Green roofs in Oslo by 2030: understand their impacts through life cycle assessment.

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Alignment between the project and the research group

This study's alignment with the URBAG research group, situated within the Institute of Environmental Science and Technology (ICTA) at the Universitat Autònoma de Barcelona (UAB), takes on a particularly relevant dimension. URBAG's exploration of Industrial Ecology provides an apt framework for investigating the multifaceted dynamics between urbanization, industry, and ecological systems. Notably, the research group is keenly attuned to the potential of green roofs as transformative elements in urban landscapes. The ascendancy of green roofs as a versatile strategy for cultivating green spaces within densely urbanized areas resonates with URBAG's mission to contribute to sustainability agendas through innovative interventions.

The strategic relevance of green roofs extends beyond the confines of academia. The city of Oslo, underscored by its ambitions to enhance environmental performance in realms like energy consumption, water management, and greenhouse gas emissions, provides a tangible context for the study's significance. As the city charts its path towards improved sustainability, green roofs emerge as pivotal components of this trajectory, offering a holistic solution to address multiple environmental challenges. This resonance between research and urban policy is further exemplified by URBAG's collaboration with the Norwegian Institute for Nature Research (NINA), which underlines the real-world applicability of this study's outcomes.

This research paper aims to comprehensively understand the nuanced impact of green roof implementation, with a specific focus on accommodating the unique climatic conditions of the Nordic region. By conducting an exhaustive life cycle assessment, the study endeavours to illuminate the environmental implications spanning the entire lifespan of extensive green roofs in Oslo. This emphasis on scrutinizing production, implementation, and end-of-life stages reflects the URBAG research group's commitment to providing actionable insights that align with urban sustainability aspirations. Ultimately, this study's integration within URBAG underscores its pivotal role in contributing to the broader discourse on sustainable urban development.

Summary of Journal's Guidelines

Name of the Journal	BUILDING AND ENVIRONMENT
Content type	Original research article.
Word limit	The total length of a regular paper should be less than 10,000 words that includes tables and figures, but not the references
Number of figures/tables	Generally, the total number of tables should be less than 5 and the total number of figures should be less than 15.
Article structure	**Introduction** State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results. **Material and methods** Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described**.** **Theory/calculation** A Theory section should extend, not repeat, the background to the article already dealt with

	in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis. **Results** Results should be clear and concise. **Discussion** This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature. **Conclusions** The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section. **Appendices** If there is more than one appendix, they should be identified as A, B, etc. Formulae and equations in appendices should be given separate numbering: Eq. (A.1), Eq. (A.2), etc.; in a subsequent appendix, Eq. (B.1) and so on. Similarly for tables and figures: Table A.1; Fig. A.1, etc.
Abstract	A concise and factual abstract of 150-250 words is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.
Keywords	Immediately after the abstract, provide a maximum of 6 keywords, using American, or English, spelling and avoiding general and plural terms and multiple concepts (avoid, for example, "and", "of"). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible. These keywords will be used for indexing purposes.
Subdivision - numbered sections	Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.
Artwork	• Make sure you use uniform lettering and sizing of your original artwork. • Preferred fonts: Arial (or Helvetica), Times New Roman (or Times), Symbol, Courier. • Number the illustrations according to their sequence in the text. • Use a logical naming convention for your artwork files. • Indicate per figure if it is a single, 1.5 or 2-column fitting image. • For Word submissions only, you may still provide figures and their captions, and tables within a single file at the revision stage. • Please note that individual figure files larger than 10 MB must be provided in separate source files.
Tables	Please submit tables as editable text and not as images. Tables can be placed either next to the relevant text in the article, or on separate page(s) at the end. Number tables consecutively in accordance with their appearance in the text and place any table notes below the table body. Be sparing in the use of tables and ensure that the data presented in them do not duplicate results described elsewhere in the article. Please avoid using vertical rules and shading in table cells.
References	Please ensure that every reference cited in the text is also present in the reference list (and vice versa). Any references cited in the abstract must be given in full. Unpublished results and personal communications are not recommended in the reference list but may be mentioned in the text. If these references are included in the reference list, they should follow the standard reference style of the journal and should include a substitution of the publication date with either 'Unpublished results' or 'Personal communication'. Citation of a reference as 'in press' implies that the item has been accepted for publication. There are no strict requirements on reference formatting at submission. References can be in

	any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct.

Description of the work done by the student:

In this study, I undertook a thorough investigation with a specific focus: quantifying the adverse environmental repercussions associated with green roofs, while recognizing their widely acknowledged benefits. Centered on the distinctive context of Oslo, Norway, my research concentrated on scrutinizing diverse structural components and substrate materials integral to green roof systems. By employing a meticulous life cycle assessment methodology, I delved into the intricate interplay between these elements and their corresponding environmental footprints. The fundamental intent was to illuminate the environmental implications embedded in the implementation of the green roof strategy. With a concentrated examination solely on the negative impacts, my research aimed to provide a comprehensive understanding of the potential downsides of this strategy. The insights garnered from this exploration are poised to offer crucial information for informed decision-making, policy development, and the promotion of environmentally conscious urban growth.

Green roofs in Oslo by 2030: understand their impacts through life cycle assessment.

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Abstract

This study presents a comprehensive life cycle assessment of green roofs in Oslo, evaluating their environmental impacts and material choices. Investigating structural components and substrate materials, we aimed to align green roof design with Oslo's sustainability goals. Our research revealed that Type 2, a streamlined structural design with root barrier, water retention, and filter layers, exhibited a significantly lower environmental impact (65-85%) compared to Types 1 and 3. Substrate 3, composed of 70% pumice, 20% gravel, and 10% compost, demonstrated the lowest impact (50-78% lower than Substrate 1, and 3-24% lower than Substrate 2). Our findings emphasize the importance of tailored design choices and highlight avenues for further sustainable urban development. This work contributes essential insights for policymakers, stakeholders, and building owners aiming to enhance urban sustainability.

Keywords

Green Roofs, Life Cycle Assessment, Environmental Impact, Sustainability, Urban development

1. Introduction

In recent years, green roofs have gained increasing popularity in urban areas due to their multifunctionality and numerous benefits. Green roofs offer a diverse range of advantages, such as reducing water runoff during precipitation events, enhancing biodiversity, decreasing building energy consumption, improving air quality, and mitigating the urban heat island effect [1–3].

Green roofs can be viewed as a layered component that primarily serves as a living foundation for specific vegetation while preserving the building's structural properties and functions [4]. There are three main types of green roofs based on the depth of the substrate layer: extensive, intensive, and semi-intensive. Extensive green roofs are lightweight and predominantly consist of drought-tolerant sedum species, requiring minimal care and maintenance throughout their lifecycle [4,5]. On the other hand, intensive green roofs are designed to withstand human activity and support a diverse array of plant life, making them more complex and expensive to install and maintain [6]. Semi-intensive green roofs fall between extensive and intensive types, supporting a wider range of vegetation with moderate maintenance requirements [5].

With the escalating impacts of climate change, green roofs have emerged as a focal point of interest for municipalities worldwide, finding active integration within comprehensive plans and policies across countries such as the Netherlands, France, Belgium, Germany, and Norway [7–9]. A notable shift is evident in Germany, where around two-thirds of cities had mandated green roofs in their development blueprints by 2019, a significant rise from just one-third in 2010 [10]. Meanwhile, Belgium's capital, Brussels, has taken a decisive step by making it obligatory for flat, non-accessible roofs larger than 100 m² and subject to planning permission to undergo conversion into green roofs [11].

In Norway, the country's municipalities bear the crucial responsibility of identifying potential adverse events that could impact their regions, assessing the likelihood of occurrence, and evaluating the potential consequences of such events [12]. Notably, climate change projections for Norway indicate a troubling escalation in the frequency and intensity of rainfall events, leading to significant stormwater management challenges in urban areas. This predicament is exacerbated by the proliferation of sealed surfaces and clayey subsoil, exacerbating the risk of urban flooding and overloading of the sewage network [12].

In response to these pressing environmental challenges, the municipality of Oslo has devised an innovative plan centred around the implementation of green roofs. At its core, this strategy sets a bold target of achieving 2030 green roofs by the year 2030, aligning with the broader objectives of Oslo's green roof strategy. This forward-thinking approach aims to leverage green roofs as a versatile and geographically targeted solution to tackle various urban environmental issues. Specifically, green roofs are envisioned as a powerful tool to address stormwater management, create habitats for biodiversity, enhance air quality, promote recreational access, and elevate the visual appeal of the cityscape [8].

However, despite their growing adoption, a significant research gap persists regarding the environmental impact of green roofs, especially within the specific context of Norway. Numerous studies have delved into the environmental dimensions of green roofs through life cycle assessments (LCA). Notably, Bianchini and Hewage [13] pinpointed rockwool, plastic drainage layers, and expanded clay as the primary sources of environmental burden in lightweight green roof systems. Their findings advocate for simpler designs, minimizing artificial layers to reduce impacts. In a similar vein, Chenani et al. [14] underscored the positive role of green roofs in curbing air pollution and enhancing environmental conditions within construction and society. However, their study also highlighted the need to address the potential toxicity stemming from polymer production, which underscores the necessity of responsible material choices.

The absence of comprehensive life cycle assessments tailored to Norwegian conditions limits our understanding of the sustainability of green roof implementations in this region. In this sense, LCA insights underscore a significant opportunity to complement the Oslo strategy. Conducting an LCA provides a holistic understanding of green roofs' implications beyond their multifunctionality, shedding light on the broader effects they offer. As of now, a comprehensive evaluation of the environmental impact of green roofs in the Norwegian context remains unexplored.

Hence, the objective of this study is to bridge the existing research gap through conducting a comprehensive life cycle assessment of extensive green roofs, specifically tailored to align the requirements of Oslo municipality. Our investigation aims to address two key aspects: (1) identifying the most suitable materials essential for the successful implementation of green roofs in Oslo based on literature review, and (2) evaluating the potential environmental performance linked with the adoption of this green roof strategy. By assessing the environmental impacts associated with the various scenarios of Oslo's green roof implementation, our study yields crucial insights that can empower well-informed choices by policymakers, building owners, and other stakeholders.

2. Materials and Methods

2.1. Study area and context

Oslo is a city of 454 km^2, of which 300 km^2 are the nationally protected Marka, serving as a greenbelt to limit urban sprawl and provide outdoor recreational opportunities [15]. The city has been growing rapidly since 2000 and has a population 709,037 in 2023 [16]. The city has a greenview index of 29% and 47% green space cover within the built zone, with 60 m^2 /inhabitant of regulated green space [15]. In addition to the surrounding forest, Oslo's urbanized areas are interspersed with green spaces and river corridors, and are situated on the Oslofjord, which boasts beaches and a terrestrial coastal zone that spans 140 km and offers various recreational activities [17].

According to the re-analyzed classification of Köppen–Geiger, Olso has a humid-continental climate [18]. Johannessen et al. [19] report that Oslo has an inland climate with low annual precipitation (122,+/- 15 days), high summer temperatures, and cold and long winters.

In 2015, the Norwegian Centre for Climate Services predicted that Norway will undergo warming across all seasons, with temperatures rising by approximately 4.5°C by the end of the century. Northern Norway may experience an even more significant increase of about 6°C. This warming will also extend the growing season by one to three months. Moreover, annual precipitation is expected to rise by an average of 18 percent, with winter seeing an 89 percent increase in heavy rainfall [12].

Despite limited ground-level space for additional green infrastructure, Oslo recognizes a significant potential for green infrastructure development on existing flat roofs. Focusing specifically on roofs with slopes less than 5°, the municipality has identified an opportunity to introduce green roofs to around 13,250,000 m2 of available roof [8].This extensive area holds immense promise for the integration of green infrastructure within the urban landscape of Oslo. Following this analysis, various installation scenarios have been devised for the municipality.

2.2. Scenarios

The year 2030 has been chosen as a time-horizon for assessing green roofs (GR) since it is the reference year in the municipal strategy for green roofs and facades [8]. To fathom the potential trajectories of GR in the city, three distinct scenarios were proposed (see Table 1). These scenarios were subjected to rigorous refinement through a workshop held in November 2021, involving input from diverse stakeholders in the Oslo GR environment (developers, municipal officers, and NGO representatives) [20]. The scenarios planned are:

S0. Reference: based on an aerial photo-survey that the municipality of Oslo carried on in 2020 for tracing the state of green roofs in 2017 [21], 928 GR were mapped across the Oslo municipality, with a total area of 190,211 m2 and an average size of 204 m2. This scenario does not look at an increase of green roofs until 2030, since its intention is only to work as a benchmark for the evaluation of the other scenarios. The survey does not differentiate between typology of GR (e.g., extensive, intensive) so it is assumed that all are extensive.

S1. Green roof strategy*:* considers the increase in the number of GR based on the estimations of the strategy for green roofs and facades [8] which states that the city will count with a total of 2030 green roofs and facades by 2030. In our case, we are assuming that the 2030 infrastructures will be all extensive GR and that these will maintain the average size (m2) observed in S0.

S2. Ambitious*:* represents a greater implementation of GR in the municipality compared to S1. For this matter, a total of 3550 GR was selected as an ambitious objective by stakeholders. The total area of GR ascends to 729,332 m2, which, same as S1, it assumes that GR maintain the average size (m2) observed in S0.

Table 1 *Established green roof scenarios.*

Scenario	Year	Number of green roofs	Total m^2
S0. Reference	2017	928	190,211
S1. Green roof strategy	2030	2,030	415,524
S2. Ambitious	2030	3,550	729,332

2.3. Life Cycle Assessment

We are utilizing life cycle assessment (LCA) to evaluate the environmental impact of green roofs. LCA is a widely recognized and commonly employed methodology for assessing the environmental impacts associated with various products, processes, and services. It is defined by the ISO 14040 standards and consists of four stages: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation [22]. LCA provides valuable insights into identifying opportunities to reduce environmental impact and informs decision-making regarding sustainable practices. For our study, we employed Simapro 9.3 software and used the Ecoinvent 3.8 database.

2.3.1. Goal and Scope

The objective of this LCA is to evaluate the environmental impacts associated with the entire life cycle of green roofs, focusing on different implementation scenarios aligned with the Oslo strategy.

To accomplish this objective, we have conducted a comprehensive review of pertinent literature, analysed existing standards [4], and gathered insights from workshops and interviews with esteemed experts and professionals in the field [23–25]. Based on these findings, we made the decision to focus the green roof analysis on two distinct components: a structural part, comprising the necessary layers for roof membrane protection, and a substrate part, consisting of the growing media essential for sustaining vegetation. Within the context of this study, we established three distinct structural designs and three different substrate options for extensive green roofs, all carefully tailored to suit the specific climatic conditions prevalent in Oslo. Furthermore, the substrates designed for this evaluation can accommodate the three structural designs intended for this study. It is important to note that throughout this study, structural designs are referred to as "Type" and substrates as "Substrate".

The functional unit selected for the LCA is the production, installation, use and dismantling of 1 m^2 of extensive green roof capable of retaining 5 mm of water for any precipitation event, considering its use over a period of 40 years in accordance with established guidelines and previous research findings [4,5,26].

The system boundaries encompass all stages of the life cycle, including (1) the extraction of raw materials and their manufacturing into components ready for use, (2) the installation process, which involves machinery for placing the different components on the roof, (3) ongoing maintenance, and (4) the end-of-life management of each component. The end-of-life stage includes machinery used for deconstruction and the different waste treatment processes for all materials. Transportation between these stages is also taken into account (see Figure 1).

While conducting this investigation, we opted to exclude the vegetation component in order to solely focus on the environmental impact of the green roof structure itself.

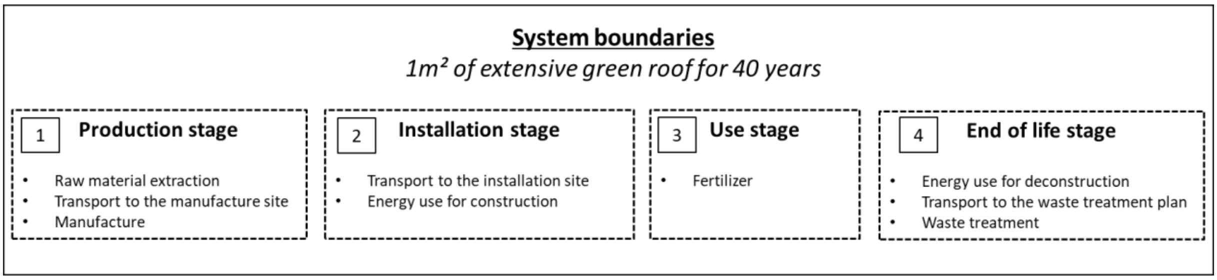


Figure 1 *System boundaries of the green roofs designed.*

2.3.2. Life Cycle Inventory

The data compilation for the system under investigation encompassed the entire life cycle, including production, transportation, construction, maintenance, and waste management of the different types and substrates designed for extensive green roofs in Oslo.

Multiple sources from the literature on extensive green roof design were considered to ensure the validity of the proposed solutions. Notably, significant references include reports on extensive green roofs in Norway [19,27] and the Norwegian standard for extensive green roofs [4]. Additionally, recent trends in materials applicable to green roof composition were considered [28].

Figure 2 provides an assessment of the evaluated types, while the specific quantities of materials utilized are detailed in Table 2-3. For a comprehensive overview of the Life Cycle Inventory data, please refer to the Supplementary Information (Table A.1-A.6).

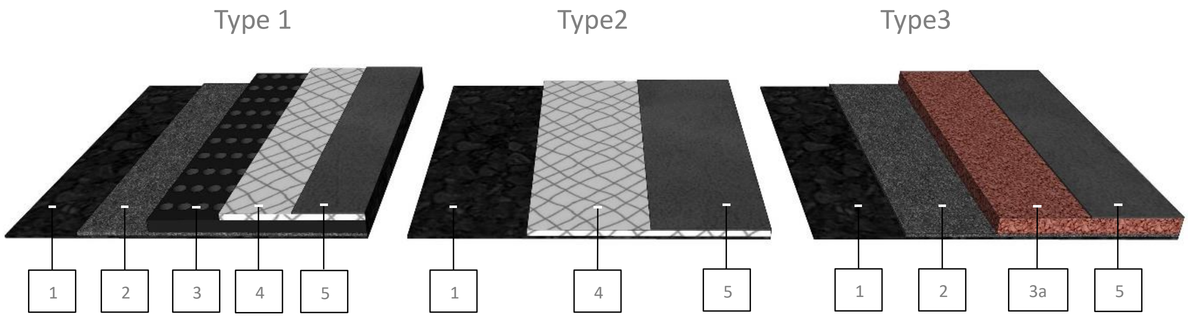


Figure 2 *Structural part of the green roofs. 1 - root barrier; 2 - protection layer; 3/3a - drainage layer; 4 - water retention felt; 5 - filter layer*

The three structural parts designed in this study contain the layers required to protect the roof membrane and support the growing medium (see Table 2). They comply with the various regulations in force concerning green roofs [4,5,29].

Type 1: the present configuration conforms to the overarching specifications delineated in various reports and standards regarding the construction of an extensive green roof system and incorporates all of the requisite layers[4,5]. This includes a root barrier to prevent plant root penetration, a protection layer such as a geotextile to safeguard the roofing membrane, a drainage layer made of plastic to facilitate water flow and prevent accumulation. Furthermore, it incorporates a water retention layer comprising fibres to supply water and manage runoff, and a filter layer of non-woven polypropylene fabric to prevent clogging and preserve the growing medium.

Type 2: includes the same root barrier, a water retention layer and a filter layer as *type 1* but removes the protection layer and the drainage layer. This configuration was defined based on a study conducted by Braskerud [27]that has demonstrated that removing the drainage layer from an extensive green roof system leads to enhanced water retention capacity and improved peak flow attenuation. These findings are consistent with other scholars in the field [5,27].Moreover, the relevant normative standard highlights that a water retention layer can fulfil the functions of both a drainage layer and a protective layer [4].

Type 3: in light of a recent investigation conducted by Kazemi et al. [28], we chose an extensive green roof that incorporates a coarse-grained material as a drainage layer (Lightweight Expanded Clay Aggregate), and maintains the root barrier, protection layer and filter layer from *type 1*. The utilization of natural aggregate serves to eliminate the need for polymeric materials, although this alternative is associated with an increase in weight and material volume.

Table 2 *Composition of each type*

Layer	Element	Weight (kg/m^2)	Height (mm)
TYPE 1			
1. Root barrier	Polyethylene (LDPE)	0.8	0.4
2. Protection layer	Polypropylene geotextile	0.3	2
3. Drainage	Dimple membrane (HDPE)	1.6	40
4. Water retention	Recycled textile fibre	1.28	10
5. Filter layer	Textile - nonwoven polypropylene	0.2	1.9
		4.18	**54.3**
TYPE 2			
1. Root Barrier	Polyethylene (LDPE)	0.8	0.4
4. Water retention	Recycled textile fibre	1.28	10
5. Filter Layer	Textile - nonwoven polypropylene	0.2	1.9
		2.28	**12.3**
TYPE 3			
1. Root Barrier	Polyethylene (LDPE)	0.8	0.4
2. Protection Layer	Polypropylene geotextile	0.3	2
3a. Drainage	Lightweight Expanded Clay Aggregate (LECA)	22.5	50
5. Filter Layer	Textile - nonwoven polypropylene	0.2	1.9
		23.8	**54.3**

Substrate Part

The substrate layer plays a vital role in supporting the growth and survival of vegetation in extensive green roofs. It ensure a suitable environment for the development of vegetation by offering a growing medium that can store and give water and nutrients to the plants [4]. Additionally, the substrate layer acts as an anchor for the plants, preventing them from being dislodged by wind or water runoff [30]. The depth and weight of the substrate layer are important factors that must be considered to ensure the structural integrity of the roof. According to FLL [29] the depth of a substrate layer for extensive green roofs can vary from 2.5 cm to 20cm.

The composition of substrate used in extensive green roofs is usually made up of mineral components and a maximum of 20% of organic matter on a volume basis [4], with natural, artificial or recycled materials being used. Each component has its own advantages and disadvantages in terms of weight, water retention capacity, and porosity [31]. The optimal substrate should have high aeration, drainage, and nutrient retention and be sturdy, permanent, and lightweight [32]. We selected 3 different substrates for the evaluation (see Table 3):

Substrate 1, consists of 10% lightweight expanded clay aggregate (LECA), 80% recycled clay bricks, and 10% compost. Similar to Chenani et al.'s life cycle assessment [14], this substrate is well-suited for extensive green roofs. Expanded shale, clay, and slate materials are commonly used in green roof substrates due to their lightweight and porous nature, allowing for water retention and drainage [31]. Crushed brick improves porosity, hydraulic conductivity, and substrate cost [33]. The organic content enhances vegetation nutrition and water retention capacity [30].

Substrate 2, is based on 20% vermiculite, 30% perlite, 20% crushed brick, 10% sand, and 20% compost. We chose to incorporate this mixture into our study based on Vijayaraghavan et al. [33] who designed this substrate when aiming to improve both runoff water quality and plant growth. The authors conducted experiments using 18 different substrates to investigate their physical and chemical properties, as well as their relationship with vegetation. Among these substrates, the 12th composition emerged as the most favourable in terms of water-holding capacity, air porosity, bulk density, and hydraulic conductivity.

Substrate 3 is made of 70% pumice, 20 % gravel and 10% compost. This composition originates from research conducted by Hanslin et al. [34] where they examined the relationship between substrate structure and vegetation in the Norwegian climate. Their analysis focused on investigating the connection between four different substrates - a fine substrate, a coarse substrate, a mixed substrate, and a layered substrate - and various Sedum plant species. The findings indicated that the fine substrate, consisting of a mixture of pumice, gravel, and compost, displayed notable advantages. It demonstrated higher shoot biomass, a reduced proportion of roots, and a higher shoot biomass per unit root length. These outcomes are consistent with the fine substrate's ability to retain water, allowing it to sustain moisture levels over an extended duration between weekly watering sessions. Considering these results, we included the fine substrate composition in our study.

Observational data collected over three years in Norway has indicated that the retention performance of extensive green roofs is primarily governed by evapotranspiration rather than the maximum water storage capacities [35]. In Oslo's temperate seasons, the estimated retention performance of extensive green roofs ranges from 35% to 60% based on both observed and modelled data [35]. In the temperate season, when the maximum storage capacity of the extensive green roof exceeds 13mm, a conservative estimate of available retention capacity for a random precipitation event is 5mm [35]. Therefore, we posit that all substrates possess a water holding capacity of at least 13mm, thereby enabling them to effectively retain up to 5mm of water during any arbitrary precipitation event.

Table 3 *Composition of each substrate*

Layer	Element	Weight (kg/m²)	Height (mm)
SUBSTRATE 1	LECA	2.5	5
	Crushed bricks	46.6	40
	Compost	2.5	5
		51.6	**50**
SUBSTRATE 2	Vermiculite	5.58	20
	Perlite	4.44	30
	Crushed bricks	23.3	20
	Sand	16.08	10
	Compost	10	20
		59.4	**100**
SUBSTRATE 3	Pumice	31.97	70
	Gravel	21.42	20
	Compost	2.50	10
		55.89	**100**

Installation Stage

The installation stage includes both the transportation and installation processes. In our study, we approximated a transportation distance of around 500 km by truck from a manufacturing facility in Sweden to the subsequent utilization phase in Oslo. This estimation is based on a green roof supplier situated in Stockholm, Sweden, and was calculated using Google Earth software to measure the distance between the two locations. During the installation process, a tower crane is employed to lift and position all the necessary materials onto the roof. We assumed an energy consumption of 0.0039 kWh/kg for the lifting operation. To address the tower crane's energy demands, we referred to the relevant data provided in Supplementary Information (Table A.1. – A.6.).

Use Stage

The use stage involves their maintenance, which is essential for sustaining their intended functionality. It is recommended to conduct annual maintenance activities biannually, specifically during the spring and late summer or early autumn [5]. To prevent excessive weed growth on the roof, Dunnett and

Kingsbury [36]suggest applying slow-acting fertilizers at a rate of 15-20 g/m2. Therefore, an application rate of 15 g/m2 per year is assumed in this study.

End of Life Stage

The end-of-life stage cover the deconstruction, transportation, and waste treatment processes. In our assessment, we considered multiple factors related to the end-of-life scenario for the materials used in the green roof assembly. This includes the energy required for their removal from the roof, the transportation distance to waste treatment facilities, and the specific waste treatment methods employed. We assumed a transportation distance of 100 km by truck to the designated waste treatment plant. Different waste treatment scenarios were considered for each component. The substrate is assumed to be landfilled, the textile-based material is slated for incineration, and the plastic-based materials are subjected to a combination of 50% recycling and 50% incineration.

2.3.3. Life Cycle Impact Assessment

For the present investigation, we have adopted the CML2001 method, which was developed by the Institute of Environmental Sciences at the University of Leiden, Netherlands. Our investigation builds upon the work conducted by Borzog Chenani et al. [14] and Stuhalah et al. [6]. To calculate the environmental impact, we utilized the CML-IA baseline V3.08 / EU25 version of the method. We selected the following impact categories; Abiotic depletion (kg Sb eq), Abiotic depletion (fossil fuels) (MJ), Global warming (GWP100a) (kg CO_2 eq), Ozone layer depletion (ODP) (kg CFC-11 eq), Human toxicity (kg 1,4-DB eq), Freshwater aquatic ecotoxicity (kg 1,4-DB eq), Marine aquatic ecotoxicity (kg 1,4-DB eq), Terrestrial ecotoxicity (kg 1,4-DB eq), Photochemical oxidation (kg C_2H_4 eq), Acidification (kg SO_2 eq), Eutrophication (kg PO_4--- eq). Please observe that Abiotic depletion (kg Sb eq) pertains to the depletion of minerals and metals (non-fossil resources), while Abiotic depletion (fossil fuels) (MJ) pertains to fossil resources.

2.3.4. Interpretation

The interpretation phase addresses a completeness and consistency check, data quality analysis, contribution analysis, and sensitivity analysis (ISO 14040-44). A sensitivity analysis was conducted in order to highlight the differences observed when each of these drainage layer materials are utilized.

The sensitivity analysis carried out in this study expands on the research conducted by Kazemi et al. [28]. Our particular focus lies on investigating the impact of varying the drainage layer. Kazemi et al. [28] extensively examined the properties of four different aggregates, including Lightweight Expanded Coarse Aggregate (LECA), Natural Coarse Aggregate (NCA), Recycled Coarse Aggregate (RCA), and even alternative materials like Incinerated Municipal Solid Waste Aggregate (IMSWA). However, in our case, we excluded the IMSWA from consideration due to the unavailability of precise manufacturing process data.

Furthermore, by incorporating these alternative materials into Type 3, we can assess the resultant changes in environmental impact compared to the other types.

3. Results

This section presents the results of the structural part (Section 3.1) and the substrate part (Section 3.2), and the overall assessment based on the different implementation scenarios (Section 3.3).

3.1. Environmental Assessment of the Structural part

The findings of the environmental assessment of the structural part are depicted in Figure 5, while further details can be found in Table B.1. within the supplementary information. Delving into the environmental evaluation of the three types of structural part of the green roofs, it becomes apparent among them, Type 2 exhibits the lowest environmental impacts. This is attributed to its streamlined structure comprising only three layers, compared to the four layers in Type 1 and the five layers in Type 3.

When compared to the other types, Type 2 demonstrates a favourable performance, with an environmental impact that is 65% to 85% lower across all impact categories (see Figure 5). This variation can be attributed to the relatively smaller number of materials used in this type. In contrast, Type 3 demonstrates the highest impact in seven out of eleven impact categories, while Type 1 has the highest impact in the remaining four. However, the difference in the impact between Type 1 and Type 3 is relatively small. Although Type 1 performs worse in four categories, the difference with Type 3 in Abiotic depletion (fossil fuels), Human toxicity, and Marine ecotoxicity is less than 7%, and 36% regarding Freshwater aquatic ecotoxicity. On the other hand, when Type 3 performs the worst, the difference with Type 1 is more significant. The minimum difference is 3%, ranging from 16% to 52% in five out of seven categories, and the maximum difference reaches 55%.

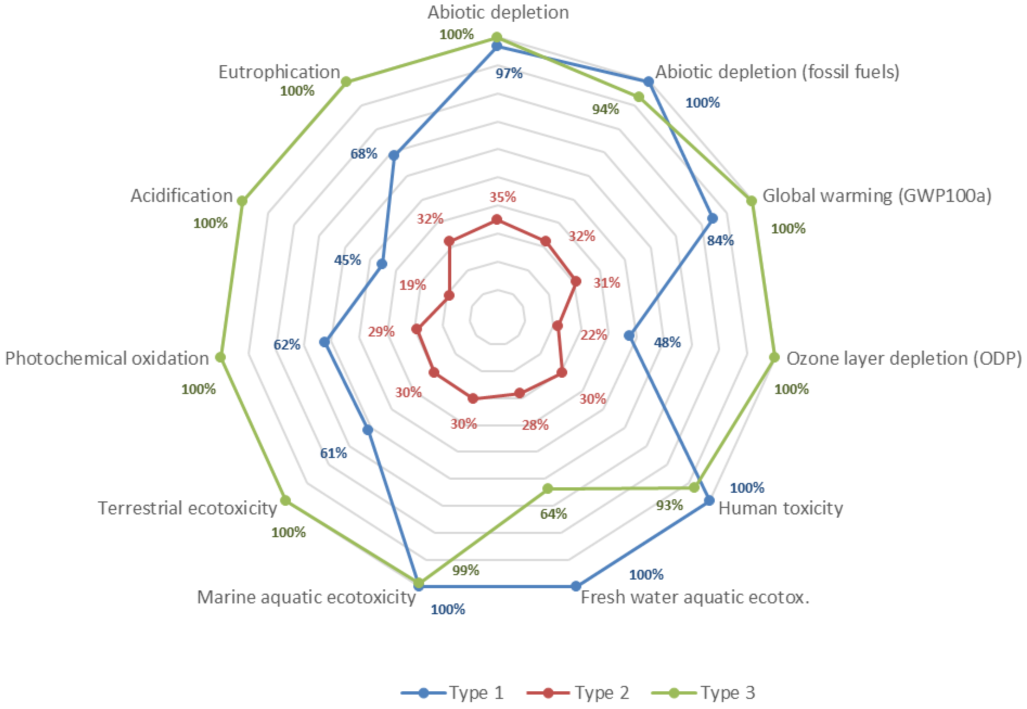


Figure 3 *Impacts of three proposed green roof types*

Figure A.1 in the supplementary data provides an overview of environmental impact distribution across different life cycle stages for each impact category. Notably, the production stage holds the highest impact for all the types across most stages. When comparing the three types across different stages, Type 3 exhibits the worst results in all impact categories during the production stage, except for Abiotic depletion and Abiotic depletion (Fossil fuels), where Type 1 scores the worst for both categories with 6% and 18% more impact respectively. Similarly, during the installation stage, Type 3 shows impact that are on average 85% higher than Type 1 and 92% higher than Type 2 across all impact categories. However, the trend shifts when considering the end-of-life scenario. In this case, Type 3 achieves the worst results in only five out of eleven impact categories, namely Abiotic depletion, Abiotic depletion (Fossil fuels), Ozone layer depletion, Terrestrial ecotoxicity, and Photochemical oxidation, with impacts that are 45% to 80% higher compared to the other types. Type 2 remains the most favourable in almost all categories, except for Eutrophication, where Type 3 has the lowest impact with 1.19E-03 kg PO4--- eq. The shift in trends during the end-of-life scenario can be attributed to the impact of the polyethylene-based material used in Type 1. This material significantly contributes to several impact categories, including Global warming, Human Toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, Acidification, and Eutrophication.

Considering that both Type 1 and Type 3 exhibit significant environmental impacts compared to Type 2, Figure 4 offers crucial insights into the influence of layers across the entire life cycle for these two types. Notably, the drainage layer emerges as the primary contributor to impact in almost all categories for both Type 1 and Type 3. Specifically, the drainage layer in Type 1 registers impacts 41% to 97% higher than other layers across all categories. Similarly, in Type 3, the drainage layer surpasses other layers in impact for ten out of eleven categories, with impacts ranging 46% to 96% higher.
The differences between the two types are exemplified by the composition of their drainage layers: Type 1 employs a high-density polyethylene dimple membrane, while Type 3 uses lightweight expanded natural aggregate (LECA) for its drainage layer.

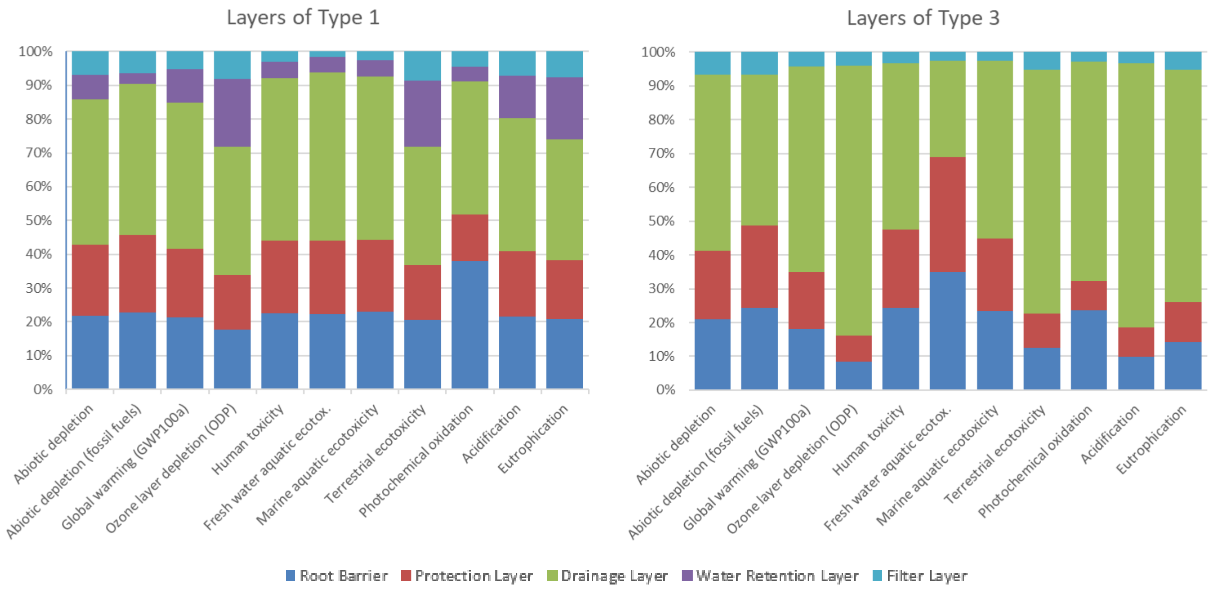


Figure 4 *Impact of the different layers of Type 1 and Type 3*

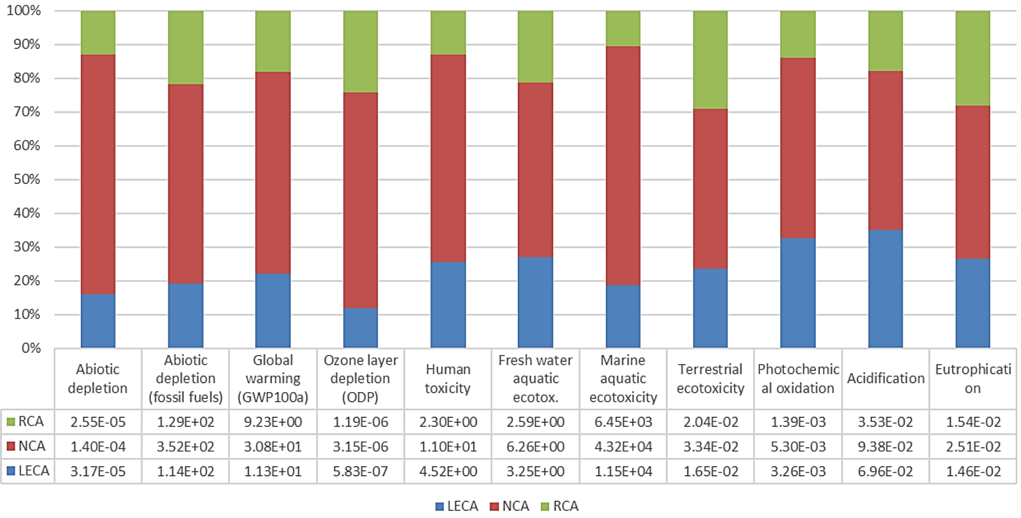
To examine whether the environmental impact of the drainage layer changes with variations in the material used, a sensitivity analysis of the drainage layer was conducted. This analysis aimed to evaluate the potential impact differences associated with altering the material composition of the drainage layer.

3.1.1. Sensitivity Analysis of the Drainage Layer

Figure 5 presents the variations observed among the three coarse aggregate layers. Notably, the Natural Coarse Aggregate (NCA) exhibits the highest impact across all impact categories, demonstrating impacts that are 26% to 85% higher compared to the other materials. In contrast, the Lightweight Expanded Clay Aggregate (LECA) shows relatively lower impacts in specific categories, namely Abiotic depletion (Fossil fuels), Ozone layer depletion, Terrestrial ecotoxicity, and Eutrophication.

On the other hand, Recycled Concrete Aggregate (RCA) demonstrates the lowest environmental impact across seven out of the remaining impact categories, with reductions ranging from 4% to 36% when compared to LECA. Considering the complete set of impact categories, it can be concluded that RCA exhibits the lowest overall environmental impact compared to other materials. Consequently, RCA has been incorporated into Type 3 to assess the potential for significant reductions in the overall environmental impact by solely modifying this layer. This new configuration is called Type3_SA.

Table 4 provides a comprehensive juxtaposition of the overall environmental impact between Type 3 and Type 3_SA, wherein the drainage layer transitions from Lightweight Expanded Clay Aggregate (LECA) to Recycled Concrete Aggregate (RCA). Remarkably, the adoption of RCA as the drainage layer engenders a pronounced reduction in impact across seven out of the eleven impact categories. Notably, significant improvements are observed in the Photochemical oxidation and Acidification impact categories, exhibiting an enhancement of 37% and 38%, respectively. However, it is important to highlight that Type 3_SA exhibits an adverse effect on the Ozone layer depletion impact category, with an increase of 45% compared to Type 3.



	Abiotic depletion	Abiotic depletion (fossil fuels)	Global warming (GWP100a)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication
🟩 RCA	2.55E-05	1.29E+02	9.23E+00	1.19E-06	2.30E+00	2.59E+00	6.45E+03	2.04E-02	1.39E-03	3.53E-02	1.54E-02
🟥 NCA	1.40E-04	3.52E+02	3.08E+01	3.15E-06	1.10E+01	6.26E+00	4.32E+04	3.34E-02	5.30E-03	9.38E-02	2.51E-02
🟦 LECA	3.17E-05	1.14E+02	1.13E+01	5.83E-07	4.52E+00	3.25E+00	1.15E+04	1.65E-02	3.26E-03	6.96E-02	1.46E-02

Figure 5 *Impact of the three coarse aggregates*

Moreover, a detailed examination of the distinct life cycle stages is warranted to identify the points at which Type 3_SA undergoes notable changes and to facilitate a comparative analysis with Type 1 and Type 3. Figure C.1. in the Supplementary Information visually depicts the distribution of impacts across the various life cycle stages for the different types.

In the production stage, Type 3_SA shows improved environmental performance compared to Type 3, with reductions ranging from 12% to 65% in all impact categories. Moreover, Type 3_SA outperforms Type 1 in eight out of eleven impact categories. Moving to the installation stage, Type 3_SA still has the highest impact, mainly due to its assembly's weight. However, the performance gap between Type 3_SA and the other types becomes more evident at this stage. At the end-of-life stage, Type 3_SA's results align with previous observations, except for scoring poorly in the eutrophication and Acidification categories, with a respective increase of 21% and 19%.

Table 4 *Comparison between the impact of Type 3 and Type3_SA*

Impact category	**Unit**	**Type 3**	**Type 3_SA**
Abiotic depletion	[kg Sb eq]	6.10E-05	5.48E-05
Abiotic depletion (fossil fuels)	[MJ]	2.57E+02	2.72E+02
Global warming (GWP100a)	[kg CO2 eq]	1.86E+01	1.66E+01
Ozone layer depletion (ODP)	[kg CFC-11 eq]	7.30E-07	1.34E-06
Human toxicity	[kg 1,4-DB eq]	9.17E+00	6.95E+00
Fresh water aquatic ecotox.	[kg 1,4-DB eq]	1.14E+01	1.08E+01
Marine aquatic ecotoxicity	[kg 1,4-DB eq]	2.19E+04	1.68E+04
Terrestrial ecotoxicity	[kg 1,4-DB eq]	2.29E-02	2.68E-02
Photochemical oxidation	[kg C2H4 eq]	5.01E-03	3.14E-03
Acidification	[kg SO2 eq]	8.89E-02	5.47E-02
Eutrophication	[kg PO4--- eq]	2.12E-02	2.21E-02

3.2. Environmental Assessment of the Substrate Part

Aligned with the established structure, the environmental impact of the substrates is visually presented in Figure 6, with comprehensive specifics provided in Table D.1. in the Supplementary Information. Upon deeper exploration of the environmental assessment for the three substrates, it is evident that Substrate 2 displays the greatest environmental impacts. In contrast, Substrate 3, which excludes artificial materials like LECA and consists of fewer components than Substrate 1 with its five materials, demonstrates a notable environmental advantage compared to Substrate 1.

Notably, substrate 2 appears to have the greatest environmental impact, as evidenced by its impact values ranging from 41% to 78% higher than those of the other alternatives. Conversely, substrate 3 stands out as the least impactful, with values ranging from 50% to 78% lower than those of substrate 1, and from 3% to 24% lower than those of substrate 2. Despite these distinctions, substrate 1 has a lower ozone-depleting impact.

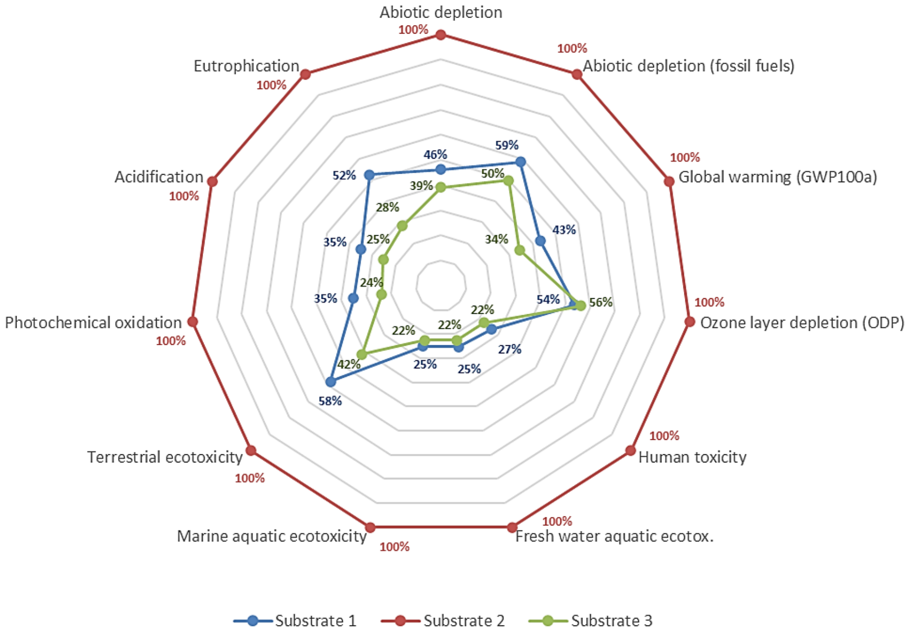


Figure 6 *Impact of the three proposed green roof substrates.*

Figure D.1. in the supplementary data presents an overview of how environmental impacts are distributed across various life cycle stages within the specified system boundaries for each impact category. Analysing the various stages of the life cycle, we find out that the use phase, which includes annual fertilization, exerts the greatest environmental impact throughout the life cycle of substrates 1 and 3.

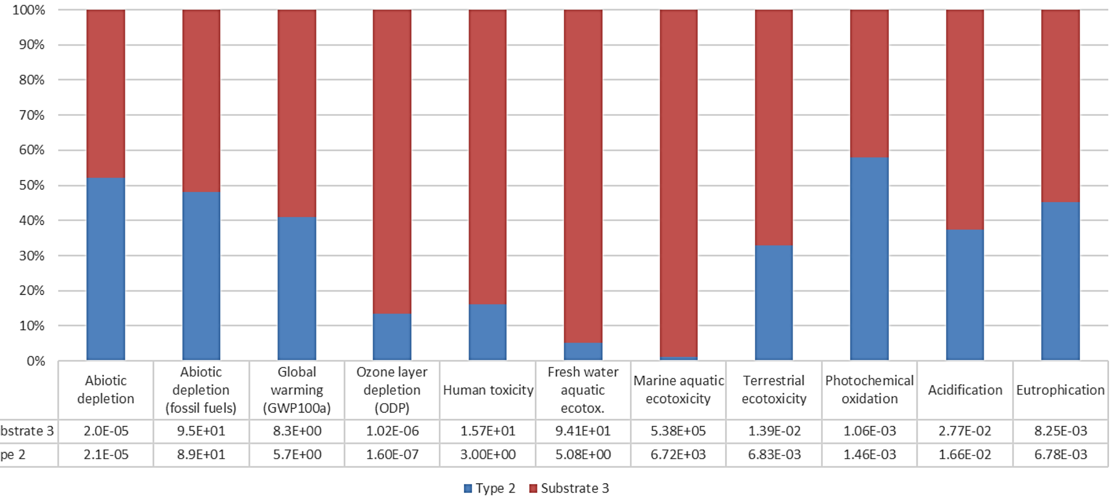
For substrate 1 and substrate 3, the use phase is the most environmentally impactful stage in eight out of the eleven impact categories, making up 39% to 85% and 45% to 88% of their total life-cycle environmental impact, respectively. Interestingly, both substrates exhibit similar unfavourable results in the end-of-life phase for Human toxicity, Fresh water aquatic ecotoxicity, and Marine aquatic ecotoxicity. However, substrate 2 follows a different pattern. In this case, the use phase is the highest impact stage in four out of the eleven impact categories, including Abiotic depletion, Abiotic depletion (fossil fuels), Ozone depletion (ODP), and Terrestrial ecotoxicity. On the contrary, the production stage has the most significant impact in terms of Global warming (GWP100a), photochemical oxidation, Acidification, and Eutrophication, contributing 33%, 57%, 54%, and 44%, respectively, to the overall impact.

To comprehensively assess the overall impact of an extensive green roof, we established a connection between the substrate and structural components. In the following section, we paired the substrate with the least environmental impact alongside the structural part having the least environmental impact. This approach allows us to gain a holistic perspective on the environmental implications of a 1m² extensive green roof in the context of Norway.

3.3. Scenarios of the municipal green roof strategy in Oslo

In this section, we present a thorough examination of the minimal expected environmental impact of extensive green roofs in Oslo, in alignment with the municipality's Green Roof Strategy. As a result, the green roof configuration (Type 2 + Substrate 3) is as follows: a lightweight polyethylene root barrier, a water retention felt crafted from recycled textiles, and a nonwoven polypropylene filter layer constitute the structural base, while the substrate is composed of 70% pumice, 20% gravel, and 10% compost. This combination results in a green roof with a total height of 22.3 mm and a weight of 61.68 kg/m².

Figure 7 visually depicts the distribution of impact between Substrate 3 and Type 2 in our chosen green roof configuration. Notably, the substrate accounts for a significant share of the overall impact. Among eleven categories, Substrate 3 demonstrates the highest impact in nine of them. However, it is essential to note that Type 2 performs 8% worse in Abiotic depletion and 27% worse in Photochemical oxidation compared to the substrate.



	Abiotic depletion	Abiotic depletion (fossil fuels)	Global warming (GWP100a)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication
🟥 Substrate 3	2.0E-05	9.5E+01	8.3E+00	1.02E-06	1.57E+01	9.41E+01	5.38E+05	1.39E-02	1.06E-03	2.77E-02	8.25E-03
🟦 Type 2	2.1E-05	8.9E+01	5.7E+00	1.60E-07	3.00E+00	5.08E+00	6.72E+03	6.83E-03	1.46E-03	1.66E-02	6.78E-03

Figure 7 *Distribution of impact shares for the least Impactful green roof type and substrate composition*

Table 5 consolidates the eleven impact categories assessed for each implementation scenario. Remarkably, a substantial difference of 54% exists between S1 (Green roof strategy scenario) and the S0 (Reference scenario), while the S2 (Ambitious scenario) shows a 74% difference from the S0. Furthermore, a comparison between S1 and the S2 reveals that the S2 is 43% more impactful than S1. This trend is attributed to the increased presence of green roofs in the S1 and S2 scenarios, leading to amplified environmental effects compared to the S0 scenario.

Table 5 *Impact of the selected green roof configuration across various implementation scenarios*

Impact categories	Unit	Result		
		S0	*S1*	*S2*
Abiotic depletion	[kg Sb eq]	7.74E+00	1.69E+01	2.97E+01
Abiotic depletion (fossil fuels)	[MJ]	3.50E+07	7.64E+07	1.34E+08
Global warming (GWP100a)	[kg CO2 eq]	2.66E+06	5.81E+06	1.02E+07
Ozone layer depletion (ODP)	[kg CFC-11 eq]	2.25E-01	4.92E-01	8.64E-01
Human toxicity	[kg 1,4-DB eq]	3.57E+06	7.79E+06	1.37E+07
Fresh water aquatic ecotox.	[kg 1,4-DB eq]	1.89E+07	4.12E+07	7.23E+07
Marine aquatic ecotoxicity	[kg 1,4-DB eq]	1.04E+11	2.26E+11	3.97E+11
Terrestrial ecotoxicity	[kg 1,4-DB eq]	3.95E+03	8.62E+03	1.51E+04
Photochemical oxidation	[kg C2H4 eq]	4.80E+02	1.05E+03	1.84E+03
Acidification	[kg SO2 eq]	8.42E+03	1.84E+04	3.23E+04
Eutrophication	[kg PO4--- eq]	2.86E+03	6.25E+03	1.10E+04

4. Discussion

The findings of this comprehensive environmental assessment offer critical insights into advancing the sustainable implementation of green roofs, particularly within the unique context of Norway. As an increasingly popular urban strategy, green roofs' multifunctionality and potential benefits have garnered significant attention. Our study, focusing on the environmental impact of different green roof typologies and substrates, contributes to the understanding of how these systems can align with broader sustainability goals.

Among the examined structural types, Type 2 emerges as a clear front-runner in terms of environmental friendliness. Comprising a root barrier, a water retention layer, and a filter layer, Type 2's distinct advantage stems from its streamlined design, judicious material utilization, while adhering to the national standard's mandatory layers [4]. Notably, the integration of a water retention felt simplifies the system's composition, reducing the need for additional drainage and protection layers. Consequently, this design choice yields superior environmental performance across all assessed impact categories. Notably, the drainage layer emerges as the material with the greatest environmental impact as a result of our examination into the various structural components. Specifically, in Type 1, the drainage layer incurs impacts 41% to 97% higher than other layers across all categories. Similarly, in Type 3, the drainage layer surpasses other layers in impact across ten of eleven categories, with impacts ranging 46% to 96% higher. This finding resonates with findings by Chenani et al. [14], who identified the drainage layer as a primary contributor to environmental impact in green roof layers above the substrate. Furthermore, this observation aligns with the principle that green roofs featuring water retention felt can retain more water without a drainage layer, as supported by relevant reports [5]. Our sensitivity analysis also illuminates the pivotal role of aggregate selection for the drainage layer in shaping overall environmental impact. While recycled aggregates from deconstruction showcase promise compared to their natural counterparts, plastic-based materials maintain an advantage due to the inherent weight of drainage systems using natural aggregates. This aligns with Rincon et al.'s findings [37], highlighting the potential for recycled rubber from used tires to outperform aggregate drainage materials. However, these studies did not consider the potential impact of recycled aggregates. A promising avenue for future research could be to explore the recycling of such aggregates post-green roof dismantling, potentially yielding reduced overall environmental impacts when integrated into green roof systems.

Shifting focus to substrate materials, our study emphasizes the necessity of tailoring substrate choices to specific plant species' requirements. Substrate 3, composed of pumice, gravel and compost, meticulously tailored to the Nordic sedum species' requirements [4], emerges as the substrate with the least environmental impact among the evaluated substrates. Notably, this substrate formulation is judiciously minimalistic in material usage, avoiding artificial components like LECA - a point concurred by Chenani et al. in their study, suggesting the exclusion of expanded clay whenever feasible. This parallel finding aligns with our own, indicating that substrates devoid of LECA exhibit the most environmentally efficient profiles. Moreover, within Substrate 3, annual fertilization emerges as the key driver of environmental impact across eight of the eleven impact categories, constituting 45% to 88% of the total impact. The substantial contribution fertilization prompts consideration for alternative materials to enhance environmental performance.

The synergy between structural and substrate components highlights the dominant influence of substrates on green roof systems' overall environmental impact. Hence, future endeavours should prioritize developing substrates with reduced environmental footprints to bolster the sustainability of green roof implementations.

A critical aspect to consider, particularly in the context of Oslo's green roof strategy, is the influence of scaling up green roof implementations. It is logical to assume that as the number of green roofs increases, so do the environmental impacts associated with their production, installation, use, and eventual dismantling. However, a deeper examination reveals a counterbalancing factor that can potentially mitigate these impacts – the water capacity retention of green roofs.

As our study assumed a green roof retention capacity of 5 mm per precipitation event, translating to a retention performance of 35% to 60% during the temperate season, this water-holding capability brings about tangible benefits. These benefits include not only the reduction of flooding and water runoff but also the decreased strain on local water treatment facilities. As the number of green roofs grows, their cumulative water retention potential increases, thereby further lessening the demand on city infrastructure and minimizing the need for expensive flood control measures. This aspect presents an interesting avenue for further research, potentially illustrating a more nuanced relationship between the growing number of green roofs and their overall net environmental impact.

However, quantifying broader benefits, such as thermal performance [38], energy savings [39], noise insulation [2], average cooling effect [1], increasing biodiversity [40], could provide a holistic understanding of green roofs' net environmental impact. Expressing these benefits in terms of environmental impact can elucidate whether the positive contributions outweigh the initial production, installation, and dismantling impacts.

5. Conclusion

This study identified the most suitable materials essential for the successful implementation of green roofs in Oslo and, in parallel, evaluated their environmental impact through a comprehensive life cycle assessment. Through meticulous analysis and evaluation, our research offers valuable insights into the environmental implications of green roof implementations and underscores their significance in sustainable urban development. Three different structural parts (Types), aiming to protect the roof membrane and support the growing medium, and three different substrates were designed, aligning with the different standards in force.

Our investigation revealed that the structural part which comprises a root barrier, water retention layer, and a filter layer (Type 2), stands out as the most environmentally conscientious choice among the different types. Type 2 exhibits an environmental impact that is substantially 65% to 85% lower across all assessed impact categories when contrasted with the other designs, Types 1 and Type 3. This finding aligns with the need for streamlined designs that minimize impacts while adhering to mandatory layers outlined in national standards. Additionally, the sensitivity analysis highlighted the potential benefits of recycled aggregates in coarse aggregate drainage layers, which showed positive outcomes compared to traditional natural aggregates.

Customization of substrate materials proved equally pivotal, with Substrate 3, formulated from 70% pumice, 20% gravel, and 10% compost, showing the lowest environmental impact among the evaluated options. Notably, the environmental impact values for Substrate 3 showcase a significant reduction, ranging from 50% to 78% lower compared to Substrate 1, and a further 3% to 24% lower compared to Substrate 2. This underscores the importance of tailoring substrates to specific plant species, optimizing both survival rates and environmental performance.

Crucially, the interplay between structural and substrate components showcased the dominant influence of the substrate on the overall environmental impact of green roofs. This emphasizes the need for continued research and development of substrates with reduced environmental footprints to foster more sustainable green roof implementations.

Moreover, our findings resonate with Oslo's strategic objectives, particularly the ambitious green roof strategy aimed at deploying 2030 green roofs by 2030. These results can be instrumental in guiding policy decisions, aiding building owners, and informing stakeholders as they navigate sustainable urban planning and development.

Looking ahead, it is evident that a comprehensive evaluation of the benefits of green roofs must encompass a broader understanding of their positive impacts. By quantifying the avoided environmental costs and expressing them in impact terms, we can gain a holistic perspective on the net contribution of green roofs to the environment. Additionally, future research could explore economies of scale, potentially mitigating overall environmental impacts through large-scale implementation, thus providing further avenues for sustainable urban development.

In closing, our study bridges critical knowledge gaps and offers practical insights into the environmental implications of green roofs in Oslo. As cities worldwide grapple with urbanization and climate change, the integration of green roofs represents a pivotal solution for enhancing environmental sustainability and resilience.

6. Acknowledgements

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8. Supplementary Information

A. Input in Simapro software

The following tables specify each element, process, unit, sources, Ecoinvent input and comment for the different structural and substrate design.

Table A. 1. *Type1'Ecoinvent input into Simparo software*

1 m^2 of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**I, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
TYPE1	**Filter Layer**	Non woven polypropylene	**Non woven polypoprylene**	40	0.2	kg/m^2	0.2			0.2	kg	Chenani et al., 2015	Textile, nonwoven polypropylene {GLO}| market for textile, nonwoven polypropylene | Cut-off, S	
			Process : extrusion							0.2	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.1	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*500km (distance from the supplier in Sweden to the installation site) = 0.1 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00078		0.00078	0.00156	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.2kg = 0.00078 kWh * 2 (construction/deconstruction) = 0.00156 kWh
			End of life: transport lorry to recycling		100	km				0.02	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*100km (distance from the site to the waste treatment plan) = 0.02tkm
			Incineration		100	%				0.2	kg	Chenani et al., 2015	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, S	
	Water retention	Felt	**Recycled textile fiber**	40	1.28	kg/m^2	1.28			1.28	kg	Braskerud, Bent C. (2014).	Textile, nonwoven polypropylene {GLO}| market for textile, nonwoven polypropylene | Cut-off, U	
			Transport		500	km				0.64	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	1,28kg/1000 = 0,00128 t --> 0,00128t*500km (distance from the supplier in Sweden to the installation site) = 0,64 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.004992		0.004992	0.009984		Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 1.28kg = 0.004992 kWh * 2 (construction/deconstruction) = 0.009984kWh
			End of life: transport lorry to recycling		100	km				0.128	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,28kg/1000 = 0,00128 t --> 0,0028t*100km (distance from the site to the waste treatment plan) = 0,128 tkm
			Incineration		100	%				1.28	kg	Own calculation	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, S	
	Drainage	HDPE dimple membrane	**Polyethylene HDPE**	40	1.6	kg/m^2	1.6			1.6	kg	Vacek et al., 2017	Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion							1.6	kg	Vacek et al., 2017	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.8	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	1,6kg/1000 = 0,0016 t --> 0,0016t*500km (distance from the supplier in Sweden to the installation site) = 0,8 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00624		0.00624	0.01248	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 1.6kg = 0.00624 kWh * 2 (construction/deconstruction) = 0.01248 kWh
			End of life: transport lorry to waste treatment plant		100	km				0.16	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,6kg/1000 = 0,0016 t --> 0,0016t*100km (distance from the site to the waste treatment plan) = 0,16 tkm
			Recycling		50	%				0.8	kh	Chenani et al., 2015	Recycling mixed plastics/RER S	
			Incineration		50	%				0.8	kg	Chenani et al., 2015	Waste polyethylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
	Proctection Layer	PP GEOTEXTILE	**Polypropylene granulate (PP)**	40	0.3	kg/m^3	0.3			0.3	kg	Vacek et al., 2017	Polypropylene, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion							0.3	kg	Vacek et al., 2017	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.15	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.3kg/1000 = 0,0003 t --> 0,0003t*500km (distance from the supplier in Sweden to the installation site) = 0,15 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00117		0.00117	0.00234	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.3kg = 0.00117 kWh * 2 (construction/deconstruction) = 0.00234 kWh
			End of life: transport lorry to recycling		100	km				0.03	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	0.3kg/1000 = 0,0016 t --> 0,0003t*100km (distance from the site to the waste treatment plan) = 0,03 tkm
			Incineration		50	%				0.15	kg	Chenani et al., 2015	Waste polypropylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
			Recycling		50	%				0.15	kg	Chenani et al., 2015	Recycling mixed plastics/RER S	
	Root Barrier	Polyethylene (LPDE)	**Polyethylene, low density - LDPE**	40	0.8	kg/m^2	0.8			0.8	kg	Chenani et al., 2015	Polyethylene, low density, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion							0.8	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.4	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.8kg/1000 = 0,0008 t --> 0,0008t*500km (distance from the supplier in Sweden to the installation site) = 0,4 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00312		0.00312	0.00624	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.8kg = 0.00312 kWh* 2 (construction/deconstruction) = 0.00624 kWh
			End of life: transport lorry to recycling		100	km				0.08	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,6kg/1000 = 0,0016 t --> 0,0016t*100km (distance from the site to the waste treatment plan) = 0,16 tkm
			Incineration		50	%				0.4	kg	Chenani et al., 2015	Waste polyethylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
			Recycling		50	%				0.4	kg	Chenani et al., 2015	Recycling mixed plastics/RER S	

Table A. 2. *Type2' Ecoinvent input into simapro software*

1 m^2 of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**C, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
TYPE 2	**Filter Layer**	Non woven polypropylene	**Non woven polypoprylene**	40	0.2	kg/m^2	0.2			0.2	kg	Chenani et al., 2015	Textile, nonwoven polypropylene {GLO}| market for textile, nonwoven polypropylene | Cut-off, S	
			Process : extrusion							0.2	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.1	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*500km (distance from the supplier in Sweden to the installation site) = 0.1 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00078		0.00078	0.00156	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.2kg = 0.00078 kWh * 2 (construction/deconstruction) = 0.00156 kWh
			End of life: transport lorry to recycling		100	km				0.02	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*100km (distance from the site to the waste treatment plan) = 0.02tkm
			Incineration		100	%				0.2	kg	Chenani et al., 2015	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, S	
	Water retention	Felt	**Recycled textile fiber**	40	1.28	kg/m^2	1.28			1.28	kg	Braskerud, Bent C. (2014).	FELT-WATER RETENTION	
			Transport		500	km				0.64	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	1,28kg/1000 = 0,00128 t --> 0,00128t*500km (distance from the supplier in Sweden to the installation site) = 0,64 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.004992		0.004992	0.009984	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 1.28kg = 0.004992 kWh * 2 (construction/deconstruction) = 0.009984kWh
			End of life: transport lorry to waste treatment plan		100	km				0.128	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,28kg/1000 = 0,00128 t --> 0,0028t*100km (distance from the site to the waste treatment plan) = 0,128 tkm
			Incineration							1.28	kg	Own calculation	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, S	
	Root Barrier	Polyethylene (LPDE)	**Polyethylene, low density - LDPE**	40	0.8	kg/m^2	0.8			0.8	kg	Chenani et al., 2015	Polyethylene, low density, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion							0.8	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.4	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.8kg/1000 = 0,0008 t --> 0,0008t*500km (distance from the supplier in Sweden to the installation site) = 0,4 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.023	kWh/kg	0.00312		0.00312	0.00624	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.8kg = 0.00312 kWh* 2 (construction/deconstruction) = 0.00624 kWh
			End of life: transport lorry to waste treatment plan		100	km				0.08	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,6kg/1000 = 0,0016 t --> 0,0016t*100km (distance from the site to the waste treatment plan) = 0,16 tkm
			Incineration		50	%				0.4	kg	Chenani et al., 2015	Waste polyethylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
			Recycling		50	%				0.4	kg	Chenani et al., 2015	Recycling mixed plastics/RER S	

Table A. 3. *Type3’ Ecoinvent input into simapro software*

1 m^2 of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**C, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
TYPE 3	**Filter Layer**	Non woven polypropylene	**Non woven polypoprylene**	40	0.2	kg/m^2	0.2			0.2	kg	Chenani et al., 2015	Textile, nonwoven polypropylene {GLO}| market for textile, nonwoven polypropylene | Cut-off, S	
			Process : extrusion							0.2	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.1	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*500km (distance from the supplier in Sweden to the installation site) = 0.1 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00078		0.00078	0.00156	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.2kg = 0.00078 kWh * 2 (construction/deconstruction) = 0.00156 kWh
			End of life: transport lorry to recycling		100	km				0.02	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	0.2kg/1000 = 0.0002 t --> 0.0002t*100km (distance from the site to the waste treatment plan) = 0.02tkm
			Incineration		100	%				0.2	kg	Chenani et al., 2015	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, S	
	Drainage	LECA	Lightweight Expanded Clay Aggregate (Leca)	40	450	kg/m^3	22.5			22.5	kg	Kazemi et al., 2023	Expanded clay {GLO}| market for | Cut-off, U	22.5kg/1000 = 0.0225 t --> 0,0225t*500km (distance from the supplier in Sweden to the installation site) = 11.25 tkm
			Transport		500	km				11.25	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.08775		0.08775	0.1755	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 22.5kg = 0.08775 kWh * 2 (construction/deconstruction) = 0.1755 kWh
			End of life: transport lorry to recycling		100	km				2.25	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	22.5kg/1000 = 0,0225 t --> 0,0225t*100km (distance from the site to the waste treatment plan) = 2.25tkm
			Landfill		100	%				22.5	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
	Proctection Layer	PP GEOTEXTILE	**Polypropylene granulate (PP)**	40	0.3	kg/m^3	0.3			0.3	kg	Vacek et al., 2017	Polypropylene, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion		2.4	kg				0.3	kg	Vacek et al., 2017	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.15	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.3kg/1000 = 0.0003 t --> 0.0003t*500km (distance from the supplier in Sweden to the installation site) = 0.15 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00117		0.00117	0.00234	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.3kg = 0.00117 kWh * 2 (construction/deconstruction) = 0.00234 kWh
			End of life: transport lorry to recycling		100	km				0.03	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	0.3kg/1000 = 0.0016 t --> 0.0003t*100km (distance from the site to the waste treatment plan) = 0.03 tkm
			Incineration		50	%				0.15	kg	Chenani et al., 2015	Waste polypropylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
			Recycling		50	%				1.2	kg	Chenani et al., 2015	Recycling mixed plastics/RER S	
	Root Barrier	Polyethylene (LPDE)	**Polyethylene, low density - LDPE**	40	0.8	kg/m^2	0.8			0.8	kg	Chenani et al., 2015	Polyethylene, low density, granulate {GLO}| market for | Cut-off, S	
			Process : extrusion		0.8	kg				0.8	kg	Chenani et al., 2015	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	
			Transport		500	km				0.4	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	0.8kg/1000 = 0.0008 t --> 0.0008t*500km (distance from the supplier in Sweden to the installation site) = 0.4 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.00312		0.00312	0.00624	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 0.8kg = 0.00312 kWh* 2 (construction/deconstruction) = 0.00624 kWh
			End of life: transport lorry to recycling		100	km				0.08	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	1,6kg/1000 = 0,0016 t --> 0.0016t*100km (distance from the site to the waste treatment plan) = 0.16 tkm
			Incineration		50	%				0.4	kg	Chenani et al., 2015	Waste polyethylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, S	
			Recycling		50	%				0.4	kg	Chenani et al., 2015	Recycling mixed plastics/RER S	

Table A. 4. *Substrate 1' Ecoinvent input into simapro sofwtare*

1 m^2 of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**I, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
SUBSTRATE 1	**Substrate**	LECA	Lightweight Expanded Clay Aggregate (Leca)	40	450	kg/m^3	2.25			2.25	kg	Chenani et al., 2015	Expanded clay {GLO}| market for | Cut-off, U	
			Transport		500	km				1.125	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*500km (distance from the supplier in Sweden to the installation site) = 1.125 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.039	kWh/kg	0.08775		0.08775	0.1755	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 2.25kg = 0.008775 kWh * 2 (construction/deconstruction) = 0.01755 kWh
			End of life: transport lorry to recycling		100	km				0.225	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*100km (distance from the site to the waste treatment plan) = 0.225tkm
			Recycling							2.25	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Crushed bricks	Crushed bricks	40	1165	kg/m^3	46.6			46.6	kg	Chenani et al., 2015	Crushed Clay brick {RER}| production | Cut-off, U	
			Transport		500	km				25.3	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.18174		0.18174	0.36348	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry to recycling		100	km				4.66	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill							46.6	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Compost	**Compost**	40	500	kg/m^3	25			2.5	kg	Chenani et al., 2015	Compost, at plant/CH U	
			Transport		km					500	km	Own calculation	Transport, lorry >32t, EURO5/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*500km (distance from the supplier in Sweden to the installation site) = 1.125 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.023	kWh/kg	2.3			2.3	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 2.25kg = 0.008775 kWh * 2 (construction/deconstruction) = 0.01755 kWh
			End of life: transport lorry waste treatment plan		100	km				0.25	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*100km (distance from the site to the waste treatment plan) = 0.225tkm
			Landfill		100	%				2.5	kg	Chenani et al., 2015	Municipal solid waste (waste scenario) {Europe without Switzerland}| Treatment of municipal solid waste, landfill | Cut-off, S	
		Slow acting Fertilizer 15g/m^2	**Fertilizer**	1	0.15	kg/m^2		0.15		7.5	kg	Sintef 2012	NPK (15-15-15) fertiliser {RER}| market for NPK (15-15-15) fertiliser | Cut-off, S	15 g/m2 per year over 40 year = 7.5kg
			Transport		500	km				3.75	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	7.5kg/1000 = 0.0075 t --> 0.0075t*500km (distance from the supplier in Sweden to the installation site) = 3.75 tkm

Table A. 5. *Substrate 2' Ecoinvent input into simapro sofwtare*

1 m ^{2} of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**I, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
SUBSTRATE 3	**Substrate**	Pumice	**Pumice**	40	450	kg/m^3	31.96			31.96	kg	Hanslin et al., 2018	Pumice {GLO}| market for | Cut-off, U	
			Transport		500	km				15.98	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	31.96kg/1000 = 0.03196 t --> 0.00225t*500km (distance from the supplier in Sweden to the installation site) = 1.125 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.1246		0.1246	0.2492	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 2.25kg = 0.008775 kWh * 2 (construction/deconstruction) = 0.01755 kWh
			End of life: transport lorry to recycling		100	km				3.16	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*100km (distance from the site to the waste treatment plan) = 0.225tkm
			Landfill		100	%				31.96	kg	Chenani et al	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Gravel	**Crushed gravel**	40	1400	kg/m^3	21.42			21.42	kg	Hanslin et al., 2018	Gravel, crushed, at mine/CH U	
			Transport		500	km				10.71	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*500km (distance from the supplier in Sweden to the installation site) = 1.125 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.083538		0.083538	0.167076	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 2.25kg = 0.008775 kWh * 2 (construction/deconstruction) = 0.01755 kWh
			End of life: transport lorry to recycling		100	km				2.142	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*100km (distance from the site to the waste treatment plan) = 0.225tkm
			Landfill		100	%				21.42	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Compost	**Compost**	40	500	kg/m^3	4.05			4.05	kg	Hanslin et al., 2018	Compost, at plant/CH U	
			Transport		500	km				1.125	km	Own calculation	Transport, lorry >32t, EURO5/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*500km (distance from the supplier in Sweden to the installation site) = 1.125 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.015795		0.015795	0.03159	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 2.25kg = 0.008775 kWh * 2 (construction/deconstruction) = 0.01755 kWh
			End of life: transport lorry waste treatment plan		100	km				0.225	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	2.25kg/1000 = 0.00225 t --> 0.00225t*100km (distance from the site to the waste treatment plan) = 0.225tkm
			Landfill		100	%				2.25	kg	Chenani et al., 2015	Municipal solid waste (waste scenario) {Europe without Switzerland}| Treatment of municipal solid waste, landfill | Cut-off, S	
		Slow acting Fertilizer 15g/m^2	**Fertilizer**	1	7.5	kg/m^2		0.15		7.5	kg	Sintef 2012	NPK (15-15-15) fertiliser {RER}| market for NPK (15-15-15) fertiliser | Cut-off, S	15 g/m2 per year over 40 year = 7.5kg
			Transport		500	km				3.75	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	7.5kg/1000 = 0.0075 t --> 0.0075t*500km (distance from the supplier in Sweden to the installation site) = 3.75 tkm

Table A. 6. *Substrate 3' Ecoinvent input into simapro sofwtare*

1 m ^{2} of extensive green roof							Construction	Operation	Deconstruction	Total years 40		Simapro input		Comment
Process	**Layer**	**Element**	**Material / processes**	**Lifetime (year)**	**Aux value**	**Aux Unit**	**I, Per m2·y**	**O, Per m2·y**	**D, Per m2·y**	**Per lifetime**	**Unit**	**Source**	**Ecoinvent**	**Note & assumption**
SUBSTRATE 2	**Substrate**	Vermiculite	**Expanded Vermiculite**	40	279	kg/m^3	5.58			5.58	kg	Vijayaraghavan et Raja, 2014	Expanded vermiculite {GLO}| market for | Cut-off, U	
			Transport		500	km				2.79	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	5.58kg/1000 = 0.00558 t --> 0.00558t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.021762		0.021762	0.043524	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry to recycling		100	km				0.558	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill		100	%				5.58	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Crushed bricks	**Crushed bricks**	40	1165	kg/m^3	23.3			23.3	kg	Vijayaraghavan et Raja, 2014	Crushed Clay brick {RER}| production | Cut-off, U	1165 kg/m^3 crushed brick, 80% of 5 cm substrate1165kg/m^3 x 0,05m x 1m x 1m x 80%
			Transport		500	km				12.815	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.09087		0.09087	0.18174	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry to recycling		100	km				2.33	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill		100	%				23.3	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Sand	**Sand**	40	1600	kg/m^3	16			16	kg	Vijayaraghavan et Raja, 2014	Sand {CH}| market for sand | Cut-off, U	
			Transport		500	km	8			8	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.0624		0.0624	0.1248	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry to recycling		100	km				1.6	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill		100	%				16	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Perlite	**Expanded Perlite**	40						4.44	kg	Vijayaraghavan et Raja, 2014	Expanded Perlite {GLO}| market for | Cut-off, U	
			Transport		500	km				2.22	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh	0.017316		0.017316	0.034632	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry to recycling		100	km				0.444	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill		100	%				4.44	kg	Chenani et al., 2015	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, S	
		Compost	**Compost**	40	500	kg/m^3	25			10	kg	Vacek et al, 2017	Compost, at plant/CH U	
			Transport		500	km				5	km	Own calculation	Transport, lorry >32t, EURO5/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*500km (distance from the supplier in Sweden to the installation site) = 23.3 tkm
			Machinery for construction / deconstruction (1/2): tower crane		0.0039	kWh/kg	0.39			0.039	kWh	Own calculation	Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, S	Tower crane -> 0.0039kWh/kg * 46.6kg =0.18174 kWh * 2 (construction/deconstruction) = 0.36348 kWh
			End of life: transport lorry waste treatment plan		100	km				1	tkm	Own calculation	Transport, lorry >16t, fleet average/RER S	46.6kg/1000 = 0.0466 t --> 0.0466t*100km (distance from the site to the waste treatment plan) = 4.66tkm
			Landfill		100	%				10	kg	Chenani et al., 2015	Municipal solid waste (waste scenario) {Europe without Switzerland}| Treatment of municipal solid waste, landfill | Cut-off, S	
		Slow acting Fertilizer 15g/m^2	**Fertilizer**	1	7.5	kg/m^2		0.15		7.5	kg	Sintef 2012	NPK (15-15-15) fertiliser {RER}| market for NPK (15-15-15) fertiliser | Cut-off, S	15 g/m2 per year over 40 year = 7.5kg
			Transport		500	km				3.75	tkm	Own calculation	Transport, lorry >32t, EURO5/RER S	7.5kg/1000 = 0.0075 t --> 0.0075t*500km (distance from the supplier in Sweden to the installation site) = 3.75 tkm

B. Detailed information about the Structural designs

The following information give the absolute value of each impact categories for the assessed types, as well as an overview of the environmental impact distribution across different life cycle stages for each impact category.

Table B. 1. *Impacts in absolute value of three proposed green roof types.*

Impact category	Unit	Type 1	Type 2	Type 3
Abiotic depletion	[kg Sb eq]	5.89E-05	2.12E-05	6.10E-05
Abiotic depletion (fossil fuels)	[MJ]	2.74E+02	8.85E+01	2.57E+02
Global warming (GWP100a)	[kg CO2 eq]	1.57E+01	5.73E+00	1.86E+01
Ozone layer depletion (ODP)	[kg CFC-11 eq]	3.49E-07	1.60E-07	7.30E-07
Human toxicity	[kg 1,4-DB eq]	9.86E+00	3.00E+00	9.17E+00
Fresh water aquatic ecotox.	[kg 1,4-DB eq]	1.79E+01	5.08E+00	1.14E+01
Marine aquatic ecotoxicity	[kg 1,4-DB eq]	2.21E+04	6.72E+03	2.19E+04
Terrestrial ecotoxicity	[kg 1,4-DB eq]	1.40E-02	6.83E-03	2.29E-02
Photochemical oxidation	[kg C2H4 eq]	3.11E-03	1.46E-03	5.01E-03
Acidification	[kg SO2 eq]	4.04E-02	1.66E-02	8.89E-02
Eutrophication	[kg PO4--- eq]	1.45E-02	6.78E-03	2.12E-02

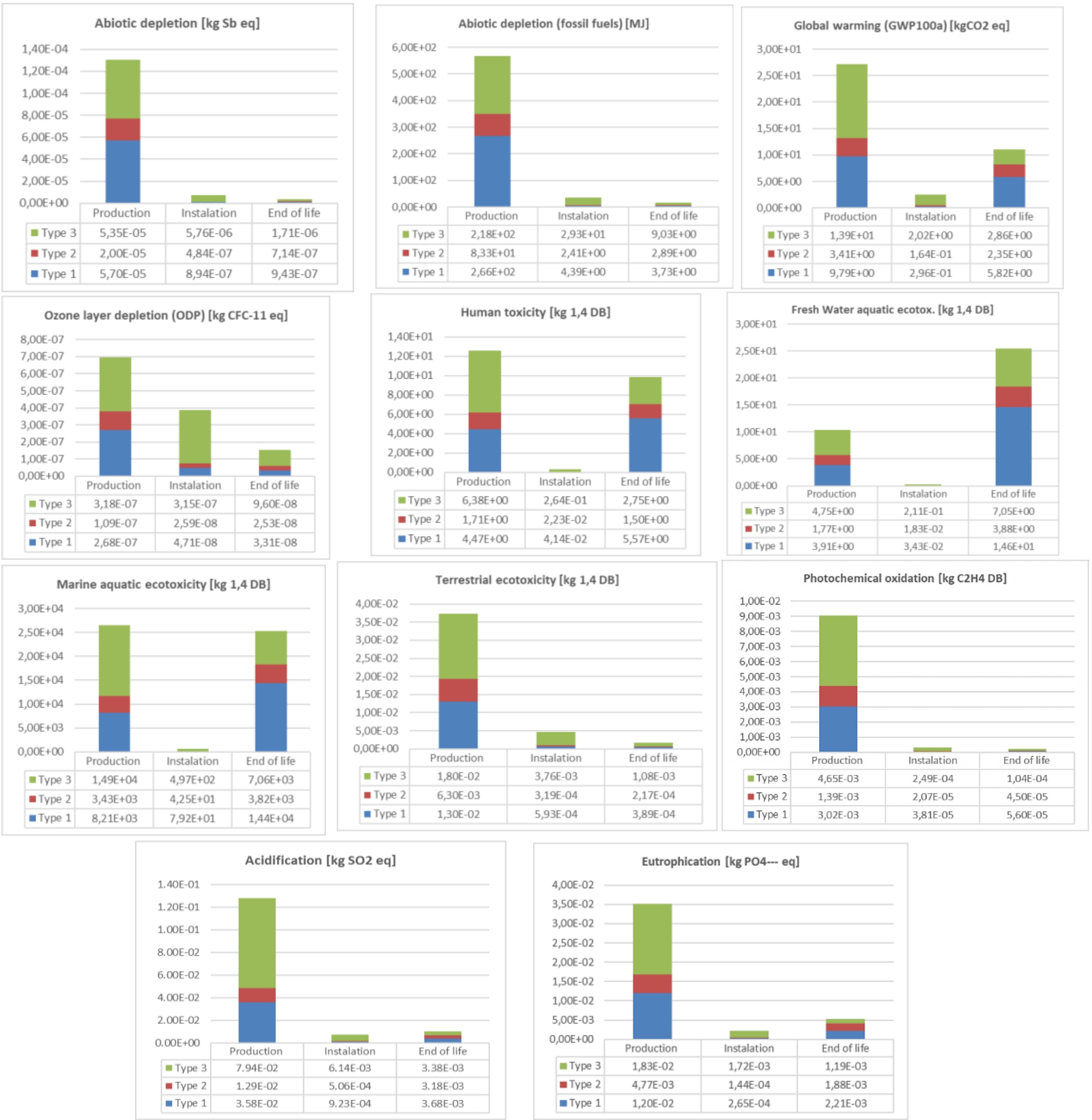

Figure B. 1. *Environmental impact distribution of the three types across different life cycle stages for each impact category*

C. Detailed information about the Sensitivity Analysis

The figures below depict the distribution of impacts across the various life cycle stages for the different types, including Type3_SA wherein the drainage layer transitions from Lightweight Expanded Clay Aggregate (LECA) to Recycled Concrete Aggregate (RCA).

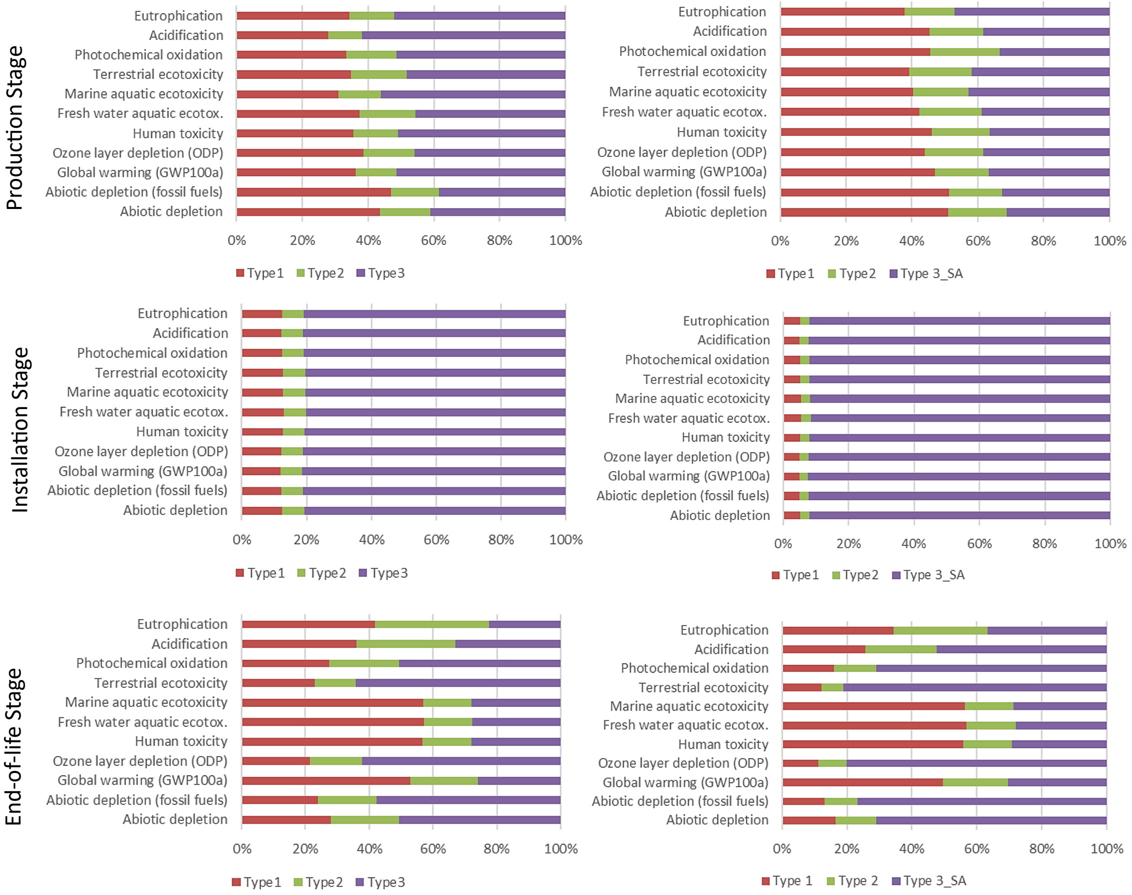

Figure C. 1. *Distribution of impacts across the various life cycle stages for the different types.*

D. Detailed information about the Substrate designs

The following information give the absolute value of each impact categories for the assessed substrates, as well as to an overview of environmental impact distribution across different life cycle stages for each impact category.

Table D. 1. *Impacts of three proposed green roof substrates.*

Impact category	**Unit**	**Substrate 1**	**Substrate 2**	**Substrate 3**
Abiotic depletion	kg Sb eq	2.30E-05	4.97E-05	1.95E-05
Abiotic depletion (fossil fuels)	MJ	1.12E+02	1.91E+02	9.53E+01
Global warming (GWP100a)	kg CO2 eq	1.04E+01	2.41E+01	8.26E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	9.79E-07	1.82E-06	1.02E-06
Human toxicity	kg 1,4-DB eq	1.86E+01	7.01E+01	1.57E+01
Fresh water aquatic ecotox.	kg 1,4-DB eq	1.06E+02	4.18E+02	9.41E+01
Marine aquatic ecotoxicity	kg 1,4-DB eq	6.02E+05	2.40E+06	5.38E+05
Terrestrial ecotoxicity	kg 1,4-DB eq	1.94E-02	3.34E-02	1.39E-02
Photochemical oxidation	kg C2H4 eq	1.57E-03	4.48E-03	1.06E-03
Acidification	kg SO2 eq	3.83E-02	1.09E-01	2.77E-02
Eutrophication	kg PO4--- eq	1.53E-02	2.91E-02	8.25E-03

Abiotic depletion [kg Sb eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	2.15E-06	1.35E-05	1.46E-04	3.89E-06
🟥 Substrate 2	3.10E-05	1.36E-05	1.46E-04	4.59E-06
🟦 Substrate 1	7.58E-06	1.52E-05	1.46E-04	1.90E-06

Abiotic depletion (fossil fuels) [MJ]

	Production	Installation	Use	EOL
🟩 Substrate 3	5.78E+00	6.88E+01	1.16E+02	2.07E+01
🟥 Substrate 2	5.87E+01	6.93E+01	1.16E+02	2.24E+01
🟦 Substrate 1	3.22E+01	7.84E+01	1.16E+02	1.05E+01

Global warming (GWP 100a) [kg CO2 eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	1.21E+00	4.75E+00	8.34E+00	2.29E+00
🟥 Substrate 2	9.14E+00	4.79E+00	8.34E+00	6.28E+00
🟦 Substrate 1	3.92E+00	5.41E+00	8.34E+00	1.74E+00

Ozone layer depletion (ODP) [kg CFC-11 eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	6.01E-08	7.40E-07	9.37E-07	2.24E-07
🟥 Substrate 2	3.52E-07	7.46E-07	9.37E-07	2.45E-07
🟦 Substrate 1	1.20E-07	8.45E-07	9.37E-07	1.14E-07

Terrestrial ecotoxicity [kg 1,4-DB eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	1.36E-03	8.80E-03	2.33E-02	3.76E-03
🟥 Substrate 2	1.07E-02	8.84E-03	2.33E-02	8.48E-03
🟦 Substrate 1	7.93E-03	9.88E-03	2.33E-02	2.65E-03

Marine aquatic ecotoxicity [kg 1,4-DB eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	2.64E+02	1.16E+03	6.60E+03	5.37E+05
🟥 Substrate 2	6.03E+03	1.16E+03	6.60E+03	2.38E+06
🟦 Substrate 1	4.82E+03	1.29E+03	6.60E+03	5.96E+05

Photochemical oxidation [kg C2H4 eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	2.39E-04	5.83E-04	1.14E-03	2.40E-04
🟥 Substrate 2	2.56E-03	5.87E-04	1.14E-03	2.89E-04
🟦 Substrate 1	8.56E-04	6.62E-04	1.14E-03	1.29E-04

Acidification [kg SO2 eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	6.25E-03	1.44E-02	3.83E-02	7.05E-03
🟥 Substrate 2	6.98E-02	1.45E-02	3.83E-02	8.69E-03
🟦 Substrate 1	2.04E-02	1.64E-02	3.83E-02	3.42E-03

Fresh water aquatic ecotox. [kg 1,4-DB eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	1.25E-01	4.93E-01	4.30E+00	9.34E+01
🟥 Substrate 2	1.97E+00	4.93E-01	4.30E+00	4.14E+02
🟦 Substrate 1	1.74E+00	5.41E-01	4.30E+00	1.04E+02

Human toxicity [kg 1,4-DB eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	2.12E-01	6.17E-01	6.92E+00	1.49E+01
🟥 Substrate 2	2.51E+00	6.19E-01	6.92E+00	6.55E+01
🟦 Substrate 1	1.51E+00	6.90E-01	6.92E+00	1.64E+01

Eutrophication [kg PO4--- eq]

	Production	Installation	Use	EOL
🟩 Substrate 3	1.69E-03	4.04E-03	1.17E-02	2.52E-03
🟥 Substrate 2	1.58E-02	4.06E-03	1.17E-02	4.86E-03
🟦 Substrate 1	9.65E-03	4.55E-03	1.17E-02	1.60E-03

Figure D. 1. *Environmental impact distribution of the three substrates across different life cycle stages for each impact category.*