

Envir: LCA of Soil Washing and Recycled Products - Closing the Loop in Soil Remediation



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Summary

Norway's construction sector is responsible for a substantial share of both national mineral extraction and total waste generation, while the country's circularity rate remains significantly below the global average. Against this backdrop, this study has assessed the environmental performance of recycling contaminated soil at Envir's facility in Bergen, compared to the conventional alternative of landfilling and virgin material production.

Using Life Cycle Assessment (LCA) methodology in accordance with ISO 14040/14044 and EN 15804, the study examined Envir's system both as a waste treatment service and as a producer of construction materials. The analysis considered multiple functional units and system boundaries to reflect the multifunctional nature of Envir's operation. The system boundaries are defined by the End-of-Waste criteria (EoW). As the waste holder, Envir defines when the criteria for EoW is reached. Two perspectives were applied: (1) waste treatment of contaminated soil, and (2) product-oriented assessment of recycled materials, including a future scenario for production of the 0–8 mm fraction.

The results show that recycling contaminated soil at Envir's facility performs better than landfilling in nearly all assessed environmental impact categories. For climate change (GWP total), recycling reduces emissions by 28 % per ton of contaminated soil treated compared to the landfill scenario, when accounting for transport and operational energy used for both scenarios. The only impact category where recycling performs worse is water deprivation, primarily due to water consumption in the washing process.

From a product perspective, Envir's recycled materials demonstrate lower environmental impacts than virgin materials in most categories. GWP total is reduced by 74 % for the current production system and by 61 % for the future 0–8 mm production scenario.

Overall, the findings indicate that soil washing and material recovery represent a viable and environmentally beneficial alternative to landfilling contaminated soil, while simultaneously contributing to reduced demand for virgin resources.

Sammendrag

Bygg- og anleggssektoren i Norge står for en betydelig andel av produksjonen av både overskuddsmasser og avfall, samtidig som gjenvinningsgraden i Norge er vesentlig lavere enn det globale gjennomsnittet. Med bakgrunn i dette vurderer denne studien miljøprestasjonen ved gjenvinning av forurenset jord ved Envirs anlegg i Bergen, sammenlignet med det konvensjonelle alternativet bestående av deponering og produksjon av jomfruelige materialer.

Ved hjelp av livsløpsvurderinger (LCA), i samsvar med ISO 14040/14044 og EN 15804 analyserer studien Envirs system både som en avfallshåndteringstjeneste og som produsent av byggematerialer. Analysen omfatter flere funksjonelle enheter og systemgrenser for å reflektere den multifunksjonelle karakteren av virksomheten. Systemgrensene defineres av kriteriene for når massene ikke lenger er å anse som avfall. Som avfallsbesitter er det Envir som fastsetter når disse kriteriene er oppfylt. To analytiske perspektiver er lagt til grunn: (1) avfallshåndtering av forurenset jord, og (2) produktorientert vurdering av resirkulerte materialer, inkludert et fremtidsscenario for produksjon av fraksjonen 0–8 mm.

Resultatene viser at gjenvinning av forurenset jord ved Envirs anlegg gir bedre resultater enn deponering i nesten alle vurderte miljøpåvirkningskategorier. Når det gjelder klimapåvirkning (GWP total), reduserer gjenvinning utslippene med 28 % per tonn behandlet forurenset jord sammenlignet med deponeringsscenariet, med transport og energibruk inkludert i begge scenariene. Den eneste påvirkningskategorien der gjenvinning gir dårligere resultater, er vannforbruk, hovedsakelig som følge av bruk av vann i vaskeprosessen.

Fra et produktperspektiv har Envirs resirkulerte materialer lavere miljøpåvirkning enn jomfruelige materialer i de fleste kategorier. Det totale globale oppvarmingspotensialet (GWP total) reduseres med 74 % for det nåværende produksjonssystemet og med 61 % for det fremtidige produksjonsscenariet for 0–8 mm.

Samlet sett indikerer resultatene at jordvasking og materialgjenvinning representerer et miljømessig gunstig og sirkulært alternativ til deponering av forurenset jord, samtidig som det bidrar til å redusere behovet for uttak av nye mineralressurser.

Nomenclature

Aggregates	Product fractions of different sizes sold after washing
EN 15804	European standard for EPDs for construction products and services
EoW	End of Waste, defined by Waste Framework Directive (Directive 2008/98/EC)
EPD	Environmental Product Declaration
GWP	Global Warming Potential
Internal waste	Materials resulting from the treatment at Envir's facility. Includes metals, asphalt, organic fraction and masses for landfill
ISO 14040	International standard describing the principles and framework for LCA
ISO 14044	International standard describing the requirements and guidelines for LCA
LCA	Life Cycle Assessment

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1 Introduction

1.1 Background

In Norway, virgin materials for construction account for the second-largest share of national extraction. In addition, only a small fraction of excavated material gets recycled, which contributes to a national circularity metric of 2.4 % - well below the global average (de Wit et al. 2020). In recent years, there has been a national and international push towards circular economy, and Norway has the potential to increase its circularity with relatively simple steps. Landfilling is the most common waste management method for contaminated soil excavated and removed from construction sites (H. L. Raadal, Makate, & Smedbye, 2025). A more circular way of handling this type of waste is to recycle it with the aim of producing valuable construction products, both to avoid landfilling and extraction of virgin materials.

In this study, Envir's recycling facility located in Bergen, Norway, has been analyzed. The facility has an annual capacity of 150 000 tons of contaminated soil/excavated materials. Contaminated soil goes through a soil washing plant where contaminants and the smallest fractions are removed, and out comes a range of washed fractions of recycled materials – products - ready for sale.

In this study, the following products have been analyzed:

- Stones; large stones that are sorted out before the material enters the soil washing plant, in addition to some cobblestones and bricks.
- Fractions after soil washing:
 - o 64-90 mm stone
 - o 32-64 mm gravel
 - o 16-32 mm gravel
 - o 8-16 mm gravel
 - o 2-8 mm gravel
 - o 0.125-2 mm sand
 - o 0.063-0.125 mm sand

These seven fractions can be sold as they are, or they can be mixed into other fractions. The most essential of these products in the context of this study is the 0-8 mm fraction, 0-8 mm being a mixture of the three smallest washed fractions (0.063-0.125 mm, 0.125-2 mm and 2-8 mm). Envir's products can be used in construction projects like road construction, backfilling, draining, aggregate for concrete/asphalt and surface water management.

Life Cycle Assessment (LCA) methodology has been applied to compare Envir's circular system to linear systems for treatment of contaminated soil and provision of aggregates for construction and infrastructure projects.

1.2 Aim of the study

The aim of the study is to quantify the potential environmental impacts of the washing and recycling of contaminated soil treated at Envir's recycling facility. Because the facility offers two services; waste treatment of contaminated soil and production of recycled products, the analysis will be performed with

different functional units, depending on if it is the waste treatment or the provision of aggregates that is being analyzed. The system boundaries between these two systems are defined by the End of waste criteria (see Chapter 2.1.7).

In order to demonstrate the benefits of recycling of contaminated soil, the potential environmental impact of treatment of contaminated soil is compared to the most common waste treatment method for contaminated soil in Norway, namely landfilling. The potential environmental impact of recycled products is compared to the production of virgin materials.

This study will provide Envir with information on the potential environmental impacts of their operation and will highlight where in the value chain the largest environmental impacts are. The study will contribute to knowledge on the environmental impact of treatment of contaminated soil, both to the stakeholders that manage contaminated soil and to purchasers of construction materials that can choose recycled products.

In addition, the study will analyze a scenario involving the planned installation of a new mixing station for production of the 0-8 mm fraction. The future production of 0-8 mm fraction will be compared to virgin production of this fraction. This analysis will provide Envir with detailed insight into the performance of the process and the potential environmental impacts of the investment.

2 Methods and systems

As described in Chapter 1, this study applies LCA to compare linear and circular systems for treatment of contaminated soil being excavated as part of infrastructure projects or construction sites. The LCA methodology is described in Chapter 2.1, while Chapter 2.2 provides a description of the system that is being analyzed; Envir's recycling facility vs. landfilling and production of virgin materials.

2.1 Methodology

2.1.1 Life Cycle Assessment (LCA)

A Life Cycle Assessment (LCA) covers the whole life cycle of a product or service and is used to analyze and assess the potential environmental impacts of a product or service along the life cycle. LCA represents a structured, comprehensive and internationally standardized (ISO, 2006a, 2006b) method for quantifying potential environmental and health impacts, resources consumed and resource depletion that are associated with any goods or services ("products"). It is applicable to products, processes, services and organizations, and is used

- to document environmental performance;
- to identify potentials for environmental improvements;
- to compare alternative options as well as to substantiate eco-labelling criteria.

In accordance with the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), Life Cycle Thinking and LCA create a scientific basis for supporting modern environmental policies and business decision support related to sustainable consumption and production.

A life cycle assessment is based on three fundamental principles:

- The entire technical system required to produce, use and dispose of the product (system analysis) is included, and not just the product itself.
- The entire material and energy flow through the value chain of the product is considered, and not just an isolated process or activity.
- Several relevant environmental impact categories for the entire system are considered, and not just one single environmental indicator (e.g. emissions of solvents or dust).

LCA can be used for different purposes, such as comparing different products or services that fulfil the same function, identifying opportunities for improvement in a production system, and as decision support (Baumann & Tillman, 2004). An important reason for applying LCA is to avoid so-called problem shifting. For instance, if one only considers the production stage of products, one might favor products with large environmental impacts in the use or end-of-life stages. Similarly, if one only focuses on a single environmental impact, like climate change, one may favor products with large impacts in other categories like local air pollution or toxicity. With the aid of LCA, such possibilities of problem shifting may be identified and addressed.

2.1.2 LCA framework

The LCA methodology consists of four main steps. In the first step, the purpose of the study and functional unit is determined, as well as the system boundaries of the system of interest. The next step is data collection, i.e. collecting information on material and energy use, emissions, and waste streams for each life cycle phase. The third step consists of calculating mass and energy balance and quantifying environmental effects by converting emissions into potential effects in different environmental impact categories. In the fourth and final step, interpretation of results, the results are discussed as the basis for conclusions and possible further work. This is an iterative process, and the interpretation phase will often make the LCA-practitioner revisit any of the other phases, as presented in Figure 1.

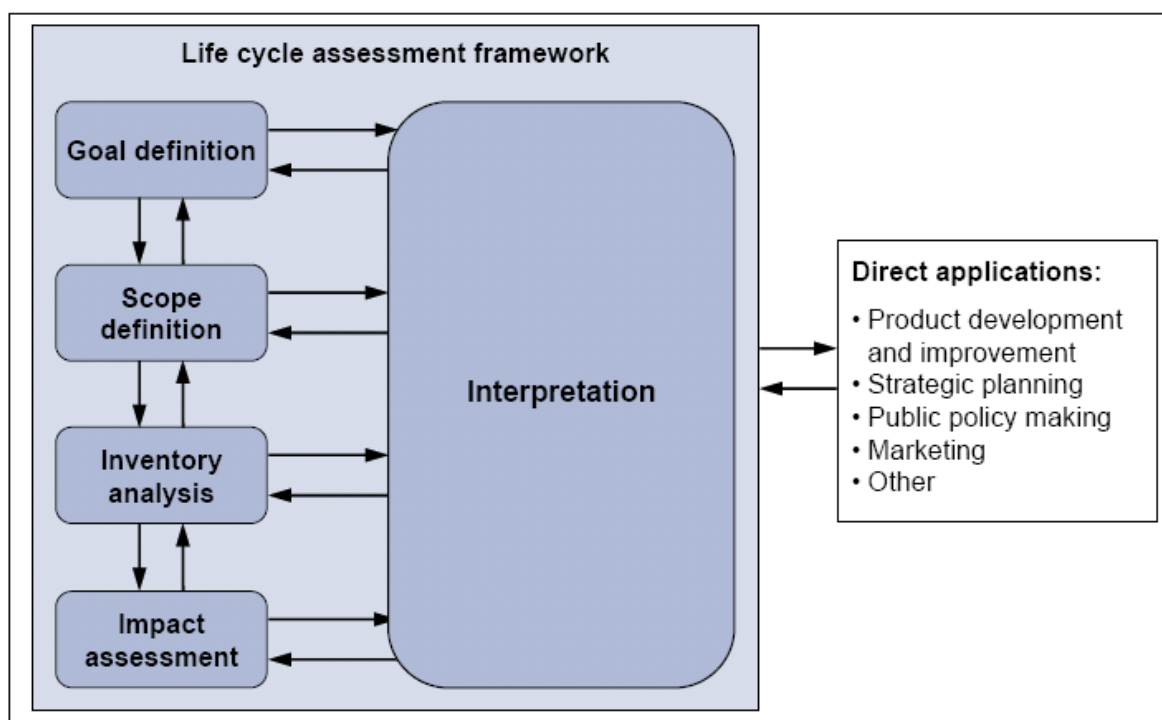


Figure 1 Framework for life cycle assessment, as described by ISO 14040 (ISO, 2006a).

The right hand of the figure shows examples of applications of LCA. Because there are many different uses, the LCA method needs to be flexible. An assessment of a company's production of a specific product requires a different level of detail, modelling and data than an assessment of the World's future energy systems. The ISO-standards describing LCA (14040 and 14044) therefore allow many approaches as long as the general framework is followed.

2.1.3 Environmental product declaration (EPD)

LCA is used for development of environmental product declarations (EPD) according to international standards, with ISO 14025 giving the general guidelines for how LCAs are translated into EPDs. An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products. It can be used for all types of goods and services and is third-party verified, which gives the information credibility and therefore is suitable for procurement. In order to make the information comparable, there are specific rules that define how the EPD shall be developed for specific products or product groups. These rules are called Product Category Rules (PCR) and EPDs based on the same PCR can be compared. The PCR set the rules for the life cycle assessment

that the EPD must meet, such as allocation rules, data quality requirements and system boundaries (EPD International, n.d.). EPD-Norge is the program operator for the Norwegian EPD program and promotes cooperation and harmonization with other environmental declaration programs.

The European standard for EPDs of construction products, EN 15804 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (CEN, 2019), divides the life cycle of a construction product into Modules A, B and C and require the results to be separately reported for each module. The different modules are shown in Figure 2. A cradle-to-grave EPD includes all three modules. The resulting system can be described as a cut-off approach, where the recycling activities are divided between the product being recycled and the product where the recycled material is used. The boundary between the life cycles is defined as the point where the recyclable material becomes a marketable product – this is the point of end-of-waste. A fourth module, Module D, includes benefits and loads that any net outflow of secondary material and energy causes in subsequent life cycles.

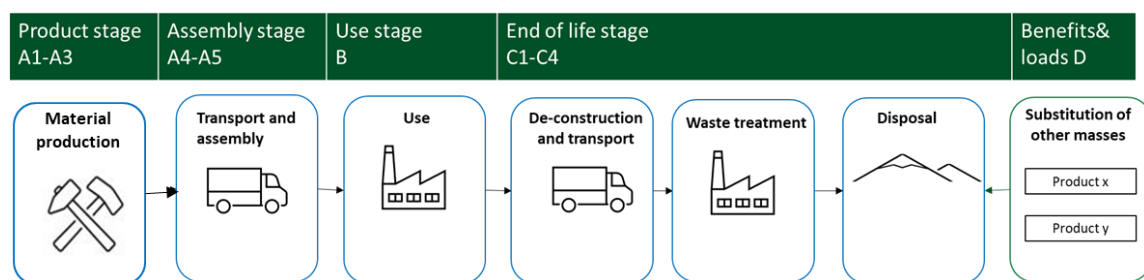


Figure 2 The life cycle stages and corresponding modules in an EPD according to EN 15804 (CEN, 2019).

The EPD system has been chosen as the methodological choice for product-oriented LCA in this study. In accordance with the General Programme Instructions for the international EPD System (EPD International, 2021) and the General Program Instructions for The Norwegian EPD Foundation (The Norwegian EPD Foundation, 2024), allocation of waste and, hence use of recycled material, shall follow the polluter pays principle and its interpretation in EN 15804 (CEN, 2019): “Processes of waste processing shall be assigned to the product system that generates the waste until the end of waste state is reached.” Moreover, the end of waste state is reached when all the following criteria for the end of waste state are fulfilled (adapted from EN 15804):

- The recovered material, component or product is commonly used for specific purposes
- A market or demand, identified, e.g. by a positive economic value, exists for such a recovered material, component or product;
- The recovered material, component or product fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- The use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

2.1.4 Life Cycle Impact Assessment (LCIA) methods

In the impact assessment step of an LCA, all the collected consumption and emission data is assessed in terms of potential environmental impacts. The potential impact is given in environmental impact categories. There are several different environmental impact categories that describe environmental issues. Examples of these are global warming potential, acidification, eutrophication, ozone depletion and environmental toxicity. These are environmental impact categories that give us information on the impact of emissions to nature. There are other impact categories that describe use of resources, both minerals, fossil fuels, water and land.

The total inventory, including all substances coming from or going back to nature, are classified into one or more impact categories. When the emissions have been classified in the right impact category, their potential effect in each category is quantified via characterization factor. The characterization factor relates the effect of a substance to a reference substance. For example, for climate change the reference substance is CO₂, and the potential effect on the climate of all greenhouse gases (GHG) are related to the effect of CO₂, and the emissions of GHGs are given in CO₂-equivalents.

There are several existing methods for life cycle impact assessments that quantify potential impacts within certain environmental categories. A full-scale LCA should cover a broad range of categories in order to avoid problem shifting (solving one problem while causing another), but it is common to select a few that can be considered most important for the system under study. Also, often impact categories follow the same pattern.

In this study the impact categories required by EPD-Global have been selected. These categories are in line with EN 15804+A2 (CEN. 2019).

2.1.5 Functional unit

The environmental load associated with a products life cycle is distributed linearly to a unit of reference, a so-called functional unit (FU). The FU is a quantitative description of a product or service that all input and output of the product life cycle is related to. The function can be related to performance or some properties of the product or service.

For the analysis of waste treatment in this study, the functional unit is 1 metric ton of contaminated soil excavated, transported and washed.

For the analysis of recycled products, the functional unit is 1 metric ton of products ready for transport to customer. This is also used as the functional unit for the analysis of the 0-8 mm fraction.

2.1.6 Allocation

In LCA the term allocation refers to the process of allocating the inputs of energy and materials and output of emissions and waste between co-products in a multi-output system. ISO 14044 and EN 15804 give priority to avoid allocation. This can be done by a more detailed modelling of sub-processes with specified input and output for each process. However, in some cases, allocation is necessary. If it is not possible to gather enough data to split the production into sub-processes or if the sub-processes or processes themselves unavoidably produce more than one product, allocation is required. In that case the environmental burdens can be allocated by different methods that reflect a physical or economic relationship between products and co-products. Different documents produce different rankings of keys to use for allocation. Several application areas recommend the use of economic allocation, because economy is most often the driver for production. At the same time, both prices and use of co-products and waste can fluctuate over time, making it more challenging to use economic allocation. Physical relationships between materials, like mass, volume or energy, can be sensible allocation keys to use in many instances where the status of the multi-products coming out of a process are similar. If physical relationships are used to allocate large environmental burdens to a co-product, this may look like attempts at greenwashing of main products.

An alternative to allocation is system expansion. This is a method where the system is expanded to include the co-products produced in alternative ways. The environmental burden of producing the co-product is subtracted from the system under study.

In this study, the environmental burdens are allocated based on mass.

2.1.7 System boundaries and end-of-waste

When performing an LCA, a model of the product system is constructed. System boundaries define which unit processes to be included in the analysis. A unit process is a production activity in the life cycle of a product for which inputs and outputs are quantified. When the LCA includes all of a product's life cycle stages, i.e. from raw material acquisition through production, use, recycling and final disposal, it is referred to as a cradle-to-grave. LCA methods may also be used for parts of the life cycle, like cradle-to-gate, which include life cycle stages until the factory gate when the product is ready for distribution (i.e. raw material acquisition and production). Other possible system boundaries are gate-to-gate or specific parts of the life cycle.

So, before one can make an LCA-model of a production process or product life cycle, the system boundaries must be established. In addition to defining which processes that belong to the system you want to analyze, the system boundaries include boundaries between nature and the Technosphere (i.e the technical system, man-made), boundaries between the technical system analyzed, and other technical systems (Finnveden et al., 2009), as well as boundaries in space and time.

Often the technical system to be analyzed is divided into a foreground system and a background system. The foreground system includes processes in the supply chain defined by the focal company, and for this system, primary, site-specific data will normally be collected. The background system contains processes taking place in other technical systems, providing auxiliary materials or services. For the background systems, secondary data from databases, public references, or estimated data based on models are used (Li, Zhang, Liu, Ke, & Alting, 2014). Typically, an LCA contains specific data of energy use from a factory under scrutiny (in the foreground system), while production data for the energy sources (in the background system) come from an LCA database.

As mentioned in 2.1.3 waste treatment is part of the value chain to the first user of the material, and the product system for the recycled material starts when the material has reached its end of waste (EoW) state. This means that for an analysis of Envir's system that is both a waste treatment system and a product system, the boundaries between these two systems are defined by the EoW-criteria. According to Article 6 of Directive 2008/98/EC (Waste Framework Directive), it is the waste holder who is responsible for ensuring and demonstrating that the EoW-criteria are fulfilled before a material ceases to be classified as waste. As the waste holder, Envir has defined that the contaminated soil has reached the EoW-state when the materials are washed and separated into the different fractions in their respective compartment after the conveyor belt.

2.2 System to be modelled

This study examines the environmental impacts of a multi-functional system involving the recycling of contaminated soil generated by excavation activities. Even though Envir provides two services, the analysis does not treat the two services as a multi-functional system. Because Envir has defined where in the process the EoW-criteria is met, the analysis treats the services as two separate systems.

2.2.1 Treatment and fractions

Envir receives contaminated soil at their treatment facility mainly by truck. The masses are weighed upon arrival and temporarily stored in the reception area. Before they are mixed with the existing material and fed

into the soil washing plant, visible non-washable items - such as asphalt, large stones, bricks, trees, branches and similar - are removed. Large stones, cobblestones and brick are stored until they are sold. The rest is treated as internal waste.

After the initial removal of these items, the rest of the masses goes into the soil washing plant. A part of the larger stones is crushed before entering the washing plant. After treatment the material is separated into seven fractions. The fractions are:

- Stone: 64-90 mm
- Gravel: 32-64 mm, 16-32 mm, 8-16 mm and 2-8 mm
- Sand: 0.125-2 mm and 0.063-0.125 mm

Using inputs of diesel, electricity, water and flocculant, the masses are treated and largely made available for further sale as seven distinct fractions, shown on the far right of Figure 3. The three smallest fractions of 0.063-0.125 mm, 0.125-2 mm and 2-8 mm can also be combined into a 0-8 mm fraction. Upon customer request, other fractions are also mixed.

Additional outflows arise from the washing process, this time as waste streams. Filter cakes are sent to landfill, organic waste is directed to energy recovery, and asphalt and metals are sent for material recycling. Consequently, the outflows of asphalt and metals may substitute for virgin material production and provide environmental benefits in downstream systems. For these outflows from the waste treatment, the transport to next stage is part of the system and is included.

Transport of sold aggregates from Envir's facility is excluded from the system boundaries.

Figure 3 illustrates the complete value chain from excavation of materials to the production of marketable products after treatment.

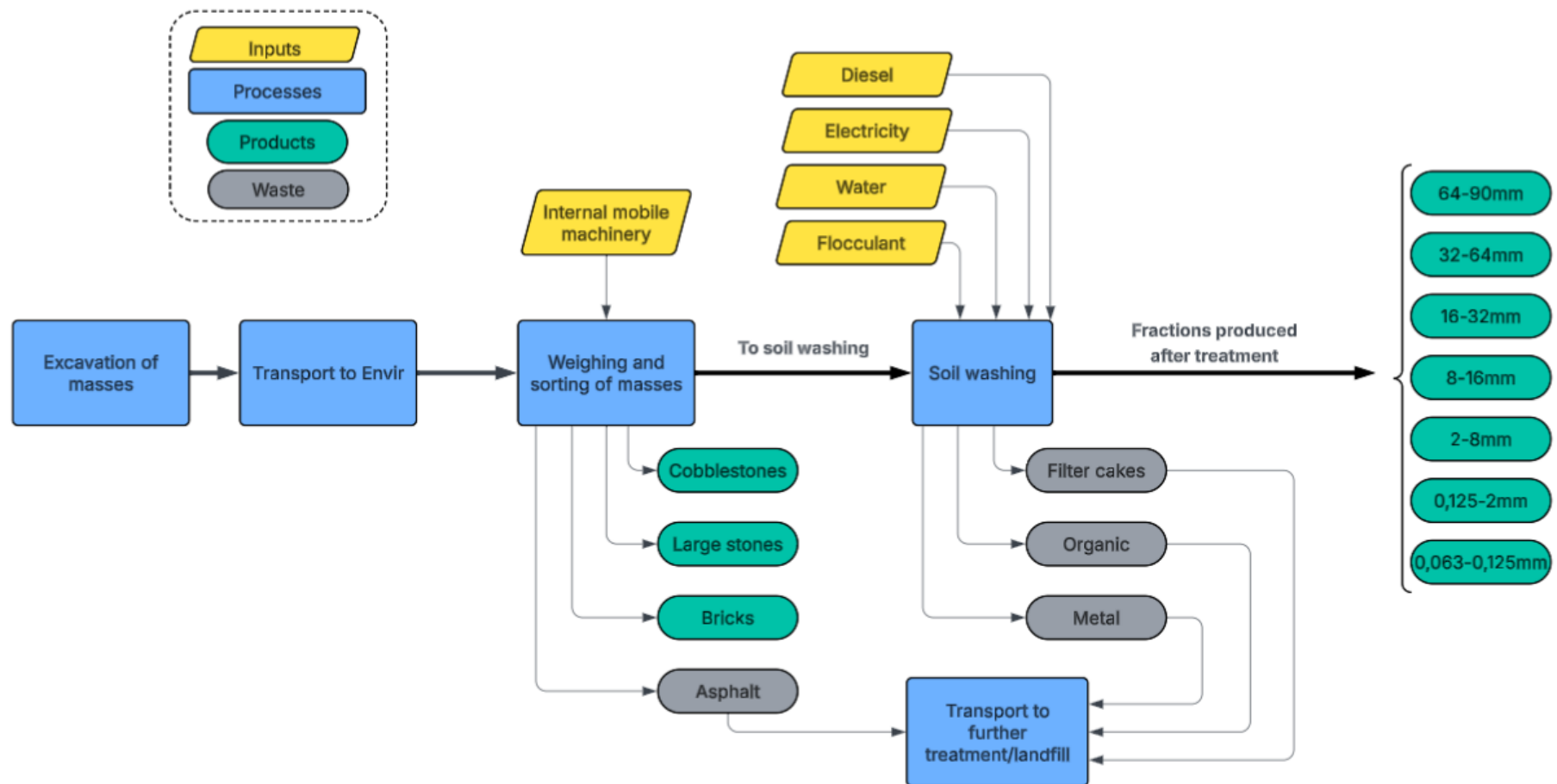


Figure 3 Flowchart illustrating the complete value chain from excavation of materials to the production of marketable products after treatment. Envir's operations center on the weighing and sorting of contaminated soil in the reception zone, followed by treatment through the soil washing process. The figure presents the key input flows required for these processes, as well as the resulting product outputs and waste streams. The end of waste criteria for contaminated soil is met after "Soil washing".

2.2.2 LCA of waste treatment

To investigate the environmental impact of Envir's waste treatment process, an LCA of waste treatment has been conducted. The soil washing at Envir is compared to a landfill scenario, as shown in Figure 4.

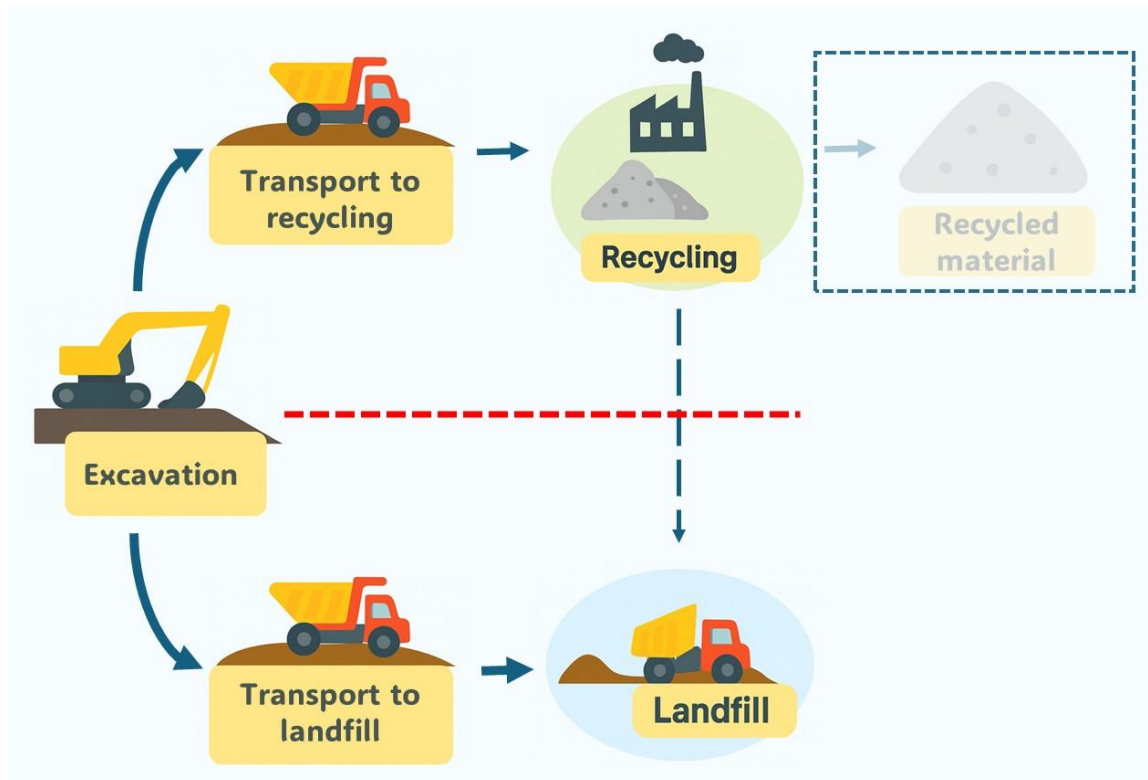


Figure 4 Two LCAs of waste treatment. The top illustrates Envir's system with recycling of material (a small amount goes to landfill) and the rest to products for sale (the process within the blue dashed line is not included in this analysis, it is included for illustrative purposes). The bottom illustrates the alternative system with landfilling. The red dashed line illustrates that this is two separate scenarios. The excavation is included in both scenarios.

Both systems start with transport to the respective locations followed by the waste treatment itself (recycling or landfill). The landfill scenario that Envir's production is compared to, represents avoided emissions. Avoided emissions in LCA are the emissions that would have occurred in a conventional system but are prevented because an alternative product or system replaces it. So, in this study, the avoided emissions are emissions from analysis of a landfill scenario that Envir's operation replace, in addition to the materials that are separated out before or during washing and sent to further treatment.

The end point of assessing Envir's system is determined by the EoW-state, while the end point of the landfill treatment is when the contaminated soil is permanently stored in the landfill. EoW is reached after washing, hence, processes that takes place after that is not within the system boundaries of the waste treatment.

The functional unit for the analysis of both waste treatments is defined as: excavation, transport and waste treatment of 1 ton contaminated soil.

2.2.3 Product-oriented LCAs

To investigate the environmental impact of recycling products a product-oriented LCA has been conducted. In this study, an LCA of Envir's products are compared to EPDs representing corresponding virgin aggregates. For the aggregates sold by Envir, the system boundaries starts when the EoW-state is reached. Hence, the excavation, transport to Envir and soil washing is outside the system boundaries. The LCA ends when the aggregates are ready to leave Envir's facility. The system boundaries for virgin materials starts with extraction of stones from bedrock in a quarry, and similar to Envir's LCA, ends at the gate, i.e. when aggregates are ready for transport.

The two production systems of recycling and virgin production with associated system boundaries, are shown in Figure 5.

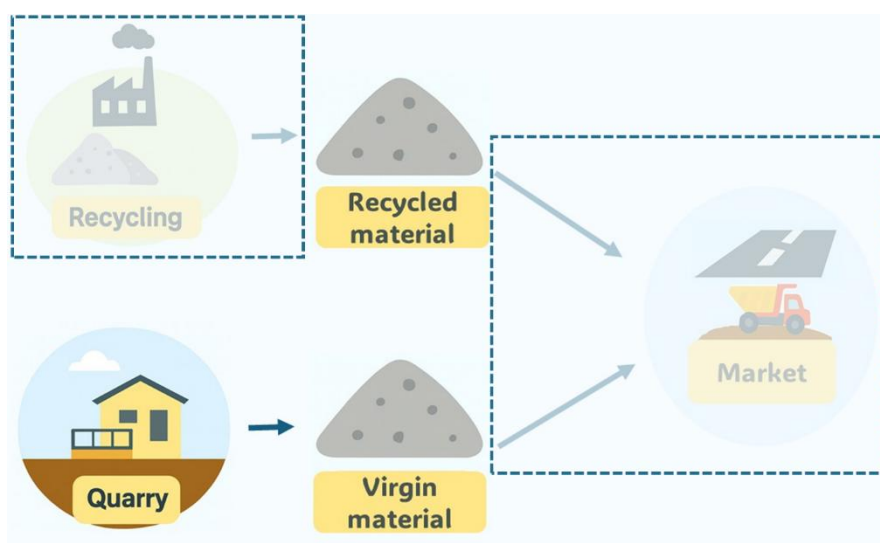


Figure 5 The two production systems for recycled and virgin materials that are compared. The top part of the figure illustrates the process taking place at Envir's site, while the bottom part illustrates virgin production of the same fractions. The processes within the dashed line are not included in the analysis, they are just included for illustrative purposes.

Envir is in the process of installing a new mixing station for 0-8 mm fraction. The future production of 0-8 mm fraction is therefore also analyzed. The 0-8 mm fraction consists of the smallest fractions (2-8 mm, 0.125-2 mm and 0.063-0.125 mm). For comparison, the results from the product-oriented LCA of 0-8 mm are compared to virgin production of 0-8 mm.

The EPD system has been chosen as the methodological choice for the product-oriented LCA in this study. Within The Norwegian EPD Foundation, the PCR for natural stone product, aggregates and fillers are relevant for the products in this study (Product category rules: NPCR 018 Part B for natural stone, aggregates and fillers).

The functional unit for the analysis is defined as: 1 ton of aggregates, ready for the market.

3 Data and assumptions

The data used for modelling the treatment of contaminated soil was derived from Envir, which supplied detailed facility-level information on treated quantities, the composition and volumes of outgoing fractions, residual amounts requiring additional waste handling, and resource inputs. The latter included diesel, electricity, flocculant and water consumption. Transport distances associated with both inbound and outbound flows of waste were also supplied. For the outbound transport of internal waste, a filling rate of 100% was consistently applied. Return trips, however, varied between a 0 % filling rate and being excluded entirely, depending on whether the transporter completed other assignments on the way back. These variations differ across transport stages and are based on stage-specific data and comments provided by Envir. Some data rely on general market-level information, such as the average electricity mix available at the medium-voltage level in Norway, as well as standard emission factors for diesel consumption and lubricating oil use, taken from the ecoinvent 3.11 allocation, cut-off (Wernet et al. 2016). The landfill scenario is based on Nørsterud (2022) and this was also used in Raadal et al. (2025). This is based on a modified version of the ecoinvent-process *Inert waste {Europe without Switzerland} | treatment of inert waste, sanitary landfill / Cut-off, U*. According to Nørsterud (2022), this is the same as used for contaminated soil in VegLCA (at that time, Asplan Viak 2021 was the most recent documentation).

For analysis of the avoided emissions, the virgin production of materials is modelled by use of published EPDs gathered from EPD-Global. These are valid EPDs for production of aggregates in Norway. Virgin production of metals and bricks are modelled by use of the international LCA-database ecoinvent 3.11 allocation, cut-off (Wernet et al. 2016). Transport is modelled by specific transport distances provided by Envir combined with transport process from ecoinvent (Transport, freight, lorry, >32 metric ton, diesel, EURO 5 {RER} | market for transport, freight, lorry, >32 metric ton, diesel, EURO 5 | Cut-off, S).

Envir provided the dataset based on 9 full months of production, covering the period from 1st of January to 1st of October 2025. The use of primary operational data increases the robustness of the analysis due to the high level of technological and operational specificity. In addition, an estimated scenario for a full year production following the planned establishment of a new mixing plant to 0/8 was analyzed. Key data used for the LCA-modelling are presented in Table 1-Table 3.

3.1 LCA of waste treatment

Table 1 provides the key parameters used to model Envir's waste treatment process, i.e. the processes occurring prior to the materials reaching the EoW-state. These data include inputs of contaminated soil (excavation and transport from excavation sites), energy consumption (electricity and diesel), consumption of water and flocculants, and transport of output waste to final waste treatment. The outputs from the waste treatment consist of several waste fractions, including asphalt, metal, and materials destined for landfill or incineration (filter cake and organic fraction). The organic fraction is sent for energy recovery. The organic fraction is modelled assuming a biogenic carbon content of 50 %, which was further assumed to be fully converted to biogenic CO₂ during incineration or landfilling. The calorific value of the organic fraction has been measured by Eurofins. The average calorific value from several samples have been used: 5.38 MJ/kg. In the analysis, this is assumed to substitute district heating. Eviny deliver district heating in Bergen, and the results reported in their EPD is used as proxy for substituted district energy. Virgin production of asphalt is based on EPDs published on EPD-Global in 2025 and 2026. In this period, 11 EPDs are published on EPD-Global for asphalt produced in Norway. The average values from these EPDs are used as proxy for virgin

production of asphalt. The landfill scenario is the same as in Nørsterud (2022) and Raadal et al. (2025). For virgin production of metals, the LCA-database ecoinvent is used.

Table 1 Main information used in the LCA-modelling of the waste treatment. Includes data of 9 full months of production from 1.1.2025-1.10.2025

Parameter	Quantity	Unit
Excavated materials delivered to Envir	82 733	tons
Transport from excavation to Envir (per trip)	9	km
Asphalt sorted out before washing	25	tons
Total transportation to asphalt recovery (14 km, 2 trips)	28	km
Materials entering the washing plant	77 651	tons
Electricity consumption (Norwegian electricity mix)	449 938	kWh
Diesel consumption (internal machinery)	38 649	liters
Water use	3 128	m ³
Flocculant	3 000	kg
Lubrication grease	100	liters
Land occupation from intermediate storage outdoors	11 000	m ²
Filter cake to landfill	16 052	tons
Diesel consumption - transport of filter cakes to harbor	1 500	liters
Diesel consumption - loading filter cakes to ship	880	liters
Boat transportation distance from Envir harbor (255 km, 10 trips)	2 550	km
Diesel consumption - unloading filter cakes from ship	880	liters
Diesel consumption - transport of filter cakes from harbor to landfill	6 260	liters
Metals to recycling	42	tons
Total transportation to metal recycling (30 km, 8 trips)	240	km
Organic fraction to energy recovery	348	tons
Total transportation to energy recycling (18 km, 37 trips)	666	km
Landfill scenario - avoided emissions		
Excavation of masses	82 733	tons
Transport to landfill	14	km
Masses to landfill	82 666	tons
Metals - virgin production pig iron (ecoinvent)	42	tons
Asphalt - virgin production (EPD)	25	tons
District heating	520	MWh

3.2 Product-oriented LCA: all fractions

Table 2 provides the data used for modelling the product-oriented LCA (i.e. the processes taking place after the masses have reached the EoW-state). Some diesel is used for sorting and loading of the fractions. This is the baseline production, i.e. before the new mixing station for the 0-8 mm fraction has been established.

For virgin production of the aggregates, published EPDs on EPD-Global's portal is used. EPDs published between 2024 and 2026 have been used to calculate an average Norwegian production of aggregates. The 10 most recent EPDs for aggregates produced in Norway, in line with NPCR 018 Part B for natural stone, aggregates and fillers, were selected. These EPDs represent virgin production of aggregates of different sizes in Norway. The production steps typically included in the EPDs are:

1. Blasting, producing run-of-quarry rock (sprengstein)
2. Primary crushing, first size reduction
3. Secondary crushing, further reduction of size
4. Tertiary crushing, further reduction of size

For comparison with the aggregates sold by Envir, environmental impact of run-of-quarry rock has been used as proxy for production of the large, natural stones that are picked out before washing. Depending on the information provided in the EPD, primary and secondary crushing has been used as proxy for aggregates of all sizes. As proxy for 0-8 mm, EPDs that provide information on production on concrete admixture have been used.

Table 2 Main information used in the product-oriented LCA. Includes data of 9 full months of production from 1.1.2025-1.10.2025.

Parameter	Quantity	Unit
Recycled materials/products after washing	74 391	tons
Recycled materials sorted out before washing (cobblestone, large stone, bricks)	50+5 000+8	tons
Diesel consumption (internal machinery) - mixing	1 075	liters
Diesel consumption (internal machinery) - loading	16 320	liters
Products for sale		
Fraction 64-90 mm	4 059	tons
Fraction 32-64 mm	17 694	tons
Fraction 16-32 mm	9 342	tons
Fraction 8-16 mm	8 266	tons
Fraction 2-8 mm	12 558	tons
Fraction 0.125-2 mm	15 009	tons
Fraction 0.063-0.125 mm	7 463	tons
Cobblestones and large stones sorted out before washing	50 + 5 000	tons
Bricks sorted out before washing	8	tons
Virgin materials – avoided emissions		
All fractions (EPD)	74 391	tons
Bricks – virgin production clay brick (ecoinvent)	8	tons
Cobblestones and large stones – virgin production gravel (EPD)	50 + 5 000	tons

3.3 Product-oriented LCA: future production of 0-8 mm fraction

Table 3 provides information on the future scenario for production of the 0-8 mm fraction with a mixing station. This includes diesel for loading the material into the mixer and electricity for mixing. In this future scenario, a general increase in amount of material processed is included, hence leading to an increased amount of 0-8 mm also. As proxy for 0-8 mm, EPDs that provide information on production on concrete admixture have been used to represent virgin production.

Table 3 Main information used in the LCA-modelling for the planned future production of fraction 0-8 mm.

Parameter	Quantity	Unit
Electricity consumption mixing station	5 000	kWh
Diesel consumption (internal machinery) - loading	3 500	liters
Fractions for sale		
Fraction 0-8 mm	39 464	tons
Virgin materials – avoided emissions		
0-8 mm fraction (EPD)	39 464	tons

4 Results

The LCA results are presented for waste treatment, recycled products and for the future production 0-8 mm fraction as it is expected to be after the installation of the new mixing station.

4.1 LCA of waste treatment

In Table 4, the results for the two waste treatment scenarios are given. The results are given per ton of contaminated soil that is excavated and transported to the recycling facility or to the landfill and subsequently treated. The impact categories are the same as those used in EPDs.

Table 4 Results for the two waste treatment scenarios per ton treated contaminated soil. The landfill scenario is modelled to fulfill the same function as the Envir waste treatment. The relative difference between the two scenarios is shown to the right as the impact of Envir's waste treatment relative to the traditional landfill scenario. The results are given for the core environmental impact categories that are mandatory according to EN15804. Method: EN15804+A2ad1.03.

Impact category	Unit	Envir waste treatment	Landfill scenario	Difference
GWP - Total	kg CO ₂ eq	8.51	11.78	28 %
GWP - Fossil	kg CO ₂ eq	4.62	7.84	41 %
GWP - Biogen	kg CO ₂ eq	3.89	3.94	1 %
GWP - LU/LUC	kg CO ₂ eq	1.70E-03	2.59E-03	35 %
Ozone depletion ODP	kg CFC11 eq	9.09E-08	1.19E-07	24 %
Acidification	mol H ⁺ eq	3.47E-02	5.42E-02	36 %
Eutrophication EP, freshwater	kg P eq	6.54E-04	2.60E-03	75 %
Eutrophication EP, marine	kg N eq	1.55E-02	2.30E-02	32 %
Eutrophication EP, terrestrial	mol N eq	1.67E-01	2.50E-01	33 %
Photochem ozone POCP	kg NMVOC eq	5.15E-02	7.80E-02	34 %
Res, min-met ADP	kg Sb eq	7.03E-06	7.87E-06	11 %
Res, fossils ADP	MJ	63.52	106.13	40 %
Water depriv AWARE	m ³ depriv.	1.94	0.56	-244 %

Table 4 shows that the impact from the landfill scenario is higher than Envir's waste treatment in all but one of the impact categories. For the GWP total, Envir's waste treatment results in a 28 % lower impact than the landfill scenario. For water deprivation, Envir's waste treatment is 244 % higher than the landfill scenario.

In Figure 6 the impact in GWP total for both waste treatments are shown per life cycle activity. The Landfill scenario includes the additional activity production of metal, asphalt and district heating in order to fulfil the same service as Envir's waste treatment. Envir's waste treatment includes excavation, transport to Envir, transport to recycling for metal and asphalt, treatment of metal scrap, transport of organic fraction to energy recycling, incineration of the organic fraction and transport to landfill for the filter cakes.

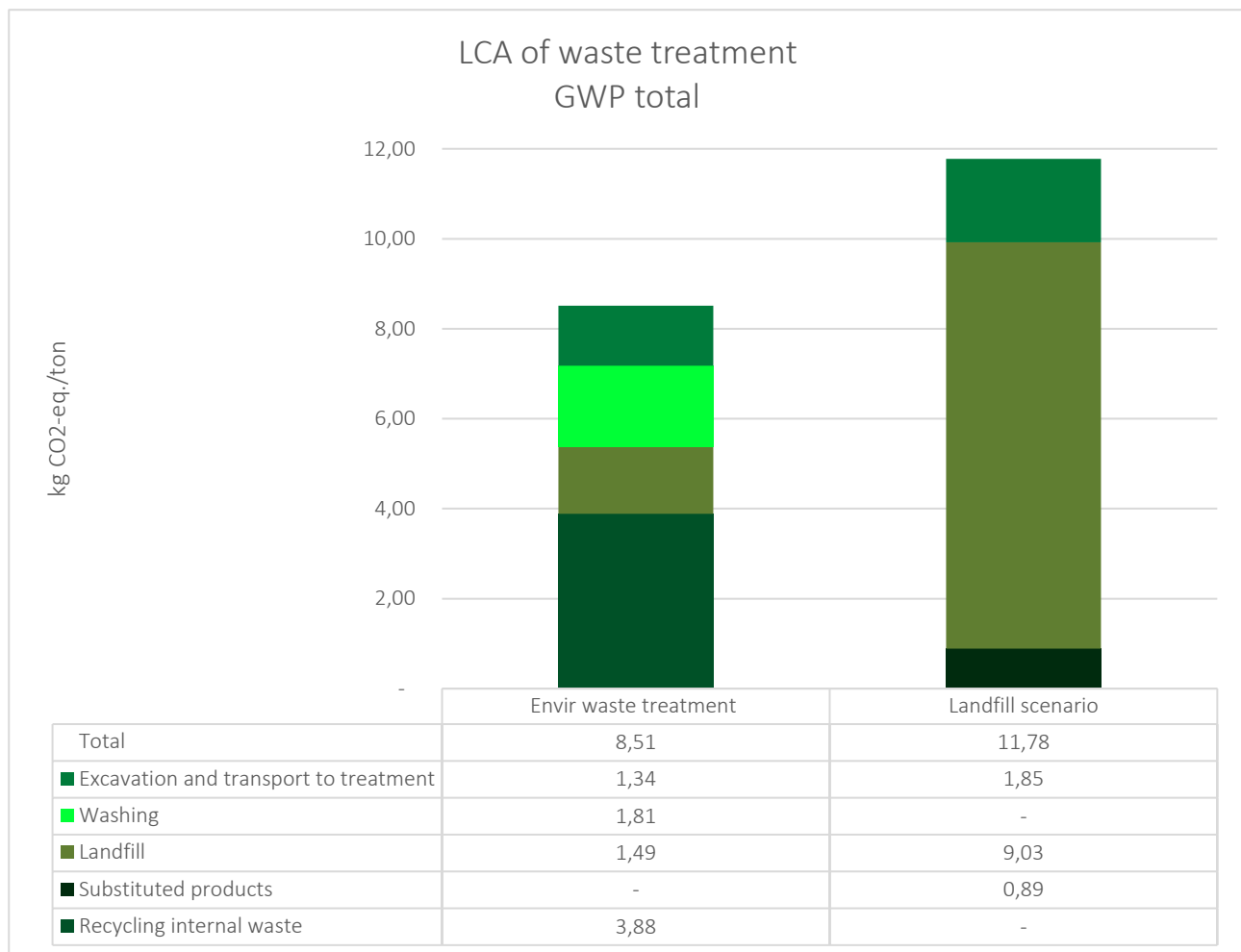


Figure 6 Impact for GWP Total related to Envir's waste treatment for contaminated soil compared to a landfill scenario. The results are given per ton contaminated soil excavated, transported and treated.

Figure 6 shows that Envir's recycling facility performs better for GWP total compared to the landfill alternative with a result of 8.51 kg CO₂-eq/ton contaminated soil, which is 28 % lower than the impact from the landfill alternative (11.78 kg CO₂-eq/ton contaminated soil). Although emissions from the recycling of internal waste constitute the dominant contribution within the recycling scenario (transport to recycling, treatment of waste and biogenic CO₂ emissions from organic fraction), the overall GWP total remains lower than that of the landfill alternative. For the landfill scenario, it is the landfilling process itself that causes the largest impact, and a large part of this impact is caused by the direct emissions from machines used at the landfill.

Looking more closely at the washing process, we see that the organic fraction contributes to 45 % of the impact to GWP total, see Figure 7. Following this, the use of digger at the facility, landfill and transport to the treatment facility are the most important processes for the impact to GWP total. It is the use of fossil fuels in hydraulic diggers that are the single most important factor, so a shift to electric construction machines will reduce the impact to GWP total and GWP fossil.

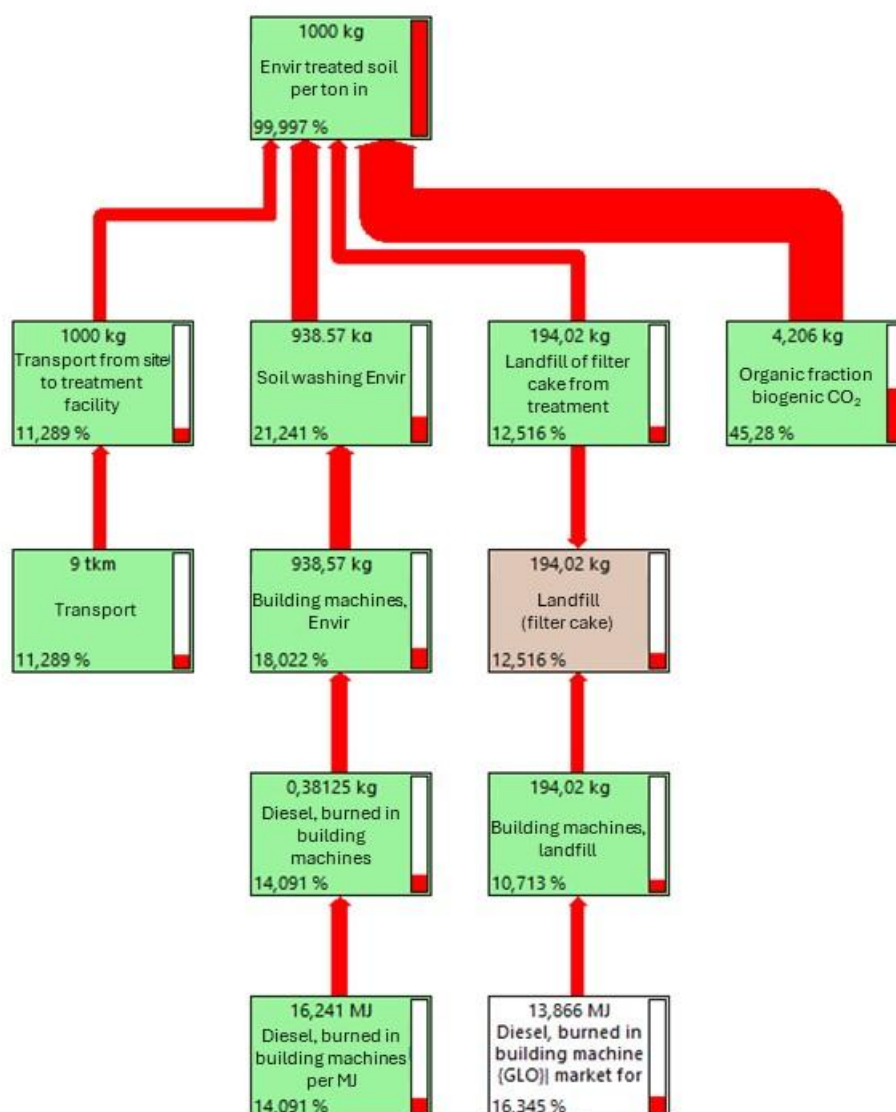


Figure 7 LCA network showing the relative contribution to GWP total from the processes taking place at Envir's facility. The thickness of the arrows indicates the relative contribution to the total impact. A 10% cut-off has been used, meaning that processes contributing to less than 10 % of the total impact are not visible in the figure. The color of the boxes is from the LCA-software and does not have a meaning.

4.2 Product-oriented LCA: all fractions

In Table 5 the results for the product-oriented LCA for all fractions/products are given. The results are given per ton of products ready for sale. For comparison, results for virgin materials are included in the table. Because mass allocation is used, the impact per ton is the same for all fractions. The indicators are the same as those used in EPDs.

Table 5 Results for the production of recycled products at Envir facility compared to production of virgin materials. The results are shown per ton product. The relative difference between the two production routes is shown to the right as the impact of Envir's production relative to virgin production (represented by EPD). The results are given for the core environmental impact categories that are mandatory according to EN15804. Method: EN15804+A2ad1.03.

Impact category	Unit	Envir products	Virgin products	Difference
GWP - Total	kg CO ₂ eq	0.86	3.33	74 %
GWP - Fossil	kg CO ₂ eq	0.86	3.33	74 %
GWP - Biogen	kg CO ₂ eq	1.74E-04	2.09E-03	92 %
GWP - LU/LUC	kg CO ₂ eq	8.81E-05	9.84E-04	91 %
Ozone depletion ODP	kg CFC11 eq	1.28E-08	4.04E-07	97 %
Acidification	mol H ⁺ eq	7.70E-03	9.69E-02	92 %
Eutrophication EP, freshwater	kg P eq	2.78E-05	8.62E-05	68 %
Eutrophication EP, marine	kg N eq	3.58E-03	3.25E-02	89 %
Eutrophication EP, terrestrial	mol N eq	3.92E-02	5.12E-01	92 %
Photochem ozone POCP	kg NMVOC eq	1.17E-02	9.80E-02	88 %
Res, min-met ADP	kg Sb eq	3.07E-07	2.37E-05	99 %
Res, fossils ADP	MJ	11.21	39.26	71 %
Water depriv AWARE	m ³ depriv.	0.02	42.74	100 %

Production of recycled products at Envir's facility results in lower impact relative to production of virgin materials in all impact categories. GWP total is 74 % lower for Envir's products than for virgin products, represented by EPD-results.

4.3 Product-oriented LCA: future production of 0-8 mm

In the following, results for the future production of 0-8 mm fraction are given in Table 6. The results are given per ton of 0-8 mm ready for sale. For comparison, results for virgin 0-8 mm fraction are included in the table. The impact categories are the same as those used in EPDs.

Table 6 Results per ton 0-8 mm produced both at Envir's recycling facility and an alternative virgin scenario. The results are shown per ton product. The relative difference between the two production routes is shown to the right as the impact of Envir's production relative to virgin production (represented by EPD). The results are given for the core environmental impact categories that are mandatory according to EN15804. Method: EN15804+A2ad1.03.

Impact category	Unit	Future production 0-8 mm	Scenario: virgin products	Difference
Climate change - Total	kg CO ₂ eq	1.29	3.26	61 %
Climate change - Fossil	kg CO ₂ eq	1.29	3.25	60 %
Climate change - Biogen	kg CO ₂ eq	2.61E-04	3.13E-03	92 %
Climate change - LU/LUC	kg CO ₂ eq	1.04E-04	1.00E-03	90 %
Ozone depletion ODP	kg CFC11 eq	2.27E-08	3.06E-07	93 %
Acidification	mol H ⁺ eq	1.17E-02	5.01E-02	77 %
Eutrophication EP, freshwater	kg P eq	3.11E-05	1.12E-04	72 %
Eutrophication EP, marine	kg N eq	5.47E-03	1.74E-02	69 %
Eutrophication EP, terrestrial	mol N eq	5.99E-02	2.85E-01	79 %
Photochem ozone POCP	kg NMVOC eq	1.79E-02	5.50E-02	67 %
Res, min-met ADP	kg Sb eq	3.57E-07	1.63E-05	98 %
Res, fossils ADP	MJ	16.76	36.8	54 %
Water depriv AWARE	m ³ depriv.	0.03	32.7	100 %

The future production of 0-8 mm at Envir's facility results in lower impacts relative to virgin 0-8 mm for all impact categories. GWP total is 61 % lower for Envir's 0-8 mm fraction than for virgin 0-8 mm fraction, represented by EPD-results.

5 Conclusions

This study demonstrates that recycling contaminated soil through soil washing and material recovery at Envir's facility provides clear environmental advantages compared to the prevailing landfill-based treatment system in Norway. When evaluated from a waste treatment perspective, the recycling alternative reduces greenhouse gas emissions and most other environmental impacts, except water use. This is true even after accounting for the energy and transport required for treatment and the waste treatment itself.

From a product-oriented perspective, recycled products recovered at Envir's facility generally outperform virgin products across all impact categories defined in EN 15804. The results confirm that recycled materials can serve as environmentally competitive substitutes for primary materials in construction applications. The planned installation of a new mixing station for the 0–8 mm fraction further strengthens this position, maintaining lower environmental impacts compared to virgin production while enabling increased utilization of recycled products. For comparison with virgin products, the environmental profile of the substituted products is important. Petrovic and Raadal (2024) have demonstrated that the variability in reported EPD values is large. Using values from several EPDs has been done as an attempt to avoid this source of error.

Although water use remain an important improvement area, the overall results support soil washing as a key strategy for advancing circular economy principles in the Norwegian construction sector. By diverting contaminated soil from landfill and transforming it into marketable construction products, Envir's system contributes both to improved waste management and to reduced extraction of virgin materials. The occupation of area is not included in the assessment, but acquisition of virgin material will continually require new land areas. With washing of contaminated soil and production of recycled aggregates, the same materials can be used over and over again.

The study thus provides robust environmental documentation that can support decision-making for Envir, waste owners and construction material purchasers, and at the same time highlights the potential for scaling up circular solutions within Norway's construction value chain.

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