525	0.05210	9.92
ECORASTER E50	ECORASTER, Arzberg DE	640	1 125	9 550		8.460	0.98954	11.70
ECORASTER E40	ECORASTER, Arzberg DE	640	1 125	5 220		4.580	0.54088	11.81
ECORASTER S50	ECORASTER, Arzberg DE	640	1 125	6 840		5.980	0.70874	11.85

APPENDIX D: INTERVIEW GUIDE AND PARTICIPANTS

This appendix records the semi-structured interview protocol used in the expert interviews reported in Section 5.10, together with the participants. Three interviews were conducted with five participants between 16 and 23 June 2026. The guide below sets out the questions prepared in advance. Because the interviews were semi-structured, the order of questions varied, and additional follow-up questions were asked where a participant raised a relevant point.

Table D.1. Interview details

No.	Interviewees	Organization	Location	Format	Date
1	Patrick Kollmeier, Onur Üzümler	Naue; Kiwa	Espelkamp, Germany	Video	16 June 2026
2	Darryl Kofi Safo	Solmax	Montreal, Canada	Video	22 June 2026
3	Johannes Hakala, Jarkko Ahonen	Meltex	Jyväskylä, Finland	In person	23 June 2026

Interview guide

Background and experience

1. Could you please introduce yourself, your current role, and your professional background?
2. How many years have you been working in the geosynthetics field?

Challenges in EPD development

3. What are the main challenges you face when developing environmental product declarations for geosynthetic products?
4. When updating an EPD, what are the main challenges, and what typically triggers an update, for example changes in production, databases, or standards?
 - When you update, do you recalculate from scratch or adjust the previous model?

Data collection and quality

5. Which life cycle inventory parameters or data inputs are the most difficult to obtain accurately?
6. How is primary data for LCA collected within your company, and how do you ensure its quality and consistency?
 - Is the verifier review rigorous enough to catch data quality problems, or is it more of a documentation check?

Uncertainty and assumptions

7. What are the main sources of uncertainty in EPD results, and which life cycle stages contribute most to these uncertainties?
8. How do you estimate emissions and energy use for processes involving older or less documented machinery?

Scaling, representativeness, and methodological validity

9. How reliable and valid is the use of reference products and scaling approaches when developing EPDs for different geosynthetic product variants?
 - In your experience, how representative are EPD results based on a single reference product when applied to a broader product range?
 - For which types of geosynthetic products is scaling more reliable, and for which is it less reliable, and why?
 - What are the main challenges when developing scaling factors or conversion models for different product variants?
 - How do differences in material composition or manufacturing processes affect the accuracy of scaling?
 - To what extent is the use of representative products or conversion factors compliant with EN 15804, and under what conditions is it acceptable?
 - How do you ensure that scaled results remain reliable and do not oversimplify real environmental impacts?

Transport scenarios and representativeness

10. How are transport scenarios such as distances, modes, and routes typically defined in EPDs for geosynthetic products, and how representative are they of real market conditions, especially when products are used in different countries?

- If EPD data is used in a different country from the one where it was developed, how should transport be adjusted to ensure accurate comparison?
- In practice, how are geosynthetic products typically transported, in terms of main routes, modes, and distances?
- What would be a realistic average transport scenario for imported geosynthetics used in Finland?
- What are the critical distances?

Critical perspectives

11. Are there common assumptions in EPDs that you consider unrealistic or oversimplified in practice?
12. How significant is the influence of the energy mix, meaning the country of production, on the final EPD results?
 - Should EPD values be normalized to a common electricity factor for cross-manufacturer comparison?
13. What are the main limitations of using EPDs for engineering decision-making in infrastructure projects?

Future outlook

14. How do you see the future development of EPDs and LCA in the geosynthetics industry, particularly regarding regulation and digitalization?

APPENDIX E: PRODUCT-LEVEL COMPARISON

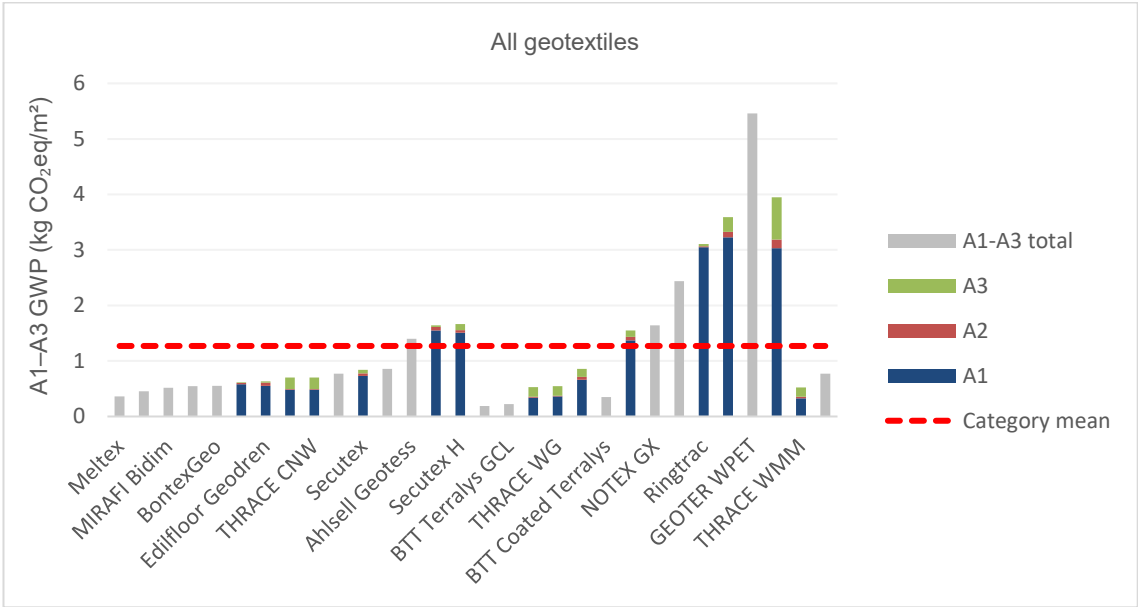


Figure E.1 Spread of product-stage emissions across all geotextiles, showing why the family is divided into subgroups

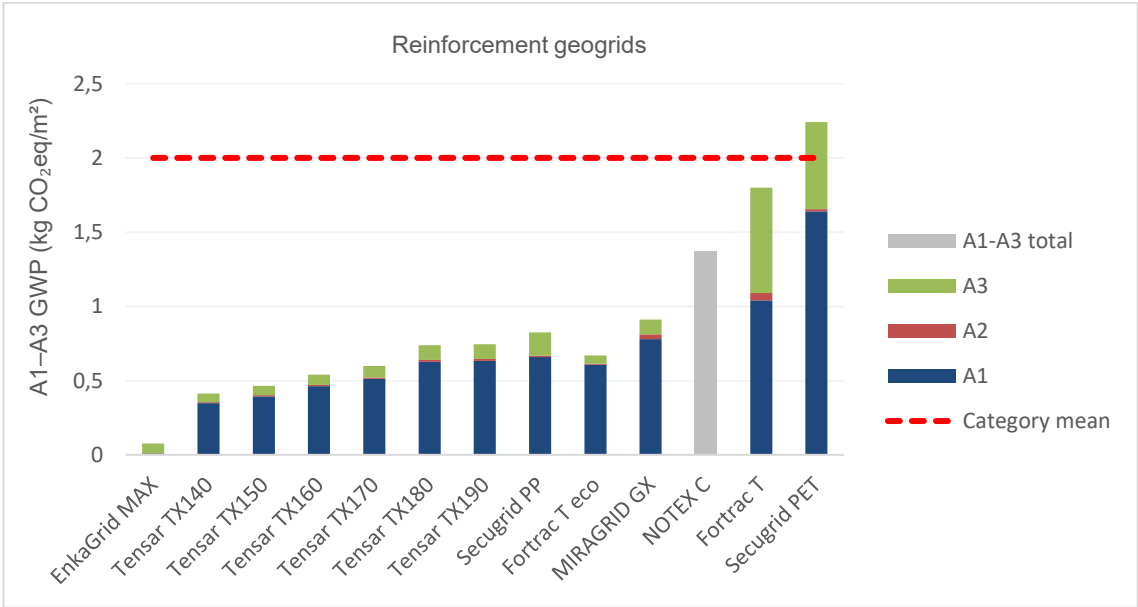


Figure E.2 Product-stage emissions of reinforcement geogrids, from lightweight PP grids to high-strength PET

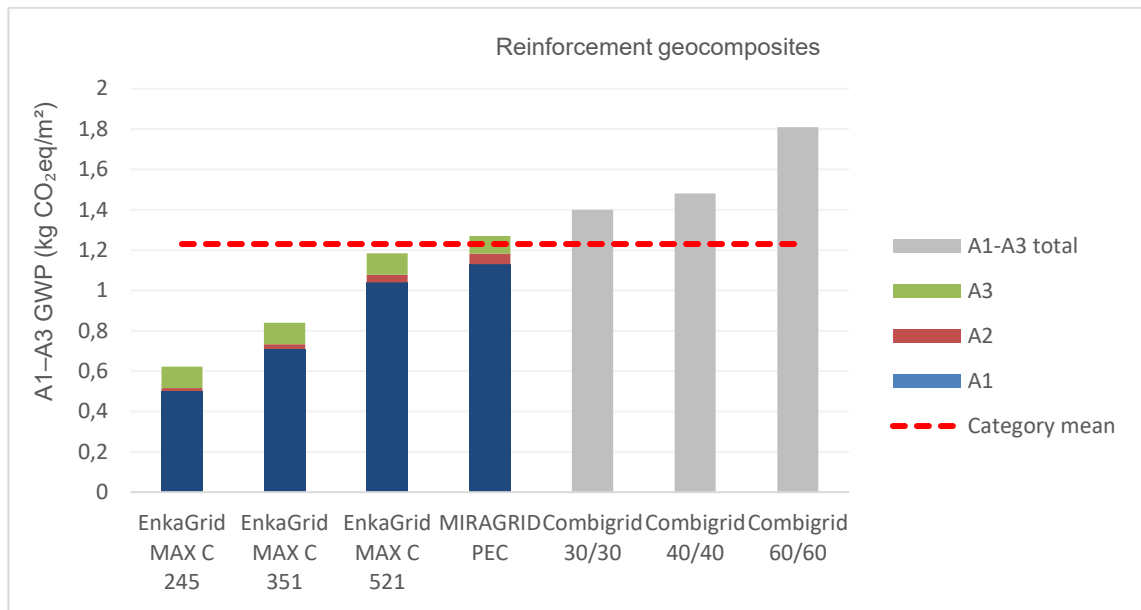


Figure E.3 Product-stage emissions of reinforcement geocomposites relative to the family representative value

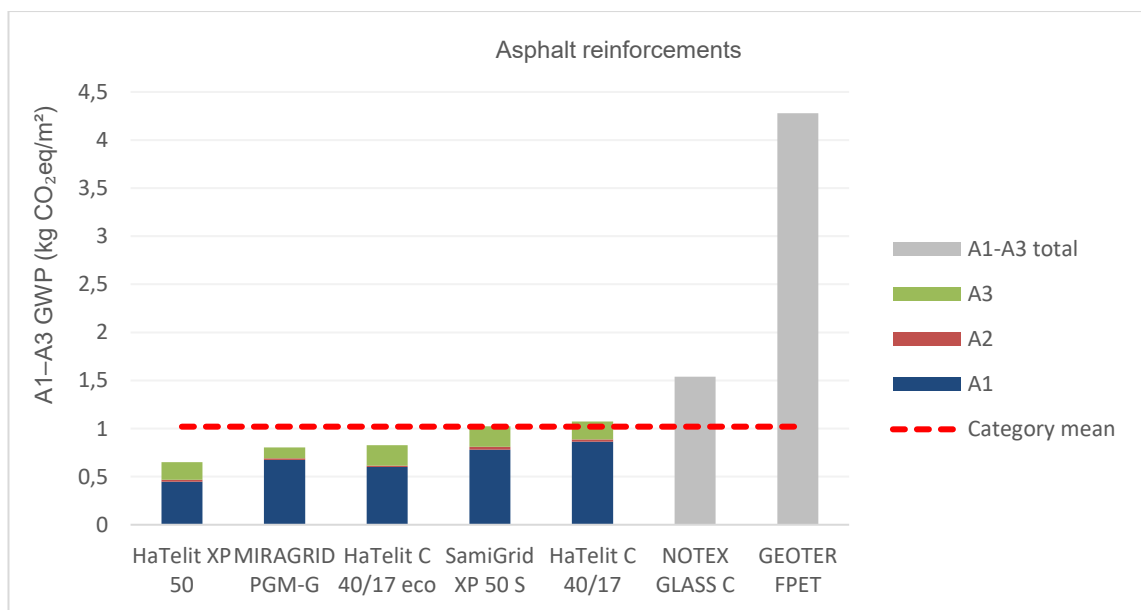


Figure E.4 Product-stage emissions of asphalt reinforcements, with the dual-function outlier shown separately from the representative value

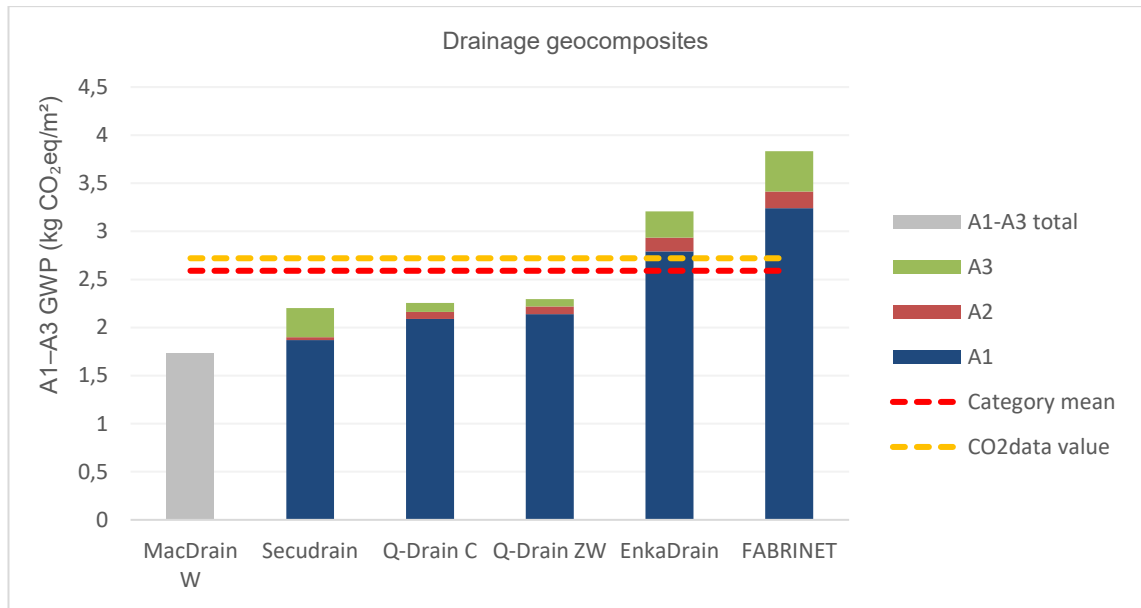


Figure E.5 Product-stage emissions of drainage geocomposites, compared with the current CO2data value

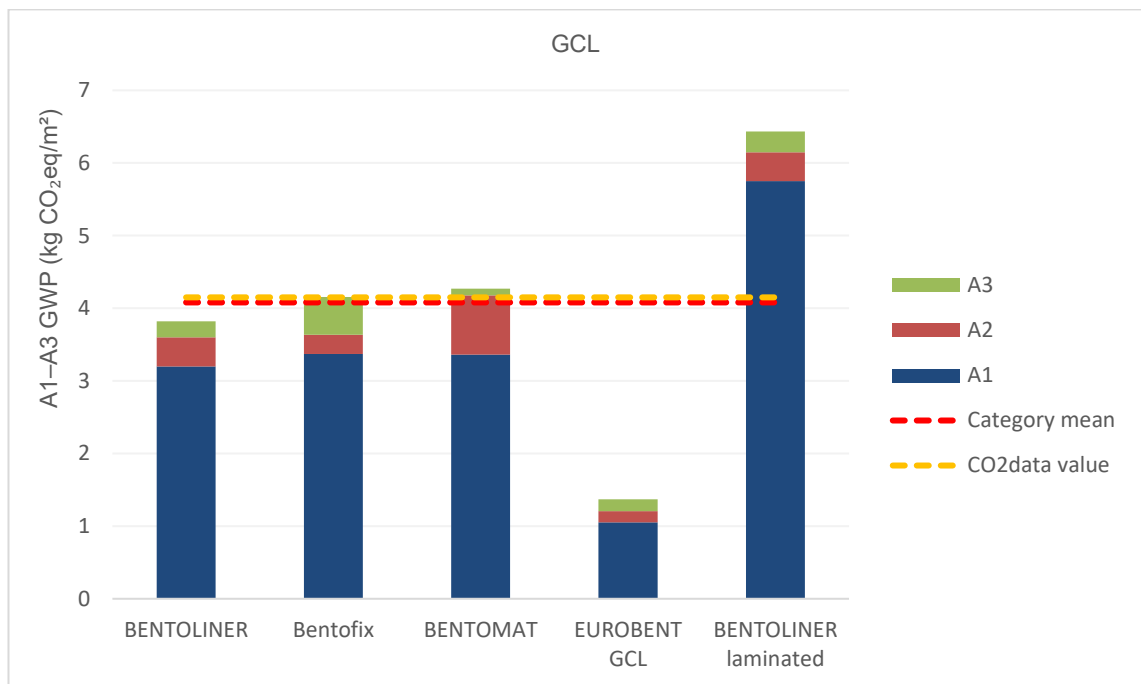


Figure E.6 Product-stage emissions of geosynthetic clay liners, compared with the current CO2data value

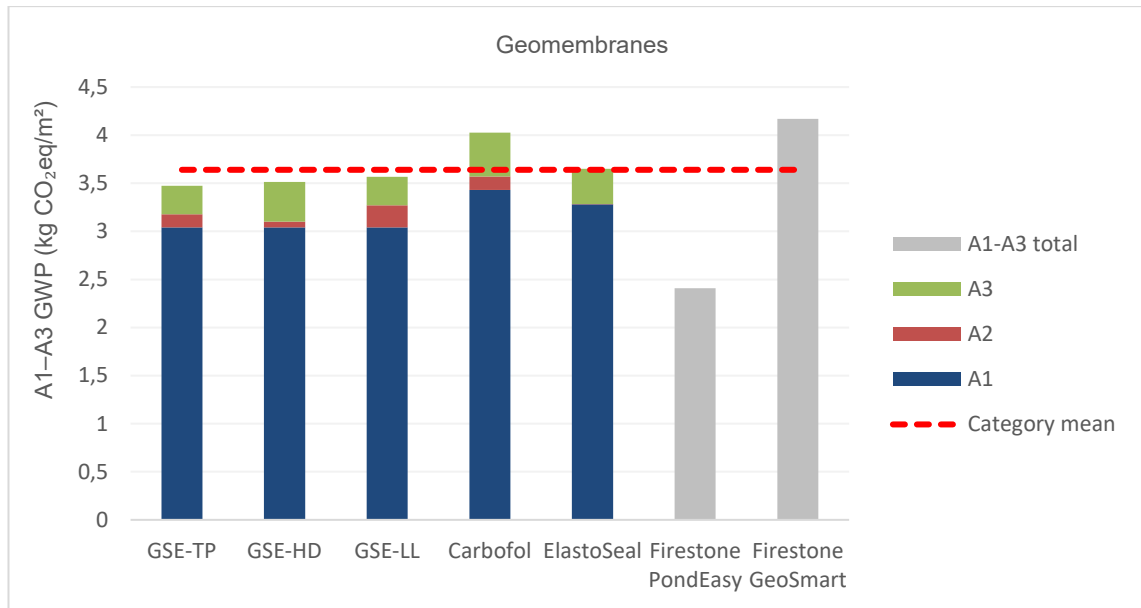


Figure E.7 Product-stage emissions of geomembranes, with the polyolefin products defining the representative value and the EPDM products shown separately

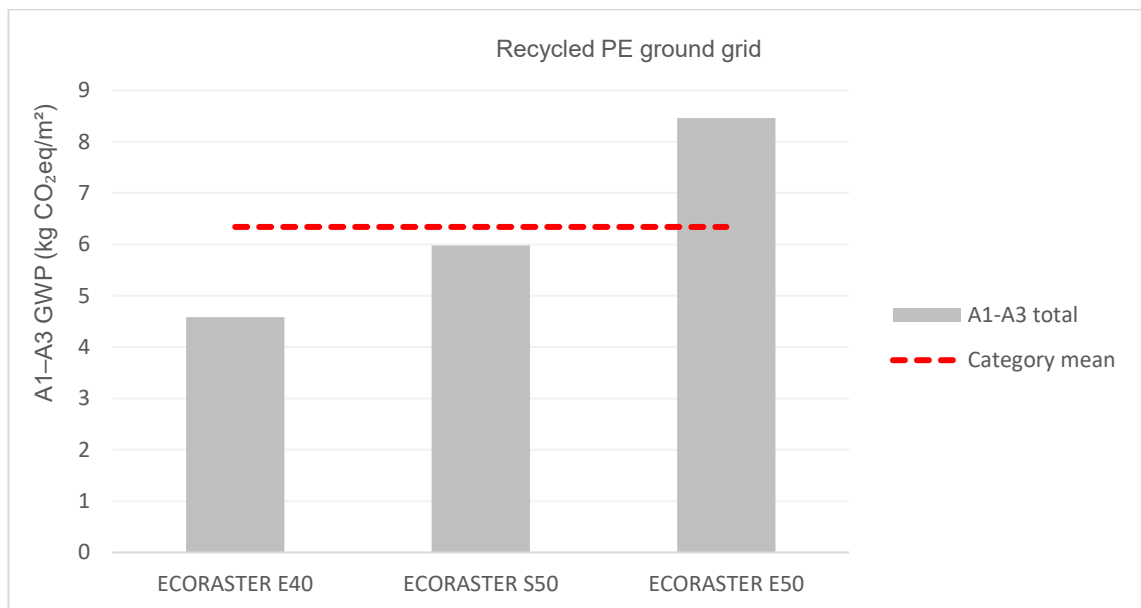


Figure E.8 Product-stage emissions of recycled polyethylene ground grids relative to the family representative value