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MASTER THESIS

Environmental impact evaluation of leachate treatment in semi aerobic landfill through life cycle assessment

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Abstract

Landfilling is an unavoidable component of a municipal waste management system; being the least sustainable option, it is on the other hand essential to manage waste materials that cannot be recycled or recovered in other ways.

Various technologies have been studied to minimize the impacts deriving from landfills, which today are complex engineering works.

The semi aerobic landfill method has been developed in Japan a few decades ago; its configuration alternates aerobic and anaerobic zones that allow to accelerate the waste stabilization, reducing the aftercare period and costs. It can be considered a compromise between an aerobic and anaerobic landfill.

Life cycle assessment (LCA) is a widespread methodology used to assess the environmental impacts of a product or system throughout its entire lifetime. This approach is adopted in many sectors and also finds application in the waste management system, where it is useful for evaluating the environmental performance of either the system as a whole or the individual technologies involved.

Some LCA studies have been performed on traditional landfills, but semi aerobic landfills are rarely modelled in detail.

To overcome the lack of assessments on this topic in the literature, Lazzarin (2015/2016) and Sciarrone (2020/2021) analysed through a LCA study the environmental impact of a semi aerobic landfill located in northern Italy.

The aforementioned studies, in accordance with most scientific literature cases, highlighted the strong contribution of leachate on the total impact of a landfill and the consequent importance of its appropriate treatment.

This project introduces the construction and operation of a leachate treatment plant as an integral part of the life cycle of a landfill, and considers a purified leachate of optimal quality, well below the legal concentration limits.

The goal of the present study is to evaluate the environmental impact of the leachate treatment plant used to treat the leachate produced over the entire life of a semi aerobic landfill; moreover, the role of leachate treatment in improving the environmental performance of the landfill will be discussed.

The LCA is conducted in compliance with the ISO 14040 and 14044 standards using the SimaPro software and the impact assessment is performed using the ReCiPe 2016 assessment method.

The leachate produced by a real landfill in the Liguria region, designed according to the semi aerobic technology (Fukoka method), was taken into account.

The functional unit is defined as "landfilling of 1 ton of wet unsorted waste in a landfill with an average depth of 10 meters for 100 years". This choice was made because the treatment plant is designed to specifically treat the leachate produced by the waste degradation in a semi aerobic landfill; therefore the treatment plant cannot be applied to any other kind of wastewater.

The system boundaries of the model include the entire life of the leachate treatment plant which is divided into 5 phases: plant construction and plant operation during the different life stages of the landfill (i.e. operation, aftercare, closure, conversion).

The leachate treatment plant is active for the entire life of the landfill; in the operational phase it consists of a combination of reverse osmosis, solar evaporation, phytoremediation and adsorption, while starting from the aftercare phase, thanks to the better quality of the leachate produced, only phytoremediation and adsorption are performed.

Each leachate treatment unit consists of a set of construction/management processes and receives as inputs the materials, natural resources and energy necessary to complete each activity involved. Similarly, outputs in terms of waste by-products such as exhausted membranes, solid salts, biowaste and spent activated carbon are also produced.

The data for the assessment are taken from the preliminary design of the leachate treatment plant, market suppliers' data, ecoinvent database and literature.

This thesis aims to evaluate the environmental impacts associated with the treatment of leachate, used as a semi aerobic landfill management tool.

The results are then compared with similar cases in the literature to highlight similarities and differences.

In the literature there is a lack of LCA studies that consider the leachate treatment plant as part of the landfill system, therefore the results obtained provide a baseline scenario from which future studies can start to assess the impacts of leachate management by modelling more complex systems.

SUMMARY

Introduction

A landfill is a site for the disposal of all the wasted materials that can't be recycled or otherwise recovered.

Although it is the least desirable solution, in the context of a circular economy it is an essential part of an integrated waste management system to close the loop; it involves bringing the residual waste materials back to earth under controlled conditions.

Landfilling, especially in the past, has often been the cause of significant environmental impacts. However, in recent decades, the entry into force of new waste regulations has led to the implementation of advanced effective engineering technologies aimed at minimising the impacts due to incorrect management of landfill sites.

The semi aerobic landfill is one of the solutions introduced in Japan which, through the special configuration, combines aerobic and anaerobic areas inside the landfill. This allows to reduce the time needed to reach a good level of waste stabilisation and improve the quality of leachate and biogas emissions.

In addition, thanks to the simple systems of natural ventilation and collection of leachate by gravity, the use of electric pumps is not foreseen and the required maintenance is not complex; this makes semi aerobic technology inexpensive and also suitable for developing countries.

Although the impacts of a semi aerobic landfill are limited compared to other traditional landfills, it is still important to try to neutralise the emissions through specific treatments. Thanks to the rapid improvement of the leachate quality since the first decades, it is possible to install a cheap and passive in situ leachate treatment plant.

In this thesis a possible leachate treatment plant based on reverse osmosis, solar evaporation, phytoremediation and adsorption was hypothesised and dimensioned, with the aim of evaluating its environmental performance and role in minimising landfill impacts.

To evaluate the total impacts of the leachate treatment plant, a life cycle assessment study has been performed. The entire life of the treatment plant was considered, starting from the construction phase and analysing its operation during all the phases of the landfill life. The model developed includes the entire life of the leachate treatment plant within the system boundaries; materials, transport and energy to build and operate the infrastructures are all considered, as well as emissions and waste by products produced by the treatment units.

From the literature case studies in the context of landfill LCA, leachate emerged as one of the major contributors to the environmental impact, even more significant than biogas. We therefore wanted to test the validity of this finding by evaluating whether a better quality of the leachate obtained through an advanced treatment was able to modify the extent of the impacts.

The first chapter, through a literature analysis, explains the concepts of semi aerobic landfill and reports an overview of the passive in situ treatments for the leachate adopted for this project. Furthermore, to contextualise the use of LCA in waste management, three case studies were examined and summarised.

The second chapter reports the essential steps of the semi aerobic landfill design, which were exhaustively described by Sciarrone (Sciarrone, 2020/2021); for more details refer to her work. In particular, leachate production calculations and leachate initial quality parameters are reported for each phase of the landfill life.

The third chapter concerns the design of the leachate treatment plant. It is divided into four modules: reverse osmosis, solar evaporation, phytoremediation and adsorption.

The fourth chapter follows with the goal and scope definition and inventory analysis. This chapter includes the aim of the project, the functional unit, the model definition and the inventory data entered in the SimaPro software.

The fifth chapter presents the results of the impact assessment performed through the ReCiPe 2016 method, focusing on each phase of the leachate treatment plant life and on the contribution of the leachate treatment plant on the environmental performance of the landfill.

In the last chapter the final considerations are drawn; the results obtained are interpreted in the light of the assumptions made and compared with scientific literature results.

1. Life Cycle Assessment methodology and management of semi aerobic landfill leachate

1.1. Life cycle assessment: applications and structure

Recently, the sensitivity for environmental issues has pushed towards the adoption of environmental policies aimed at achieving certain objectives with a view to sustainable technological, economic and social development. Life cycle thinking has assumed a decisive role in the elaboration of these environmental policies. LCA is a tool for quantifying the environmental performance of products (and services) by tracing their entire life cycle, starting from the production of raw materials to the final disposal of products, including recycling of materials if necessary. LCA is truly versatile and therefore boasts applications in countless fields by both public and private institutions. Through it, it is possible to identify opportunities for improvement (hot spots) in the life cycle of a product with the aim of improving its environmental performance; it also represents the basis for comparing products and for environmental declarations (i.e. ecolabel certifications).

To perform an LCA, reference is made to the official guidelines:

- ISO 14040:2020 Environmental management - Life cycle assessment – Principles and framework;
- ISO 14044:2020 Environmental management – Life cycle assessment – Requirements and guidelines.

These standards outline the main steps involved in the LCA methodology, as well as the relationships between them, limitations and optional elements; however, they do not propose a detailed technique to employ. Since these general guidance documents are applicable to a wide range of different decision-contexts and sectors, they cannot directly provide tailor-made, specific provisions, such as product-group specific guidance. They can however serve as "parent" document for specific guidance documents, such as for Product Category Rules (PCR) and other product-group specific guidance documents and for simplified yet reliable tools, such as ecodesign type tools (ILCD Handbook, 2010).

According to the ISO standards, a life cycle assessment study is composed of four phases:

- Goal and scope definition
- Inventory analysis
- Impact assessment

- Interpretation of the results

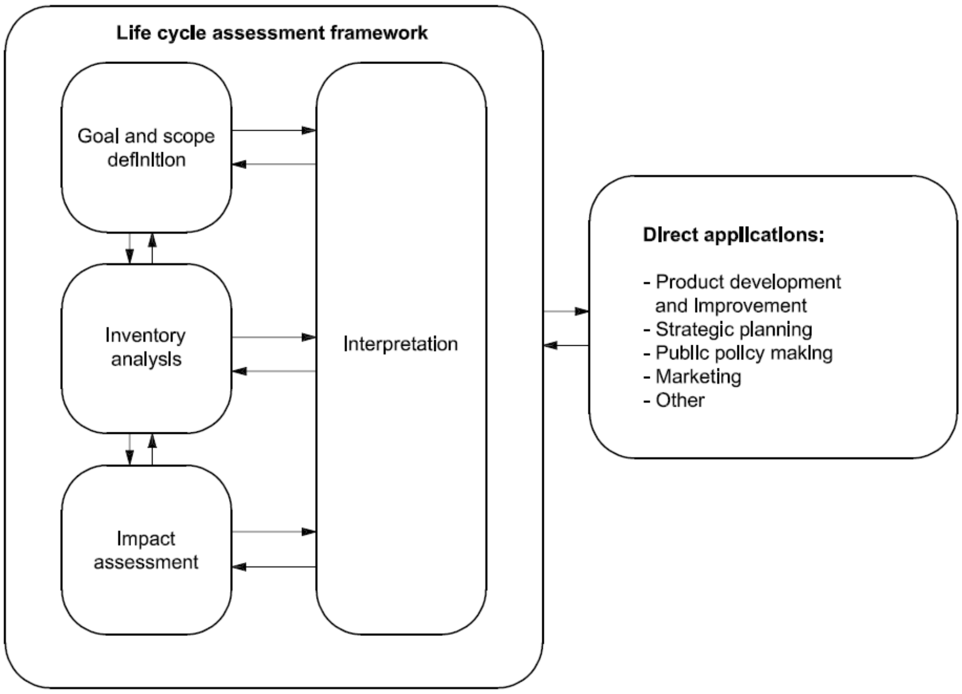


Figure 1. Phases of LCA study (ISO, 2020a).

Goal and scope definition is the first step to carefully deal with. The challenge for a LCA practitioner is to develop the model of a product, service or system life cycle in such a way that the simplifications and distortions of the complex reality do not influence the results too much. For this reason goal and scope definition is a phase of key importance, defining the most critical (often subjective) choices.

The goal defines the application of the study and the targeted audience.

The scope of the study describes the most important methodological choices, assumptions, and limitations. It explains what function the product under study fulfils and defines its quantified performance, the so-called "functional unit".

Furthermore, the system boundaries are accurately identified and the quality of the required data is specified. The boundaries of the system to be modelled can vary according to the level of detail of the analysis. Sometimes there is not enough data to model an entire life cycle, so we are limited to analysing a restricted number of system phases; other times some unit processes can be neglected because they do not have a

significant contribution to the entire system. As the boundaries vary, we would therefore have systems such as "cradle to gate", "cradle to grave" or "cradle to customer".
Moreover, in this first section, the study is classified as comparative or single assessment and the requirements for a critical review are defined.
An LCA is an iterative process, this means that the initial set of choices and requirements may be adapted later when more information becomes available.
The life cycle inventory represents the second phase of an LCA and involves the definition of the model in terms of processes and flows and the collection of input/output data. Flows are expressed in terms of mass or energy and represent the quantity of product, natural resources, energy consumed or produced, waste and environmental emissions.
Life cycle impact assessment is the third step to perform and it is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.
ISO 14040/44 distinguishes between obligatory elements (classification and characterization) and optional elements (normalization, ranking, grouping, weighting).
Through classification, the elementary flows from the inventory are assigned to the impact categories according to the substances ability to contribute to different environmental problems (i.e. climate change, ozone depletion etc.).
Since substances all contribute differently to each environmental problem, the overall contribution to a single category is determined by using the IPCC equivalency factors. In the characterization stage, life cycle inventory results are multiplied with a characterization factor before they can be added to compute the impact category indicator result. In this way the units of the contributors are defined as a reference to a substance (like CO_2 equivalents, kg CFC11 equivalent etc.).
Normalization and weighting are used to simplify the interpretation of the results. Normalization shows to what extent an impact category indicator result has a relatively high or a relatively low value compared to a reference. This is done by dividing each impact category indicator result by the normalized value (i.e. average annual impact of a European citizen in a year). Normalization also solves the incompatibility of units among the different impact categories.

Weighting means assessing the relative importance of each impact category and it is by definition not based on natural science but very subjective. In comparative assertions disclosed to the public ISO does not allow weighting; it is more commonly used for internal decision-making. Several possibilities are applied to perform weighting, usually a panel of experts determines default weights to associate to each impact category.

To conclude the assessment, a sensitivity analysis is conducted to evaluate the influence that the most important assumptions have on the results. For example, changing one or more input parameters often leads to completely different and often misleading results; therefore it is necessary to evaluate the accuracy of the data to improve the interpretation of the results.

By interpreting the results, conclusions are drawn by discussing the significance, limitations and reasonableness of the results obtained from the previous phases. In particular, compliance with the goal and scope of the study is verified.

1.2. Sanitary landfill: the semi aerobic technology

Landfilling of non-recoverable waste, even if limited to the bare minimum, is an integral part of an efficient waste management system. In the context of the circular economy, it is a matter of returning waste materials "back to earth"; in fact, in a landfill complex biological processes take place, which, in a more or less long time interval, lead to the complete mineralization of the buried material. In the past, the damage caused by inappropriate management and incorrect design of containment measures has been considerable, but today the Italian and European legislation on the subject has made it possible to overcome these errors. Not only modern landfills are complex engineering works capable of preventing the pollution of surface water, groundwater, soil and air, but they represent a means of allocating land for useful use. More and more often we see entertainment parks or renewable energy plants rising on landfills in operation or at the end of their life.

The most common types of sanitary landfills are anaerobic and aerobic landfills. Both equipped with containment barriers composed of layers of natural and synthetic impermeable material and of systems for leachate and gas extraction, they differ mainly from the technology chosen for the biodegradation of buried waste.

In the case of an anaerobic landfill, as the term suggests, the waste is completely encapsulated by impermeable liners in order to totally avoid contact with the air and improve the slow anaerobic biodegradation of the waste. The biogas produced by the chemical-biological processes inside the landfill body is extracted with pipes and often purified to obtain methane to be sold as natural gas or fuel, or burned in an open chamber. The aerobic landfill is a solution to accelerate the biodegradation kinetics of waste. Generally electric pumps inject medium-high pressure air into the landfill body through vertical pipes, resulting in a high energy consumption and cost of operation.

An intermediate way between the two technologies just described is the "semi-aerobic landfill", introduced by the University of Fukuoka, in Japan, a few decades ago.

Large leachate collection pipes incorporated in a medium-coarse size gravel drainage system at the bottom of the landfill allow the simultaneous entrance of air in the body and circulation of leachate, which is removed by gravity thanks to the slope of the bottom and without the use of pumps.

The thermal gradient due to the different temperature between the outside and the inside of the landfill allows the ambient air to flow naturally by convection into the waste body creating some aerobic spots alternated to anaerobic ones. To increase the aerobic areas, natural ventilation can be improved by installing vertical gas venting pipes at regular intervals. Consequently the leachate and biogas quality are improved thanks to the enhancement of the aerobic degradation processes in the waste body (Wen-Jing Lu et al, 2011).

Typically, the extracted leachate shows a rapid decrease of BOD and COD; nitrogen can be completely removed by combined nitrification and denitrification and the mobility of heavy metals is reduced.

The aerobic areas improve the gasification producing a biogas almost completely made up of CO_2 and with relatively low concentrations of methane. Furthermore, the conversion of methane into carbon dioxide can be increased by installing a semi permeable top cover made of compost mixed with soil.

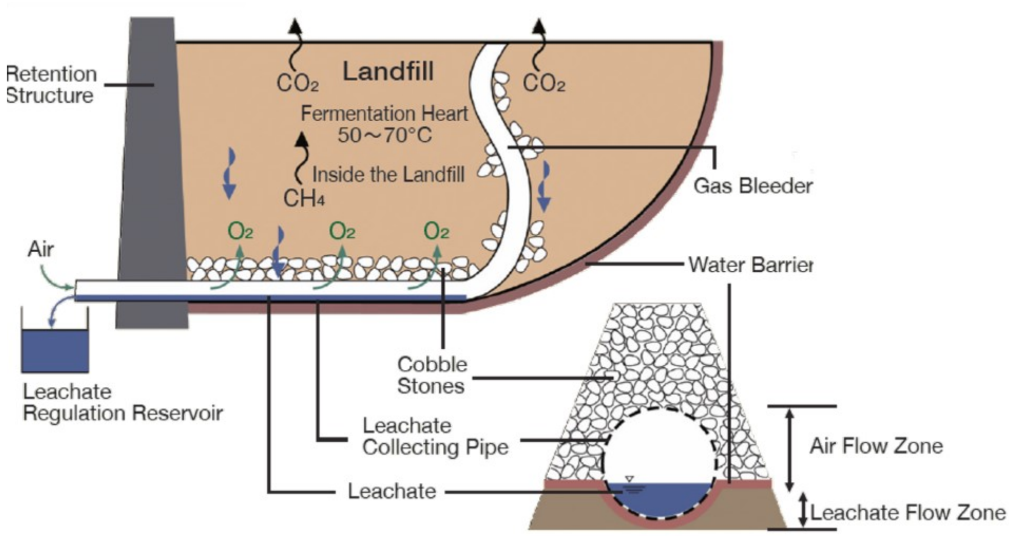


Figure 2. Simplified scheme of a semi aerobic landfill (JICA, 2007).

Like all types of landfills, the waste disposal volume is configured as a reservoir above or underground. The filling volume is divided into a number of sectors, each one equipped with independent drainage and venting systems.

The drainage system consists of a layer of gravel (typically Ø = 50-150mm), capable of guaranteeing the appropriate permeability, in which the leachate collection pipes are immersed. A main slotted pipe in HDPE with a circular section of at least 600 mm diameter ensure the full collection of leachate and a sufficient air flow. Perpendicular to it, leachate collection pipes of smaller size (Ø = 400 mm) are arranged at different distances to form an overall "herringbone" structure to facilitate the collection of leachate towards the main pipe.

When applicable, a leachate recirculation system is incorporated, where the leachate collected is recirculated by using a pump from the top into the waste layers. The waste mass plays a role as a natural filter medium for the leachate and subsequently improves the leachate quality after each round of recirculation.

Vertical slotted venting pipes are installed approximately every 20 to 40 metres, in order to facilitate the diffusion of air coming from the outside through the leachate drainage pipes. To prevent uncontrolled emissions of biogas, the top of the venting pipes might not be opened to the external atmosphere, by adopting specific technological solutions.

Even for a semi-aerobic landfill it is essential to have a bottom liner to isolate potentially contaminating waste from environmental matrices. The bottom lining system is a multilayer barrier built in accordance with the national law.

We can reassume the advantages of the Fukuoka method in few points:

- The quality of leachate is improved significantly by accelerating decomposition of the waste materials;
- Methane gas is reduced, contributing to the prevention of global warming;
- Enhanced stabilisation makes it possible to utilise the completed landfill earlier;
- Natural ventilation and leachate extraction by gravity make the Fukuoka Method cost-effective and simple in the technology, and allows a high degree of freedom of material choices.

1.3. Leachate management systems overview

Degradation of municipal solid waste in landfills is a long-term process, generating heavily polluted gases (i.e. landfill gas) and liquids (i.e. leachate), which are the main source of the environmental impact associated with this practice (Di Maria et al., 2017). Therefore, it is of prime importance to identify more sustainable technologies for their treatment in order to reduce the environmental concerns of the entire MSW management system (Di Maria et al., 2017).

Furthermore, the stricter requirements for pollution control and new discharge standards set by the national legislation have incentivized more research on landfill leachate treatment.

In general, landfill leachate is defined as any contaminated liquid effluent percolating through deposited waste and emitted within a landfill or dump site through external sources (Foo et al., 2009).

Leachate generation rate and composition are influenced by many factors (Figure 3), such as rainfall, groundwater level, surface runoff, soil properties, landfill cover, age of the landfill, characteristics of the deposited waste and degree of compaction. From among the factors, the age of the landfill can be one of the most influential: the temporal evolution of the characteristics of the leachate reflects, indeed, the degradation processes that take place in the landfill. Therefore, the composition of the leachate can be estimated based on its age, which can be divided into four main stages: aerobic, acidogenic, methanogenic and stabilisation (Reshadi et al., 2020).

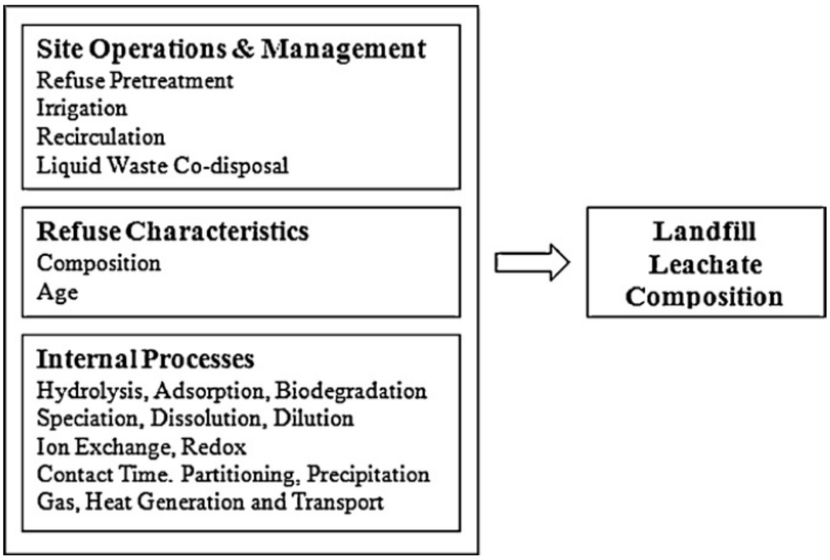


Figure 3. Factors influencing leachate composition in landfills (Foo et al., 2009).

Four major groups of pollutants can be found in landfill leachate: dissolved organic matter, inorganic macro-components, heavy metals and xenobiotic organic compounds.

Dissolved organic matter comprises a wide range of organic species, from methane (CH_4), volatile fatty acids (VFA) to more refractory humic and fulvic-like compounds. It is estimated in terms of biological oxygen demand (BOD) and chemical oxygen demand (COD); it is well understood that ageing causes reduction of BOD content and as a result, the leachate will become more stable due to the presence of refractory compounds and the decrease in the BOD/COD ratio (Reshadi et al., 2020).

Inorganic constituents consist of ions (i.e. calcium, chlorine, sodium, ammonium etc.) usually coupled with heavy metals (arsenic, cadmium, chromium, cobalt, copper, lead, mercury, nickel and zinc). They are present in very low concentrations, in the order of microgram per litre to few milligram per litre, because they are released very slowly but for almost the entire life of the landfill and beyond; so they represent a long-term source of emission.

Ammonia, one of the major forms of nitrogen in aquatic systems, has been identified as one of the most significant long-term components of landfill leachate, due to the fact that there is no dominant mechanism by which ammonia could be degraded under methanogenic conditions present in the landfill (Reshadi et al., 2020). In the case of a semi aerobic landfill, the ammonia removal mechanism is improved by the coexistence of aerobic and anaerobic areas inside the landfill body, which favour a continuous nitrification and denitrification cycle.

Whereas, the presence of a disproportionate amount of xenobiotic organic compounds is originated from the household and industrial chemicals and treatment sludges, with a broad variety of aromatic hydrocarbons, phenols and chlorinated aliphatics (Foo et al., 2009).

Since leachate is a wastewater with heterogeneous characteristics in terms of composition and with variations in time and space, the choice of the ideal treatment is complex.

The flexibility of the plant is a fundamental requirement, since it is necessary to cope with the changing properties of the wastewater to be treated.

The large number of contaminants to be removed does not make it possible to rely on a single treatment unit, but the combination of biological and chemical-physical processes is the most effective solution.

The following paragraphs expose some fundamental concepts taken from the literature regarding the treatment technologies that have been adopted to treat the leachate of the semi aerobic landfill under study; they are: reverse osmosis, solar evaporation, phytoremediation and adsorption.

The following is a descriptive overview; as regards the sizing and technical characteristics of the plants, as well as the estimate of the quantity and quality of the leachate, refer to chapters 3 and 2, respectively.

1.3.1. Reverse osmosis

Pressure-driven membrane-based processes are considered to be the most promising and practical desalination options owing to high energy efficiency, low space requirement, process and plant compactness, operational simplicity, and ease of process automation (Qasim et al., 2019).

Membrane processes involve the separation of different components in a solution by filtration and are characterised according to the dimension of the component to be separated (Cossu and Stegmann, 2018).

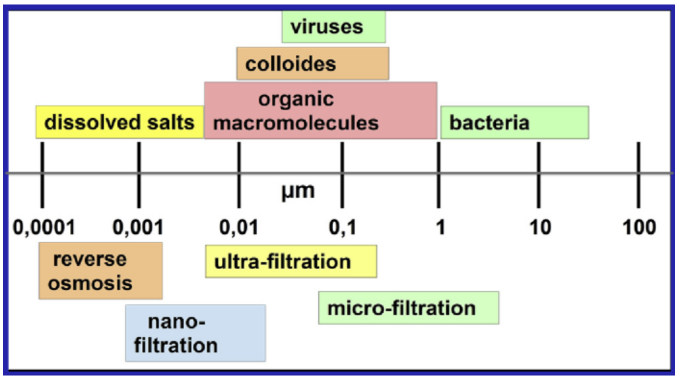


Figure 4. Dimension range of different water compounds (mm) (upper part) and permeation range of different membrane processes (Cossu and Stegmann, 2018).

Reverse osmosis (RO) is currently the most reliable technology for seawater and brackish water desalination.

Osmosis, in simplest terms, can be defined as a natural process in which water molecules spontaneously move from a solution of low solute concentration (low osmotic pressure) to a solution of high solute concentration (high osmotic pressure) across a semipermeable membrane (Qasim et al., 2019). The solutes are rejected by the semipermeable membrane and only water molecules can pass through. This process stops when a state of osmotic equilibrium is reached, i.e. when the chemical potentials across the membrane become equal.

By exerting an external pressure on the solution of higher concentration (feed solution), when the pressure difference is greater in magnitude than the osmotic pressure, the water molecules are forced to flow in a direction opposite to that of the natural osmosis phenomenon. In this case the process that is occurring is called reverse osmosis (Figure 5).

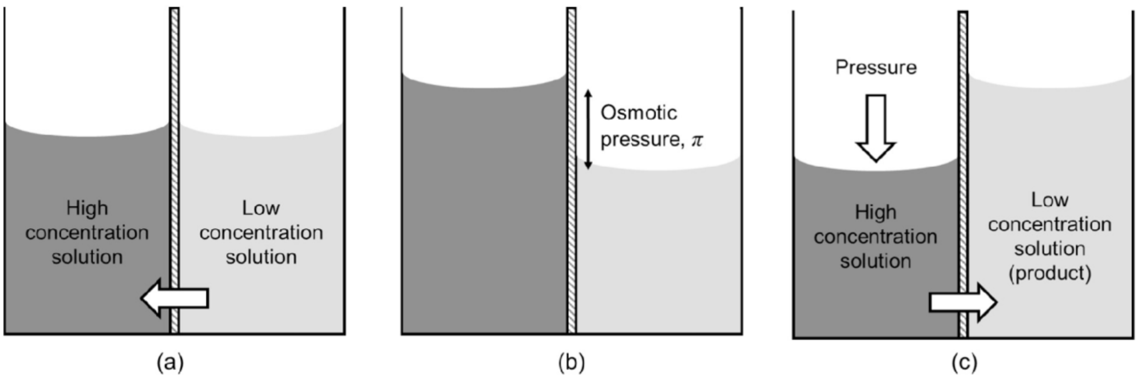


Figure 5. Schematic of (a) osmosis (b) osmotic equilibrium (c) RO (Qasim et al., 2019).

For ideal dilute solutions, the osmotic pressure (π) can be estimated using the Van't Hoff equation:

$$\pi = \Delta CRT$$

where, ΔC is the difference of molar concentrations of the solutions across the membrane (mol/L), R is the universal gas constant (0.08206 L atm/mol K), and T is the absolute temperature (K).

Three parameters can be used to identify the performance of the process:

$$Recovery, R = \frac{C_f - C_p}{C_f} \cdot 100$$

$$Salt\ transport, ST = \frac{C_p}{C_f} \cdot 100$$

$$Volumetric\ concentration\ factor, C_{fv} = \frac{Q_f}{Q_c} \cdot 100$$

Where C_f is the feed (raw wastewater) concentration, C_p is the permeate concentration, Q_f is the raw wastewater flow rate and Q_c is the concentrate flow rate (Figure 6).

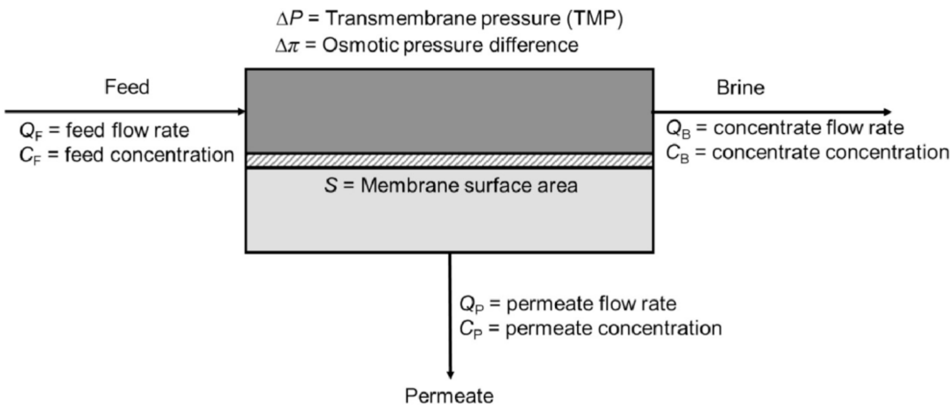


Figure 6. Schematic of a continuous RO system (Qasim et al., 2019). In the image the concentrate is called brine.

Membrane transport models are important tools in understanding the transport mechanism of solutes and water through the RO membrane, making possible to reliably predict membrane performance. According to the Merten model (Merten, 1966), permeate and concentrate flow can be described by the following equations (Weber and Holz, 1989):

$$\emptyset_p = \frac{K_p\, a}{1}(\Delta P - \pi) = A(\Delta P - \pi)$$

$$\emptyset_s = \frac{K_s\, a}{1}\left(C_f - C_p\right) = A(C_f - C_p)$$

$$\emptyset_s = \emptyset_p C_p$$

Where K_p is the permeability coefficient of membrane versus permeate, a is the membrane surface area, l is the membrane thickness, K_s is the permeability coefficient of membrane versus salt and A is the membrane permeability to permeate.

Membranes for RO are manufactured in four different types of modules: plate and frame, tubular, spiral wound, and hollow fibre. Hollow fibre and spiral wound modules are the most widely used due to their high packing density.

A hollow fibre module (Figure 7) is composed of numerous small-diameter (hair-like) fibres contained within a pressure vessel. On one side, the fibres ends are potted in epoxy but kept open for permeate flow. On the other side, the fibre ends are sealed in epoxy to prevent bypassing of the feed to the concentrate outlet. The pressurised feed water enters the module through a porous distributor (core tube), which runs along the entire length of the module. Water molecules permeate radially into the fibres and exit through the open fibre ends in the epoxy tube sheet while the concentrate leaves the module at the same end as the feed inlet. These membranes are suitable for industrial scale desalination of both brackish and seawater and exhibit salt rejections up to 99.6% (Qasim et al., 2019). However, they are difficult to clean and show a relevant tendency to fouling due to small fibre spacing.

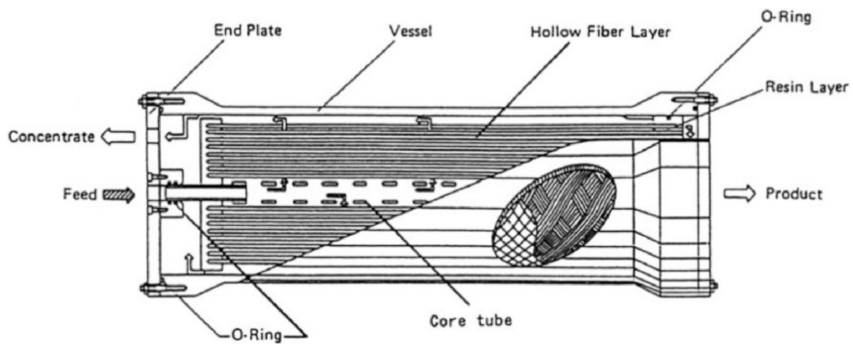


Figure 7. Hollow fiber RO membrane module (Qasim et al., 2019).

Spiral wound modules (Figure 8) are currently the most common membrane configuration used for RO desalination. The basic structure consists of two membrane sheets, with a permeate spacer in between, glued together from three sides with the fourth side left open and connected to a central perforated permeate collector tube. This structure is repeated a number of times by connecting together the single units with a feed/concentrate mesh spacer and wrapping the components around the permeate collector tube to create a spiral configuration. The module is finally placed inside a pressure vessel. Feed water is injected from one end of the module and travels axially along the length of the module. Water molecules are forced through the membrane and are collected as permeate through the perforated permeate collector tube, while the concentrate leaves the module at the end opposite to the feed (Qasim et al., 2019). Spiral wound modules allow for high mass transfer rates thanks to the presence of feed spacers, but they are susceptible to fouling if pre-treatment is inadequate and result in high feed side pressure drop.

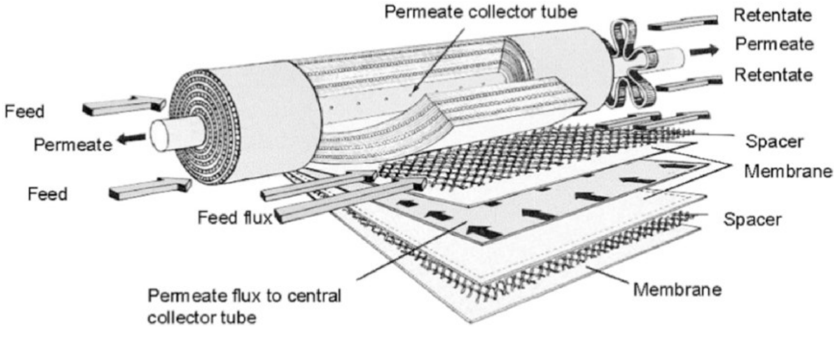


Figure 8. Spiral wound RO membrane module (Qasim et al., 2019).

The most important operational and economic challenge that RO has to face is membrane fouling.
The most frequently encountered phenomenon is external fouling, which occurs when foulants accumulate on the membrane surface; but in some cases particles may accumulate also within the membrane pores (internal fouling). The result is a significant decline in the water permeation rates due to the gradually decreasing active membrane area. As consequence, the membrane lifespan is reduced and increase in feed pressure and energy requirement take place.
Membrane fouling can be classified as colloidal fouling, organic fouling, inorganic fouling, or biofouling.
Colloidal fouling occurs when colloids present in the feed (i.e. fine suspended particles including minerals, proteins, carbohydrates, fats etc.) to the membrane surface resulting in formation of a cake layer, which hinders the back-diffusion of salts and, consequently, increases the salt concentration near the membrane surface.
Inorganic fouling (scaling) is caused by inorganic compounds such as calcium sulphate, calcium carbonate, calcium phosphate, barium sulphate, and silica present in a supersaturated feed water that crystallise and deposit on the membrane surface.
Organic fouling is a consequence of organic matter present in the feed, in the form of natural organic matter (consisting of humic substances), extracellular and intracellular macromolecules and cellular debris, polysaccharides, proteins, enzymes etc.
Among all types of fouling, biofouling is the major contributor. It is caused by the deposition, proliferation, and metabolism of microorganisms (bacteria, algae, protozoa, and fungi) feeding on the feed water nutrients and leading to the creation of a biofilm on the membrane surface.
The most effective strategies to solve the problem are installing a pre-treatment unit (especially in the presence of high organic loads) and regular maintenance operations such as physical (i.e. backwashing) and chemical cleaning, as well as membrane replacement.
Monitoring of RO membrane fouling is crucial in order to conduct timely membrane cleaning and preserve the performance of the modules close to the initial one. Typically, operating parameters such as decline in permeate flux, increase in transmembrane

pressure, pressure drop, and product quality are indicators to constantly keep under observation to assess the degree of severity of fouling and plan the maintenance.

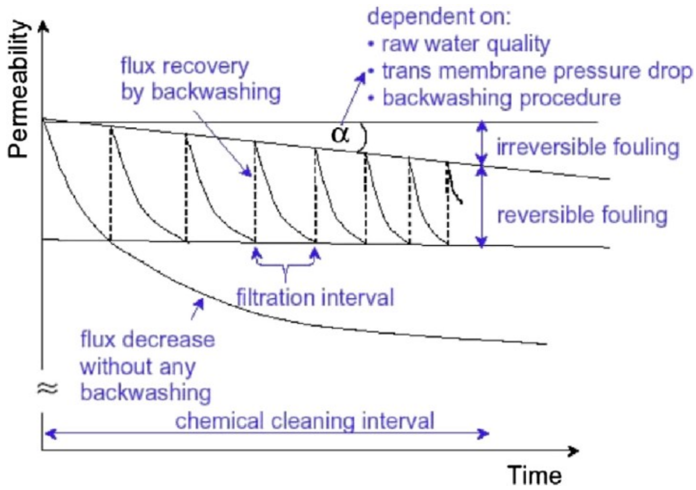


Figure 9. Principle of flux decrease without backwashing and cleaning. Flux recovery by backwashing and resulting elimination of reversible fouling and remaining irreversible fouling (Cossu and Stegmann, 2018).

Two types of materials are used in membrane manufacturing: cellulose acetate (diacetate and triacetate) and aromatic polyamide.

Conventional polymeric RO membranes are asymmetric and consist of a thin dense layer supported on a porous sublayer.

Cellulose acetate membranes are widely used due to their chemical and physical stability. In particular, resistance to chlorine is one of their primary strengths; this property is extremely relevant when using strong oxidants to reduce the risk of membrane fouling (Cossu and Stegmann, 2018).

In order to improve membrane performance in terms of increased permeate flux, salt rejection, and fouling resistance, CA-based membranes have been modified by adopting several methods of fabrication.

Thin film composite (TFC) membranes are by far the most common membranes for RO applications and their spiral wound configuration account for over 90% of the market sales (Qasim et al., 2019). Thin film composite (TFC) membranes are essentially composites of two polymers that are cast on a fabric support.

Material	Aromatic Polyamide	Cellulose Acetate
Configuration	Hollow fine-fiber modules	Tubular, spiral wound and hollow fine-fiber modules
Normal working pressure	28 bar	30–42 bar
Maximum back-pressure of treated water	3–5 bar	
Maximum operating temperature	45°C	30°C
Maximum storage temperature	40°C	30°C
pH acceptable	2–12	4–6.5
Hydrolysis	Unaffected	Highly sensitive
Bacterial attack	Unaffected	Highly sensitive
Chlorine	Highly sensitive	Unaffected
Operating life	3–5 years	2–3 years
Salt passage (NaCl)	5%–10%	5%–10%

Figure 10. Characteristics of acetate and polyamide membranes (Cossu and Stegmann, 2018).

According to literature and full-scale plants RO systems are capable of removing percentages of leachate compounds higher than 98%.

Operating with water recoveries from 35% to 85%, RO plants generate huge volumes of concentrates containing all the retained compounds that are commonly discharged to water bodies and constitute a potentially serious threat to marine ecosystems; therefore there is an urgent need for environmentally friendly management options of RO concentrates such as evaporation (Pèrez-Gonzàlez et al., 2011).

The end product of evaporation is a mix of soluble solids mostly characterised as a hazardous waste and should be disposed of in special landfills designed to ensure the safety of the surrounding environment.

1.3.2. Solar evaporation

Evaporation techniques have been widely applied for concentrate management, since it allows to reduce its volume (up to 98% reduction) and/or decrease the pollutant load, avoiding the associated disposal costs.

Sometimes recovering of commercial by products from RO concentrates is applied to gain economic profitability; this is done, for example, by isolating salts of the required morphology and purity.

In solar evaporation, the RO concentrate is placed in a shallow lined pond where natural evaporation of water by solar energy takes place.

Once evaporation is complete, the salt residue is removed for disposal or further recovery (i.e. thermal recovery or isolated salts recycling).

Evaporation ponds are relatively easy to construct and operate and, except for pumps to convey the wastewater to the pond, no mechanical equipment is required.

Evaporation rates from water bodies are dependent on many factors such as wind speed, temperature, and vapour pressure. Two main approaches exist for determining evaporation: energy budget and mass transfer methods.

The energy budget method is based on the principle of energy conservation, used to estimate the amount of energy needed by water to change from liquid to vapour phase:

$$Q_e = E\rho L$$

Where Q_e is the energy used in evaporation (W/m^2), E is the rate at which water is evaporated (mm/d), ρ is the mass density of the evaporated liquid (kg/m^3), and L is the latent heat of vaporisation at the liquid surface temperature (KJ/kg).

While, the mass transfer method considers diffusion as mechanism of vapour removal. The rate of vaporisation of liquid into gas is given by the Dalton's equation:

$$E = C_1(e_w - e_a)$$

Where E is the evaporation rate (mm/d), C_l is an empirical coefficient, e_w is the partial pressure of liquid (mm of Hg), and e_a is the partial pressure of air (mm of Hg).

According to literature, the estimated productivity of the process is quite low (around 4 L/m^2d), so to achieve full evaporation large areas are usually needed in combination to a pond depth ranging between 25 and 45 cm (Pèrez-Gonzàlez et al., 2011). The following formula calculates easily the open surface area of the evaporation pond:

$$A = \frac{V_{reject}}{E}$$

Where A is the open surface area of evaporation pond (m^2), V_{reject} is the volume of rejected water (m^3/d), E is the evaporation rate (m/d).

The depth required to store the volume of water is calculated using the formula:

$$d = E$$

Where d is the depth (m), E is the evaporation rate (m/d).
In addition, one must ensure that the evaporation depth exceeds the depth of water that would have to be stored in the pond. A freeboard of 200 mm (defined as the depth above the normal reject water surface) must be provided so that rainfall and periods of abnormally low evaporation do not cause reject water to spill out of the pond (Ahmed et al., 2000).
In general, the walls of ponds are constructed above the ground level.
The most important feature of an evaporation pond is the bottom liner; as in the case of a landfill, it is of high concern to prevent any leakage potentially contaminating for the surrounding environment. All liners must be strong enough to withstand stress caused by salt cleaning, which is done by skid steer loaders during dry months.
Another important factor is the position of the basin, which must be oriented according to the predominant direction of the wind.
Around the base, banks should be elevated and compacted using a sheep foot roller. Banks should be 1 m in height and 2.4 m wide at the crest to allow for the movement of light vehicles; to minimise bank erosion, an inside slope of 1:5 is recommended (Ahmed et al., 2000).
As for maintenance, erosion control, wildlife management, and seepage control are commonly adopted measures. Indeed, pipes may be affected by cavitation due to the high dissolved gas levels in the pumped saline water. Deterioration of pipes and pumps may occur also due to the iron sludge formed by the presence of iron bacteria.

1.3.3. Phytoremediation

Leachate irrigation to land can provide an opportunity for closing the nutrient cycling loop and simultaneously producing effluent of a suitable quality for discharge (Jones et al., 2005).
Phytoremediation systems utilise the potential of the natural or actively managed soil–plant system to detoxify, degrade and inactivate potentially toxic elements in the leachate (Jones et al., 2005). The potentially contaminating constituents found in the wastewater

(organic compounds, salts and nutrients) represent important nutritional sources for plant species to be used in photosynthesis.

Raw municipal wastewater has been tested on cultivations of Typha latifolia, Arundo donax and Phragmites australis, resulting in an up to 54% increase in average biomass yields compared to plants irrigated with conventional water (Garbo et al., 2016). We can therefore consider wastewater as a kind of natural fertiliser.

Phytoremediation process involves a combination of above and below ground processes triggered by the symbiotic relationships that develop in the plant kingdom between the different species, i.e. plants, fungi and bacteria.

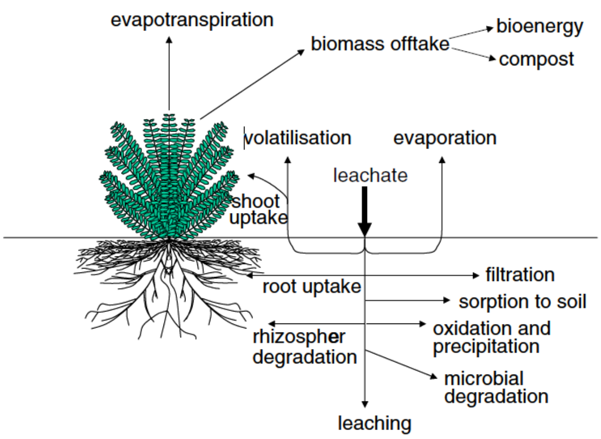


Figure 11. Schematic representation of the soil–plant bioreactor for the plant–soil based treatment of landfill leachate (Jones et al., 2005).

It is possible to distinguish the following biological processes:

- Phytostabilization: the plant immobilises inorganic impurities in its roots and does not eliminate them, with binding occurring mainly through the mechanism of complexation;
- Phytoaccumulation or phytoextraction: pollutants accumulate in different parts of the plant. This process, which uses the mechanism of hyperaccumulation, is very significant in respect to heavy metal removal;
- Phytodegradation or phytotransformation: plants metabolise, using the mechanism of degradation within the plant, organic pollutants taken from water or soil into less toxic substances;

- Phytovolatilization: plants absorb organic and inorganic pollutants and then eliminate them through the processes of transpiration;
- Rhizofiltration: the roots of the plant create conditions favourable to soil-dwelling microorganisms, which then biologically degrade organic and inorganic pollutants present within that root system (Polinska et al., 2021).

Phytoremediation systems are classified according to type of plant species used and the characteristics of the hydraulic path of the wastewater.

In particular, based on the development of the roots, a distinction is made between: systems with floating macrophytes, systems with submerged rooted macrophytes, systems with emerging rooted macrophytes and mixed systems.

In relation to the hydraulic path of the wastewater, phytodepuration systems are divided into:

- SFS-h or HF (Subsurface Flow System - horizontal or Horizontal Flow): horizontal submerged flow systems are basins filled with inert material, where the wastewater flows horizontally in conditions of continuous saturation ("plug-flow" reactors) and the plant species used belong to emerging rooted macrophytes;
- SFS-v or VF (Subsurface Flow System - vertical or Vertical Flow): vertical submerged flow systems are trays filled with inert material, where the wastewater flows vertically in alternating saturation conditions ("batch" reactors) and the used species belong to emerging rooted macrophytes;
- FW or FWS (Free Water or Free Water Surface): the free flow systems reproduce, as closely as possible, a natural marsh area, where the water is in direct contact with the atmosphere and generally not very deep, and the plant species that are included in it belong to the groups of hydrophytes and helophytes (ISPRA, Manuali e Linee Guida 81/2012).

Frequently the types of systems explained above are combined (i.e. hybrid systems) with the aim of optimising purification yields and to cope with fluctuations in organic and/or hydraulic load, both daily and weekly.

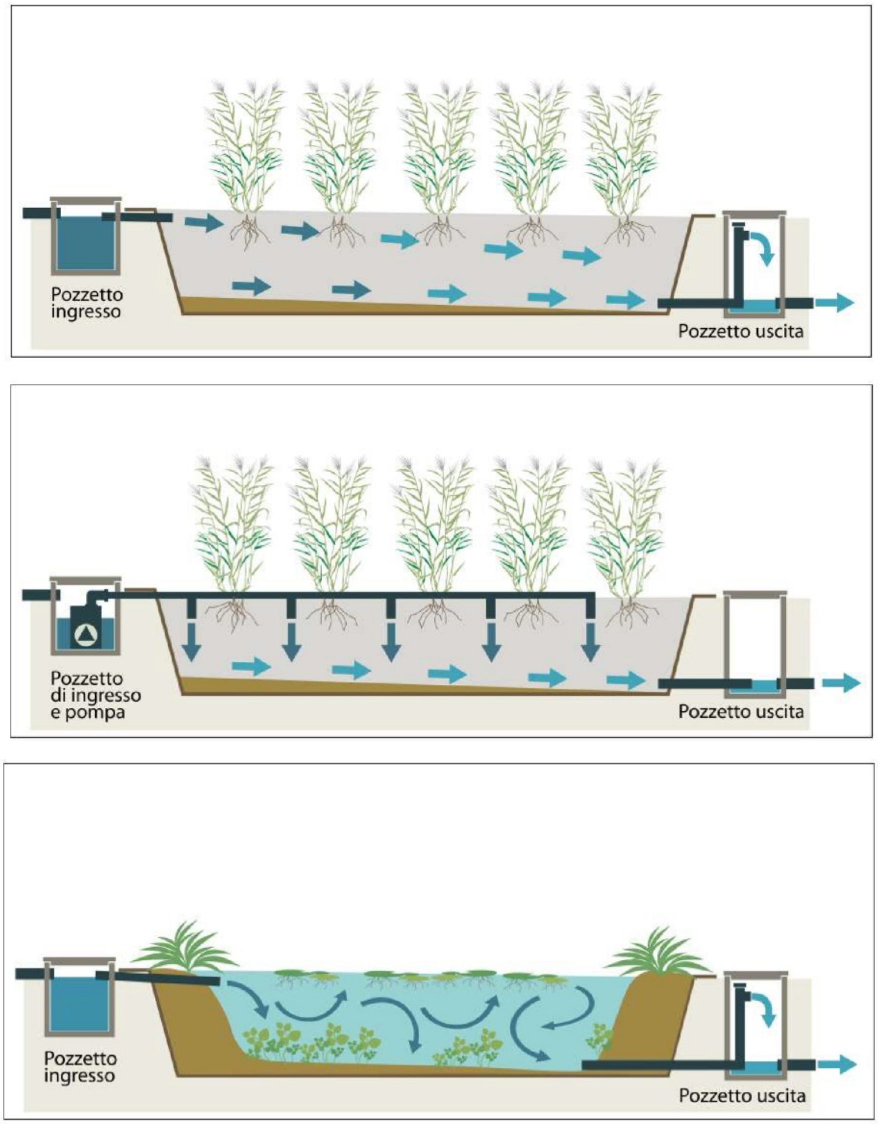


Figure 12. Types of flows in phytoremediation basins: horizontal flow, vertical flow, free water (ISPRA, Manuali e Linee Guida 81/2012).

In all cases, the basins used for plants growth must be suitably lined with plastic membranes (i.e. PE or PVC), before being filled with inert material with high hydraulic conductivity (sand, gravel, natural soil).

The general arrangement of a constructed wetland plant, as shown in Figure 12, therefore consists of waterproofed basins filled with draining substrate, on which the plant species lie.

Irrigation is carried out through pipes regularly distributed and positioned differently according to the configurations (HF, VF or FWS), and by pumps if necessary. At the ends of each basin there are wells for collecting the leachate (inlet and outlet wells), and for partitioning between several basins in parallel if required.

The most widely used engineering solution in Europe is represented by submerged flow systems. In particular, horizontal flow (HF) systems are able to guarantee good removal of suspended solids, organic matter and surfactants. Furthermore, the alternation of zones with different dissolved oxygen content together with the long retention times favour a high mortality of bacterial populations, including pathogens, introduced with the influent (ISPRA, Manuali e Linee guida 81/2012). HF systems have the advantage of working by gravity and in the absence of electrical devices, with a consequent simplification of maintenance operations and cost reduction both in the realisation and in the management phase.

In recent years, to meet increasingly stringent quality standards, there has been growing interest in vertical flow and combined systems, which boast greater nitrogen removal capabilities. In fact, vertical flow (VF) systems allow efficient nitrification thanks to the greater oxygenation of the wastewater compared to horizontal flow systems but, at the same time, they are not very effective in denitrification. For this reason, the recirculation of wastewater towards a horizontal flow system, characterised by low aeration levels, contributes to considerably improving the denitrification process, which is essential for the complete removal of nitrogen.

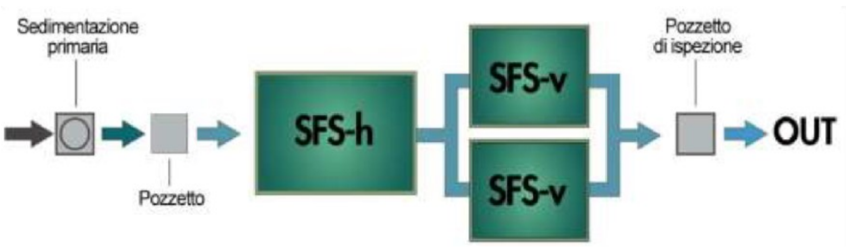


Figure 13. Diagram of a hybrid HF + VF phytodepuration plant in series (ISPRA, Manuali e line guida 81/2012).

Surface flow systems (FWS) are not very common in Italy in consideration of the problems associated with direct contact between wastewater and the atmosphere, which often proves to be a source of bad smells and proliferation of insects in the vicinity. Furthermore, although they are simpler to make than submerged flow systems, they

require significantly larger surfaces. In addition, cold climates could pose a threat to the efficiency of the system due to the formation of surface ice in the winter months.
In general, phytotreatment plants guarantee good purification yields in the range of 70-90% removal (especially for parameters such as COD, BOD_5, Suspended Solids and Nitrogen), as well as significantly reduced environmental impact and energy consumption compared to other purification systems. Moreover, it was demonstrated that, during the process, a significant wastewater volume reduction (up to 80% of inlet wastewater) can be achieved by evapo-transpiration (Garbo et al., 2016).
The choice of the best plant configuration must be evaluated case by case, on the basis of information relating to the quantity and type of wastewater to be treated, the availability of surface to be used for treatment, the climatic conditions of the area and the characteristics of the final receptor (water body, soil, reuse, etc.).
Based on the empirical results obtained by the plants currently active on the Italian territory, it is estimated that the minimum surface necessary to guarantee compliance with the discharge limits in surface waters envisaged at national level (Legislative Decree 152/2006) is 3-5 m^2 per people equivalent.
The national reference legislation (Legislative Decree 152/2006), in article 74 paragraph 1 letter a), defines the people equivalent as the biodegradable organic load having a 5-day biochemical oxygen demand (BOD_5) equal to 60 grams of oxygen per day (ISPRA, Manuali e Linee guida 81/2012).
Constructed wetlands have a simple management that does not require a continuous commitment or specialised labour.
Generally, the malfunctioning conditions of a well-designed system are found in correspondence with hydraulic and/or pollutant overload, malfunction of the primary treatment systems, clogging of pipes or of the filling medium.
The time required for operation of the constructed wetlands systems are rather long: it typically takes 1-2 years to achieve a good development of the aerial part and the root system of the plants.
The plant species used in the previously described natural purification systems mainly belong to herbaceous species. The most common systems in Europe are those that use emerging rooted macrophytes (HF and VF), for example Phragmites australis and Typha latifolia, due to their greater speed of growth and diffusion. Generally, to obtain the best

results in terms of vegetation development, it is recommended to use native plant species, already adapted to the environmental conditions of the site (ISPRA, Manuali e Linee guida 81/2012).

In submerged flow systems, the choice of plants must take into account the penetration of the root system (which typically extends from 30 to 90 cm in depth), which is useful for calculating both the height of the beds and for obtaining good purification yields. The depth and extension of the root system are, in fact, important parameters to consider as they are connected to the degree of oxygen transfer and to the extension of the contact surface between the wastewater and the rhizosphere.

The propagation of plant species can take place through sowing, planting rhizomes or plant essences of various sizes; however sowing, requiring longer times for plant growth, is not advisable.

Furthermore, the design of extensive phytodepuration systems represents an opportunity to redevelop degraded areas from a naturalistic and landscape point of view or to restore areas of ecological connection and/or necessary for the protection of the biodiversity; very often these areas are made accessible to citizens (park areas, areas with educational paths, etc.).

Another incentive to use phytodepuration of wastewater is the possibility of planting energy crops (e.g. sunflower, rapeseed and soybean), defined as low-cost and fast-growing plants used to produce bioenergy and biofuels (such as bioethanol or biodiesel) or which can be burned to generate electricity or heat. The use of energy crops in the decontamination of wastewaters is of increasing interest and solicited by the European Union, particularly in view of the widespread scarcity of water in many countries worldwide and of the possibility of obtaining renewable sources of energy (Garbo et al., 2016).

1.3.4. Adsorption

Adsorption is a physical-chemical treatment commonly implemented for the removal of organic and inorganic substances from wastewaters. It is often used in combination with a biological pre-treatment to eliminate the remaining refractory compounds.

Treating landfill leachate using adsorption has shown successful outcomes so far, especially in the removal of organic compounds and ammonia nitrogen (Reshadi et al., 2020).

Previous studies highlighted activated carbon performance on leachate treatment. It has been reported that 85% removal of non-biodegradable materials is possible, as well as 80% removal of total carbon (Reshadi et al., 2020). Besides, adsorption by activated carbon is a suitable method to remove more than 75% of total iron and PO4-P, alongside high removal rate of heavy metals (up to 90%) and ammonium (up to 40%) (Reshadi et al., 2020).

Basically, the process involves the transfer of organic substances from a liquid/gaseous phase onto the surface of a solid phase; this happens when species are attracted to the surface of a highly porous structure through physical and chemical bonds (Reshadi et al., 2020).

Being simple in design, vastly available, and low in preparation cost, as well as with its large porous surface area, controllable pore structure, thermostability and low acid/base reactivity, activated carbon has led the way in adsorption processes worldwide; however, nowadays new generations of porous materials are also recommended for higher adsorption capacities and less environmental impacts (Reshadi et al., 2020).

A wide range of absorbent materials are marketed today including natural materials, improved natural materials (e.g. activated carbon), synthetic materials like resins and zeolites, agricultural and industrial wastes and by-products and biological adsorbents. There are various classifications reported in literature, but the fundamental property which must be referred to in the choice of the suitable material is a high porosity, i.e. a high surface area/volume ratio.

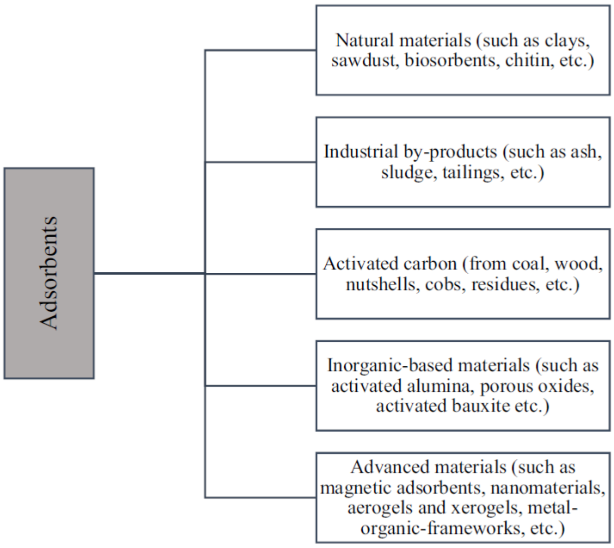


Figure 14. A simple classification of adsorbents (Reshadi et al., 2020).

Activated carbon can be found in the form of granular activated carbon (GAC) or powdered activated carbon (PAC).

It is estimated that over 40% of commercial activated carbon is derived from coal, but any material containing a high content of carbon could be used as a feedstock, including wood, peat, nutshells, tobacco, and lignite. Other carbonaceous sources, which are mainly agricultural products, include sugarcane bagasse, soybean hulls, olive stones, cotton residues, corn straws, peach stones, pinecones, rice hulls, rice straw, banana peels, apricot stones, corn cobs, peanut hulls, oat hulls, bamboo, pith etc. (Reshadi et al., 2020). Another approach for satisfying both environmental and economic concerns is using food waste as a carbon source.

To produce activated carbon, a continuous two-stage process consisting of carbonization and physical-chemical activation is usually implemented.

A pretreatment is also employed to gain the appropriate size of the raw material; this stage includes crushing and milling followed by sieving.

Carbonization is performed under high temperatures, through pyrolysis, to create the initial porosity, while activation enhances the pores structure.

In physical activation, the carbonised material is subjected to a jet of oxidising gas which is generally hot steam or CO_2; while in chemical activation, the material is mixed with chemical activating agents (e.g. metal oxides, alkaline hydroxides), followed by heating at lower temperatures in an inert atmosphere, to gain an even higher surface area.

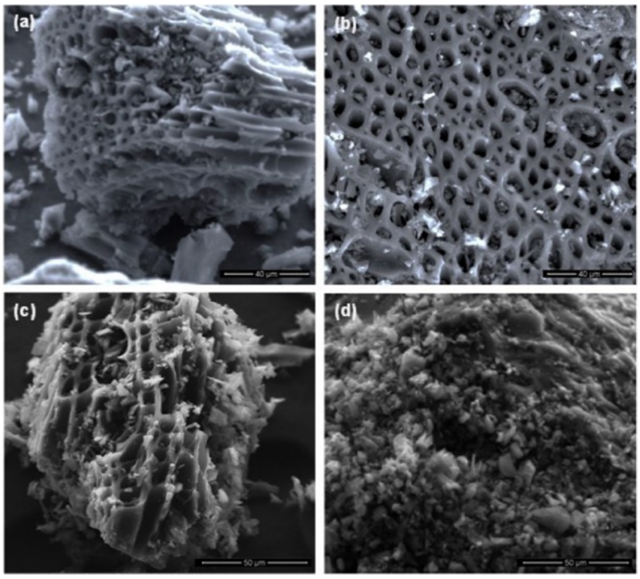


Figure 15. Scanning electron microscope images of conocarpus pruning waste activated carbon (a) activated with KOH, (b) activated with $ZnCl_2$, (c) non-activated, (d) commercial activated carbon (Reshadi et al., 2020).

PAC has a particle size of less than 150 µm (typically between 4 and 70 µm), while GAC particle size ranges between of 0.2 mm and 5 mm.

Spent GAC carbon can be thermally reactivated for a few tens of cycles, with less than 10% loss in mass during each reactivation. This process consists in the oxidation, through gasification, and following incineration of the adsorbed organic substances. PAC instead cannot be reactivated.

Typically PAC is dosed and poured into a mixing tank, and subsequently separated by flocculation and settling. The carbon/water suspension is not stable and may lead to precipitation and clogging of pipes; for this reason, pipes should be short and cleaned on a routine basis (Cossu and Stegmann, 2018).

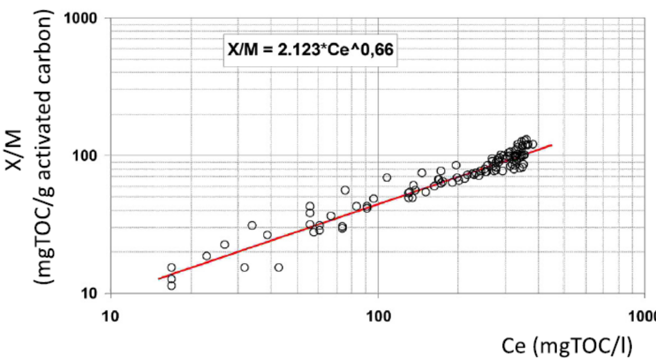
Instead, the GAC is preferred as filling material for a system of filtering columns in series, even though it can be used as suspension in a reactor in the same way as the PAC.

Practice demonstrates that PAC is significantly less effective than GAC and these two technologies often complement each other.

An interesting use of the PAC is to incorporate it into activated sludge processes. Indeed, PAC may contribute with a synergy effect for providing an attachment surface for bio-regeneration (microorganisms) and serving as a nucleus for the occurrence of floc formation (Foo et al., 2009).

Under steady state conditions the concentration of a substance on the inner surface area of the carbon is in equilibrium with the solution in the surrounding liquid. This means that the transport of the contaminants continues as long as their concentration in the leachate is higher than the one in the solid phase.

The adsorption process can be described by the adsorption isotherm, which represents the mass of adsorbed material per mass of activated carbon (e.g., mg COD or TOC/g activated carbon) as a function of the equilibrium concentration in the leachate (for example: mg COD/L or mg TOC/L) (Cossu and Stegmann, 2018).



Freundlich isotherm:

X/M = K * Ce^n

X/M = load of organics per weight of activated carbon (e.g. mg COD or TOC / g activated carbon)

Ce = Equilibrium concentration in the solution = remaining concentration after adsorption (e.g. mg COD or TOC /l).

K and n are the characteristic parameters of the isotherm

The Freundlich isotherm may for experimental purposes conveniently be transformed into a linear equation:

log X/M = log K + n * log Ce

In a regression analysis, log K is the interception and n the slope

Figure 16. Relationship between effluent values Ce [COD or TOC (mg/L)] and activated carbon load X/M (mg COD or TOC/g activated carbon) (Cossu and Stegmann, 2018).

Depending on their use, PAC and GAC systems have different equilibrium concentrations. Experimental tests show that the X/M load of GAC filter systems is much higher than for PAC in mixing tanks; as a consequence the carbon requirement is lower for GAC columns.

PAC is dosed in a mixing tank and the equilibrium concentration coincides with the effluent concentration. On the other hand, the optimum usage of GAC is achieved when the effluent values of the first filter are approximately similar to influent values, that is, the first filter has been exploited in its entire height.

For both systems, the carbon requirement is calculated with the following formula:

$$Carbon\ requirement = \frac{influent\ COD\ or\ TOC\ \left(\frac{mg}{l}\right) - effluent\ COD\ or\ TOC\ \left(\frac{mg}{l}\right)}{\frac{X}{M}\left(mg\ COD\ or\ TOC/g\ activated\ carbon\right)}$$

Leachate composition exerts a significant effect on the adsorption capacity of activated carbon since the large variety of pollutants contained in the leachate are characterised by highly diverse adsorption rates. Measured adsorption capacities are in the range of 100-250 g COD/kg carbon.

1.4. Literature review on the state of the art in the application of LCA to waste management, landfills and leachate management

In recent years, the LCA method has assumed an important role in assessing the environmental impacts deriving from systems in the most diverse sectors. In particular, LCA has found fertile ground in the field of waste management.

As this is an area of marked social, economic and environmental importance, LCA is seen as a tool for analysing the performance of waste management systems, both as a whole and in its individual components.

Waste management is an integrated system, consisting of a series of interrelated activities, which starts with the separate collection of waste at the municipal level, passes through the recovery and recycling of materials, and ends with the disposal of waste.

The technologies adopted in this sector are innumerable and it is very useful to evaluate the environmental performance within the system in which they are inserted, so as to identify critical points and better alternatives to develop effective waste policies.

Traditionally LCA was applied to product system assessment and was focused overall on production and usage stages. But waste LCA differs from typical product system assessment, since the boundaries of the system consider only the end-of-life stage of a product excluding the rest of its life. This is the so called "zero burden" approach.
In the next paragraphs some meaningful examples from literature are reported. In the specific, the topics that most closely concern this thesis are examined: state of the art of waste LCA in Italy, LCA applied to landfills, LCA applied to leachate management.

1.4.1. Life cycle assessment applied to waste management in Italy: A mini-review of characteristics and methodological perspectives for local assessment

The study is a mini-review of existing reports in the Italian context, whose aim is suggesting key points for the practical implementation of life cycle thinking (LCT) to waste management for promoting sustainable initiatives for cities and regions that want to enhance their environmental performance. Methodology, implementation and limitations of LCT for the local waste management were investigated from a comprehensive perspective, with particular focus on the topics explored by life cycle studies in the local context, on the related methodological characteristics and on the issues emerged from literature.
Scopus and Web of Science were used as databases for conducting the literature review; data collected and extracted from selected publications were directly used to illustrate the results. From the bibliometric results it was possible to notice that LCT applied to waste is a growing research topic in Italy: 381 sources were selected in the review process, most of them being case studies performed on an industrial perspective. 81% of the publications used LCA as a tool for impact assessment, but carbon and water footprints were also often used to measure waste management impacts (13% of the publications); while others proposed a mixed approach.
Among various subjects addressed by the LCA studies, seven topics seemed to be the most debated: water distribution and wastewater treatment, food and agricultural residues, organic waste, waste production and entire supply chain of goods, singular waste flows typically managed at local level (e.g. WEEE, WC&D), the entire waste management system and, finally, the strategic planning policies.
LCA dealing with water cycle seeks to investigate the environmental performance of the resource management system from water availability to delivery, considering the

organisation of the entire system. Wastewater is analysed both individually and treated in combination with other waste fractions. Different treatment plants are often compared with a view to technological optimization. The return of wastewater to the environment after treatment is also investigated.

LCT is also used to assess the organic cycle, related to the agro-food sector and biowaste, from cradle to grave. The contribution of cultivation, agriculture and farming activities to the environmental impacts was often evaluated. Many food chains were investigated in Italy (e.g. tomatoes, wine, sustainable foods indicators). Moreover, studies addressed distribution, diet and consumer behaviour, as well as management technologies for biowaste (e.g. composting and anaerobic digestion) and the related thermal recovery and energy production.

Studies on the product cycle, from extraction to waste, were mainly developed from an industrial perspective (Camana et al., 2021). Specific sectors were frequently investigated: appliances, materials, services, construction and demolition materials. Ecolabel and eco-design were only partially examined, as well as social perspective, while economic aspects were addressed in many studies. Some common observation arising from the literature were the need of new technologies due to material deterioration during recycling, the role of plants dimension in reducing environmental impacts associated to the processes and management changes in enterprises as starting point towards a more sustainable supply chain.

Witnessing the significant increase in material and energy flows in recent decades, as consequence to the population growth and consumption patterns, LCT applied to urban management is more and more widespread to analyse the impacts in cities concerning waste management, energy use and material and water consumption.

Several publications addressed particular waste flows (e.g. construction and demolition waste, electric and electronic equipment, packaging) or single flows (e.g. tyres, shredded automotive residue, absorbent hygiene products). Waste recycling is the most investigated strategy but interest is also given to thermal recovery.

LCA is generally used to compare different scenarios involved in municipal solid waste (MSW) management. Possible treatments, collection strategies, economic performances of the solutions were extensively studied. Thermal recovery, incineration and landfill impacts have been significantly investigated over the last 10 years (Camana et al., 2021).

Biorefinery processes, which convert waste residues into new valuable materials (e.g. biofuel, bioethanol, bioplastics), is also a topic gaining attention.

Selections and assumptions in LCA studies, such as system boundaries, allocation procedures of material and energy, avoided burdens of materials and energy recovered, time frame, impact category selection and weighting of priority factors, are decisive and significantly influence environmental outcomes (Camana et al., 2021).

The selection of a coherent functional unit, adapted for the technosphere and the ecosphere, is of key importance, especially in a heterogeneous system such as waste management. Lot of care should be given to the definition of the boundaries, burden shifting and input materials composition. Sometimes impacts may be time-related, such as in the case of landfill emissions, which occur at low concentrations for a very long time, or if we consider the durability of products.

Attributional and consequential LCA studies have been developed to deal with avoided burdens and allocation procedures. In fact waste can be reused or recycled for a finite number of cycles, and recovered energy and heat must be accounted as avoided emissions.

Waste studies may consider many impact categories. The most studied one is global warming, but limiting to only one category is always not recommended: the different impacts tend to increase or decrease as the scenarios analysed vary and limiting to a single impact could prove to be restrictive. When it comes to impact assessment, characterisation factors are internationally defined but appropriate selection of local factors and weighting factors proved to be crucial. Moreover, LCA results are not always the optimal economic solutions.

The complexity of data may make difficult to compare many different scenarios with different impacts, for this reason LCA methodology is often combined with other tools, such as integrated indicators and multi-criteria models. Nevertheless, LCA allows the analysis of its methodological limits by itself through sensitivity and uncertainty analysis. In this way the reliability of the assumptions can be tested. For result interpretation, hotspot analysis proves useful in identifying the parts/phases of the system with the greatest impact.

There are transversal themes in sustainable local waste management policies that emerge from most of the public reviews and can be considered strategic. Territorial synergies, especially at regional level, includes well-defined logistics and relationships between communities, local plants and infrastructures. Environmental pollution from traffic and transport may be greater than that generated from waste treatment phases, even with energy recovery. Consequently, proximity and local use of waste products are keys to success, in particular for the food and energy chain. The efficiency of the plants, their location and dimension are often responsible for the environmental impacts and economic gains of the processes. In the case of electricity/heat recovery, avoided burden should always be referred to the national energy grid. Moreover, the waste hierarchy proposed by European policies is not the optimal environmental solution in all situations: source separation and recycling are strictly dependent on the availability of appropriate infrastructures and technologies, as well as the presence of a market for the secondary raw materials produced. Since each territory has its own characteristics regarding population density, existing plants, industry and social and institutional behaviour, local accounting and management can be advantageous to provide stability to the investments. Compared to the existing international scientific literature, this review leads to similar results in highlighting the limitations of the LCA methodology applied to waste management (e.g. methodological choices, data transparency, uncertainties and communicability of the studies). The list of weaknesses can be used by experts to verify whether the studies available can credibly guide policy choices (Camana et al., 2021). The multidisciplinary nature of this sector is also recognized internationally, leading to the need for an integrated approach, which includes territorial characteristics, transport impacts, proximity and energy issues, waste hierarchy and social and economic concerns. If the objective is moving towards sustainability, burden shifting from a waste stream to another must be avoided. Organisational LCA can help to measure any environmental shifting. All waste generation steps and all treatment plants might be considered as boxes of the entire organisation, that is, the territory in which the waste is managed (Camana et al., 2021). Different system boundaries for the local organisational LCA are defined depending on the dimension of the context considered (e.g. optimum territorial area, local MSW management, regional framework). Ensure reliable results regarding waste management is imperative and the synergy between different environmental assessment tools is recommended by the scientific community. A contribution could be made by developing LCA databases for policy users and integrating them with territorial data including georeferencing of treatment plants, transport monitoring and optimisation and attention to local effects on soil, water and air.

Finally, the study confirmed the advantages and limitations of the LCA methodology for waste systems and provided examples based on the studies conducted in Italy. More attention must be paid in the future to methodological aspects and transversal themes of the life cycle approach for waste management in order to improve the robustness of its results. Additionally, the integration with other technical tools, decision-making strategies and economic and social aspects is always desirable.

1.4.2. Environmental assessment of solid waste landfilling technologies by means of LCA-modelling

The purpose of the study is to compare the environmental performance via life cycle assessment (LCA) of six different landfilling technologies: open dump (used as worst-case reference), conventional landfill with flares, conventional landfill with energy recovery, standard bioreactor landfill, flushing bioreactor landfill and semi-aerobic landfill. The resulted environmental benefits and drawbacks, related to the measures adopted to prevent uncontrolled gas and leachate emissions, allowed to evaluate the degree of sustainability of each system, namely the ability to decrease the environmental impacts from solid waste landfilling.

The environmental assessment was performed by means of the LCA-based tool EASEWASTE and the functional unit utilized was ‘‘landfilling of 1 ton of wet household waste in a 10 m deep landfill for 100 years”. Standard impact categories and toxicity-related impact categories were assessed. Emissions of biogenic CO_2 was considered neutral to global warming because the CO_2 originates from organic matter generated by an equivalent biological uptake during plant growth (IPCC, 2006).

The landfill consisted of separate cells filled with waste within 2 years. According to the boundaries the material input to all landfills consisted of 1 ton of wet household waste and a variable amount of clay and soil to be used as construction material. Only the transportation of input material was taken into account, while its collection, extraction and production were excluded from the system. Emissions associated with the electricity generation and combustion of diesel were accounted for. To better represent the time-dependent processes, such as gas and leachate generation, composition and utilisation, as well as the deterioration over time of the equipment, EASEWASTE allowed the division of the overall time horizon of the assessment into sets of independent time periods (four periods in the study). Leachate and biogas concentrations and the associated removal efficiencies varied across technologies and were taken from literature or full-scale plants. When energy recovery from biogas utilisation was implemented (e.g. CHP engine), the produced energy was assumed to substitute 100% for energy production at a coal-fired power plant and the saved emissions were credited to the system. Gas control, collection and extraction systems included vertical and horizontal wells, flare and oxidation top cover. Leachate control measures included a bottom liner and leachate collection system, whose efficiency was assumed to decrease over time in order to better evaluate the potential impacts arising from leakages. The collected leachate was further treated prior to discharge; the direct emissions from leachate aeration in the WWTP were disregarded, as well as the emissions from sludge management. In the case of bioreactor landfills active technologies, such as leachate recirculation, waste flushing and temporary aerobic degradation were implemented to improve waste stabilisation.

The potential impacts resulted from the life cycle impact assessment were given as ‘‘normalised impact potentials”. Emissions of landfill gas and leachate represent the principal contributor to environmental impacts in almost all the impact categories; this was particularly evident in the case of the open dump, where no measures for landfill emissions control were taken. A key parameter was, therefore, the efficiency of the collection systems. Gas energy recovery leads to significant savings in GHG emissions resulting in a negative numerical contribution to global warming. It was shown that ammonia/ammonium emission to surface water bodies through leachate was responsible for the potential impacts on nutrients enrichment and acidification. When nitrogen was removed through leachate nitrification/on-site denitrification, applying leachate recirculation, and soluble waste constituents were flushed-out through waste flushing, the environmental performance improved. Moreover, specific emissions from gas treatment and especially combustion products affected mainly water ecotoxicity and human toxicity via air. A good environmental performance was achieved by the semi-aerobic technology, due to the reduced leachate generation caused by the aerobic waste degradation step. The potential impacts on human toxicity via soil remain significant in all the landfilling technologies due to benzene disperse emissions to air and VOCs from gas treatment.

Bioreactor and semi-aerobic technologies achieved an environmental performance quite similar to the one of conventional landfills for a LCA time horizon of 100 years. Small improvements were found only in the categories related to nutrient enrichment, acidification and human toxicity via soil. Focusing only on the first time period (0–15 years), results showed that bioreactor and semi-aerobic technologies reduce significantly the amounts of greenhouse emissions compared to the conventional landfill with energy recovery due to the faster waste degradation and the consequent full exploitation of the methane generation potential in a reduced time span. On the other hand, the contribution to human toxicity via soil and via air is larger than in the conventional landfill technologies, because of the emissions released to the atmosphere from the treatment of a consistent amount of gas. Looking to the time frame 16-100 years the open dump continued to impact substantially since direct emissions of landfill gas and leachate were still significant. It is noteworthy that conventional landfills led to relatively high impacts on human toxicity via soil and via air, while bioreactor and semi-aerobic technologies were able to decrease them significantly. This fact was explained by the extinction of emissions relating to the aforementioned impact categories in the first 15 years. At the end of the time horizon (100 years) substances of various nature are left in the waste (e.g. C, N, Cl, heavy metals etc.), in other words landfills can be considered like "sinks". The magnitude of the accumulation is associated to nature of the substance, waste degradation and duration of the LCA time horizon. Regarding this issue it was highlighted that a significant fraction (50–58%) of the carbon entering the landfilling systems, composed almost entirely of biogenic carbon, remains stored at the end the LCA time horizon. This amount of carbon bound in the landfill may be credited to the system as saved CO2 emissions causing a reduction of the global warming potential of the system (but not considered by the authors as assumption in the assessment). The same could be discussed for heavy metals, since a longer time horizon may better represent their leaching process. With the exception of the first degradation phase, landfill leachate is neutral to alkaline for almost all the entire life of the landfill. In such condition the mobility of heavy metals is reduced and their concentrations in leachate are typically very low and therefore they are removed from the system very slowly, impacting for a very long time. But by adopting a longer time horizon the quality of the results of the assessment could be compromised, as landfills long-term data are not available and reliable.

In conclusion, the study underlined the importance of ensuring the highest collection efficiency of landfill gas and leachate implementing carefully planned and long-lasting solutions. Moreover, gas utilisation for energy recovery resulted an essential component since it leads to saved emissions and avoided impact potentials in several environmental categories. While, in reference to the short term, active interventions such as bioreactor and semi-aerobic landfills help considerably to speed up the stabilisation of waste by extinguishing the emission potential in a relatively short period.

1.4.3. A life cycle assessment of conventional technologies for landfill leachate treatment

Di Maria et al. (2017), in their study, used life cycle assessment (LCA) to compare different leachate treatment methods, based on conventional and advanced technologies, for an existing landfill. The aim was to identify the scheme with the lowest impact. In fact, although advanced technologies make it possible to obtain excellent quality effluents, it is also true that the direct and indirect impacts caused by the high consumption of energy and materials make them not very eco-friendly, creating a conflict of interest between two contradictory goals: to guarantee the highest performance and simultaneously not negatively impact the environment. In particular, on-site treatment based mainly on RO and evaporation were compared with the most diffused off-site combined treatment with civil sewage in wastewater treatment plants (WWTP).

The object of study was a sanitary landfill located in central Italy and in operation since 1995 (the filling phase ended in the 2014). Disposed waste was mainly municipal solid waste coming from separated collection after mechanical biological treatment. The landfill was equipped with systems for the collection and treatment of gas and leachate. The volume of gas generated and the methane content of 50–54% v/v allow it to be used as fuel in a combined heat and power plant (CHP). The electricity was sold to the national grid and the recovered heat was delivered to the existing on-site leachate treatment system, based on evaporation. The scenario just described (BS) was considered as a baseline reference, while three other different scenarios were set up to be compared by LCA.

Specifically, the basic scenario (BS) included both on-site and off-site treatments. 33% of the leachate was treated on-site, while the remaining 67% was co-treated off-site together with civil sewage in an existing WWTP 170 km far away from the site. In the on-site system, the leachate was first subjected to two-stages evaporation, where temperature and pressure were maintained by a thermal resistance and a volumetric pump. The heat recovered by the CHP engine was used here. The fraction of leachate not evaporated at the first stage was further processed in the second evaporator. The evaporated fractions, instead, were then condensed and processed by a reverse osmosis (RO) unit, composed of 5 modules of polyamide membranes. The permeate was subsequently treated with activated carbon, ion exchange resins and pH adjustment before being discharged. While the concentrate was sent to the off-site WWTP. For each m^3 of treated leachate, the facility consumes 70 kWh of electricity.

To reduce the dependence on the conventional off-site WWTP and at the same time cope with the important volume of leachate to be treated every day (about 125 m^3/d) effectively without the availability of large spaces where to carry out biological treatments independently, three more scenarios were considered:

First modified scenario (MS1): Improvement of the existing on-site system treatment capacity by adding a third evaporator stage and a new RO pre-treatment unit. The concentrate was processed in the improved evaporation plant producing a small volume of residues to send off-site (3% of the volume of the inlet leachate). The heat recovered by CHP engine still guaranteed thermal autonomy and 40 kWh/m^3 of electricity are provided by the national grid.

Second modified scenario (MS2): Replacement of the existing on-site system with a new three-stage RO unit. The concentrate was entirely sent off-site to the WWTP. This treatment scheme required 8.5 kWh/m^3 of electricity;

Third scenario: the possibility of off-site co-processing the whole amount of leachate with civil sewage in a WWTP was also considered.

All the schemes considered aimed to treat the same amount of leachate generated by the landfill in the year 2014. For not introducing bias due to the absence of direct full-scale data related to the treatment efficiencies, in all the cases the quality of the discharged effluents was assumed to be the same as the water exiting the WWTP. The latter can be considered a cautious assumption, as generally the performance of advanced technologies exceeds that of conventional ones.

The LCA was performed according to the ILCD Handbook in compliance with the standards ISO 14040 (2006), ISO 14044 (2006). Calculations were made using SimaPro 8.2. The functional unit was the treatment of 1m³ of leachate.
For the comparison of the different scenarios in a LCA perspective, the boundaries included the leachate treatment plant, the production of chemicals and energy required to run the system, the emissions released and the treated water discharged. The inventory was built on the base of data reported by the plant builders or, if not available, on average market data taken from Ecoinvent 3.0. Capital goods related to the different technologies were excluded from the analysis. The transport of materials and leachate from on-site to off-site WWTP was considered. Since the electricity from gas recovery was sold to the national grid, producing economic revenues, the amount of electricity necessary for feeding the leachate treatment systems was assumed to be completely purchased from the national grid (the Italian energy mix was considered). Emissions and surface water returned by the processes were taken as flows exiting the system. The system boundaries, including the leachate treatment schemes analysed, were expanded to solve the multi-functionality issue.
The impact assessment was performed following the ILCD 2011 midpoint method, considering the climate change, human toxicity and ecotoxicity impact categories, as well as resource depletion ones. To highlight the categories on which the scenarios had the greatest impact, the results were normalised using the normalisation factors of the EU 27 domestic extraction of resources and emissions per person with respect to the year 2010. The results showed that the impact categories most affected by the scenarios were human toxicity non-cancer effects (HTnc), human toxicity cancer effects (HTc), fresh water eutrophication (FEW), fresh water ecotoxicity (FWec) and mineral, fossil and renewable Resource Depletion (RD). The BS and WWTP scenarios, when off-site co-treatment with civil sewage in the wastewater treatment plant was largely exploited, were characterised by the highest impact, with the exception of RD and ozone depletion potential (ODP). The large amount of energy and chemicals required by the evaporation system contributed mostly on RD for the MS1 and BS scenarios. Emissions from transport played a minor role for on-site scenarios, while they were not negligible for the WWTP and BS scenario due to the significant transport distance from the landfill to the treatment plant. MS2

scenario was the one performing better in all cases, indicating RO as the most promising method among the new technologies for COD, heavy metals and salts removal.
An uncertainty analysis to test the accuracy of the model was performed by assessing the error associated with the values of the impact categories. The approach proposed by Di Maria et al. (2016a) and Di Maria et al. (2016b) was used, focusing on the most relevant categories (e.g. HTnc, HTc, FWE and FWec). The outcome confirmed the obtained results qualitatively for more than 80% of possible values. MS1 scenario seemed to be the less uncertain, except for FWec.
Concluding, the life cycle study confirmed that leachate treatment is an activity that affects mainly human health and freshwater quality and that more effective treatment of the leachate is a key factor for improving the environmental sustainability of landfills. Average impacts resulted higher for the conventional off-site co-treatment in wastewater treatment plants, while impacts were lower for the advanced on-site treatment based on reverse osmosis. The impact from the combined RO-evaporation system was always higher than the one of pure reverse osmosis due to high chemicals and energy consumption, making the latter the most efficient solution even with the quite large amount of liquid concentrate returned by the process.

1.5. Key concepts highlighted by the literature analysis on waste LCA

Literature highlights the different modalities in which LCA can be applied to waste management systems.
In most of the case studies, life cycle assessment is used to compare a number of different scenarios, characterised by different technologies, to find the most environmental friendly option. Other times, a single plant may be assessed to figure out what can be improved to achieve better performances and at the same time reduce pollutants emissions.
Climate change, resource depletion and toxic emissions to the ecosystems and humans represent the impact categories of great concern for all of the examples.
A recurrent assumption is the zero burden concept, according to which only the collection, transport, treatment and disposal of waste is considered, neglecting the way of production.
Advantages and limitations of the LCA methodology for waste systems are also underlined to improve the robustness of the results.

When it comes to evaluating individual plants, as in the case of landfills and leachate treatment plants, capital goods and infrastructure construction operations are often not embedded within the system boundaries, leading to misleading results, especially if their contribution is considerable.

The environmental impacts deriving from waste treatment technologies, especially in the case of disposal, often occur over a very long period of time and the homogeneity of this time-frame between the different case studies would be desirable. For a landfill, this time frame is set at 100 years in most of the scientific literature.

Life cycle studies confirmed that leachate and biogas treatment are key factors for improving the environmental sustainability of landfills.

The methods of managing emissions are an integral part of the life stages of a landfill. Since the regulatory limits for the discharge of pollutants into the atmosphere and into water bodies have become more stringent, every landfill manager has to choose the best treatment, and more and more often on-site plants are implemented, rather than opting for off-site cotreatment.

Therefore, it is of fundamental importance to understand if the resources exploited to remedy potentially contaminating emissions are able to offset the emissions themselves. Typically, average impacts result higher for the conventional off-site co-treatment in wastewater treatment plants, while impacts are lower for the advanced on-site treatment based on reverse osmosis and passive technologies like phytoremediation.

It comes out also that LCA integration with other technical tools, decision-making strategies and economic and social aspects is always considered desirable if a comprehensive view of the reality is the objective.

2. Semi aerobic landfill case study

To analyse the potential impact of leachate treatment, the leachate produced by a semi aerobic landfill was considered. A case study related to an existing landfill in the northern part of Italy has been examined.

The site is located in the municipality of Cairo Montenotte in the Liguria region (Northwest of Italy).

For this LCA the lifetime of the landfill was established at 100 years. For convenience, according to the transformations that take place in a landfill during its life cycle and the related activities, it seemed reasonable to divide the entire time span into 5 phases:

- Construction;
- Operation, lasting 20 years;
- Aftercare, lasting 40 years;
- Closure, lasting 1 year;
- Conversion, lasting 39 years.

The leachate treatment plant is built during landfill construction and will be active starting from the operation phase until the end of the landfill life.

The data necessary for the assessment and all the assumptions made in the design of the semi-aerobic landfill are reassumed in the next paragraphs; for a detailed description refer to Sciarrone (2020/2021).

2.1. Site description

The area served by the waste management system, which is in charge of the collection and treatment of the waste, includes 23 municipalities of the Savona province in the Ligurian region.

The landfill is located in the municipality of Cairo Montenotte (locality of La Filippa), at 340 m.a.s.l in the inland part of the province of Savona.

The landfill site is easy accessible via a network of roads and railways and generally presents no traffic problems.

The climate in the locality of Cairo Montenotte is warm and temperate. The average annual temperature is 11.9 ° C and ranges between a maximum temperature of 21 ° C in July and a minimum of 3 ° C in January.

Rainfall is consistent throughout the year, even in the dry summer months. It ranges from a minimum of 5 to a maximum of 9 rainy days per month with rainfall from 73 to 155 mm per month and humidity always above 70%.

The wind is stronger during the colder months in winter.

2.2. Waste production and characterization

Separate waste collection is applied at the municipal level.

In this project it is considered that only the non-segregated fraction is sent directly to the landfill without any pre-treatment. The other fractions are instead appropriately recycled or recovered.

The quantity of waste disposed of in the landfill each year is 11000 tons and, according to the semi-aerobic technology, it is assumed to have a density of 0.8 t/m^3.

The landfill continues to be filled for 20 consecutive years until its entire volume is occupied.

Tables 1 and 2 respectively report landfill size and waste composition assumed for this project.

Table 1. Landfill main characteristics (Sciarrone, 2020/2021).

Waste	11000	t/y
Time filling	20	y
Total waste	22000	ton
Waste density in landfill	0.8	t/m^3
Landfill volume	275000	m^3
Mean landfill height	10	m
Landfill surface	27500	m^2

Table 2. Waste composition (Sciarrone, 2020/2021).

Fraction	**%**
Food waste	10
Garden waste	5.2
Paper	15.3
Cardboard	12
Wood	5.6
Textiles	5.6
Plastics	26.1
Glass and inerts	5.6
Metals	2.7
Napkins	10.5
Undersieve	1.4
Total	100

2.3. Landfill phases

The semi aerobic landfill modelled by Sciarrone (2020/2021) was described according to the management activities and biochemical processes which take place over time.

For this reason it was useful to divide the entire landfill life into five phases.

This paragraph describes the essential processes involved in each life phase of the landfill; for more details related to design parameters and calculations refer to the complete study of Sciarrone (2020/2021).

2.3.1. Landfill construction

The landfill construction phase involves all the operations related to the site preparation and the landfill structures and barriers realization.

An area with a pre-existent good soil, previously used as quarry for clay extraction, was selected as optimal site to build the landfill.

Land clearance is the first step in preparing the area; 32000 m^2 of land are cleared and the first 30 cm of topsoil removed.

To model the shape of the landfill, the ground is levelled through excavation and filling; the excavated volume is about 10000 m^3 and the one to be filled is 2291 m^3.

Figure 17 shows the plan of the landfill site, from which the two sectors that compose it are identified.

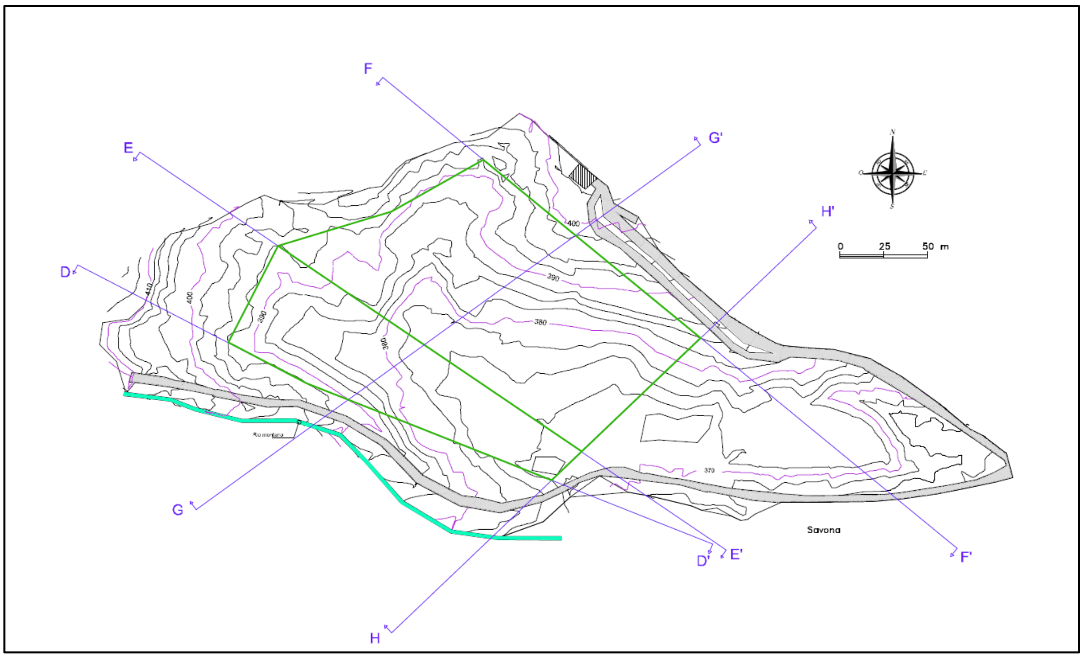


Figure 17. Landfill planimetry (Sciarrone, 2020/2021).

A fence is realized along the perimeter of the landfill to mitigate the impacts due to the operational phase and to prevent unauthorized access.

For this project it was decided to realize a 2 m high fence made of an iron grid and wooden poles every 2.5 m. The barrier includes autochthonous maple trees together with the fence. In the study it was decided to neglect the impact of trees production since the avoided impact due to CO_2 sequestration is greater than zero.

All materials are bought in the market and transported for an assumed distance of 100 km.

After the preliminary preparation of the site is completed, we proceed with the construction of the bottom barriers of the landfill, in order to isolate it from the surrounding environment in case of any leachate leakages.

A bottom and transversal slope of 2% and 1.5% respectively were obtained to ensure adequate drainage of the leachate.

The bottom liner was made in accordance with current legislation (Giunta della Lombardia, 2014) and consists of the following layers:

- Natural geological barrier of thickness s≥1 m with a permeability greater than 10^{-9} m/s (already present on the site);
- Supplementary clay barrier of thickness s≥1 m with a permeability greater than 10^{-9} m/s;
- A HDPE geomembrane of thickness s≥2.5 mm;
- Non-woven textile, with minimum tensile strength in both longitudinal and transversal direction of 60 kN/m, with a minimum resistance to static punching of 10 kN, with a minimum mass per unit area of 1200 g/m^2 (Giunta regionale della Lombardia, 2014).

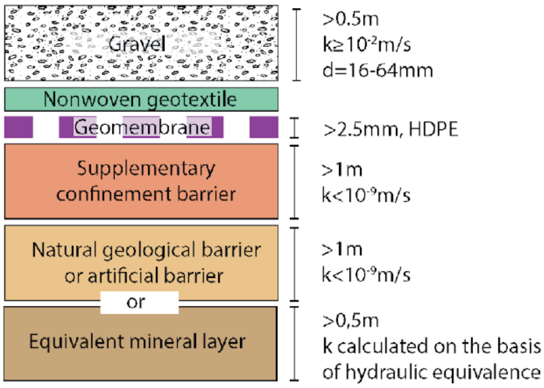


Figure 18. Bottom liner configuration (Giunta regionale della Lombardia, 2014).

A drainage layer to collect the leachate is then installed on top of the lining system. It consists of a series of slotted primary and secondary pipes immersed in a permeable layer of medium-coarse size gravel which facilitates the flow of the leachate towards the pipes.

To allow the simultaneous flow of leachate and air, the diameter of the primary pipes is quite large and equal to 600 mm; while the secondary pipes are narrower with a diameter of 400 mm.

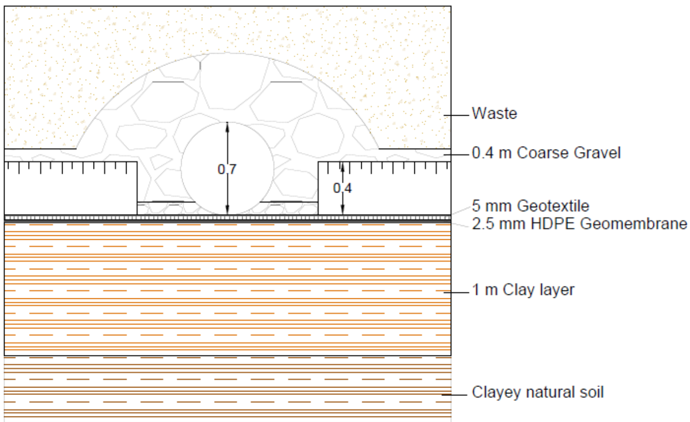


Figure 19. Primary pipes details (Lazzarin, 2015/2016).

Along the entire perimeter of the landfill, containment embankments in mixed sand and clay are erected to prevent the sliding of the top cover, which is installed when the filling phase is completed.

Finally, a rainfall water collection system is installed to manage the run off water diverted by the top cover. For this purpose a network of HDPE pipes with a diameter of 700-750 mm are designed considering the most intense precipitation with a return period of 10 years.
Each of the 2 landfill sectors has its own rainfall water collection system which reconnects before the water is released.
During the construction phase, the equipment necessary for the leachate treatment plant is also built. The reverse osmosis module is installed, the evaporation pond and basins for phytoremediation are built and the contact bed for adsorption is prepared, as well as other auxiliary tools; for more design details refer to chapter 3.

2.3.2. Landfill operation

Once the installation of the necessary structures has been completed, the operation phase of the landfill begins.
In this phase the waste is transported for an average distance of 12 km from the municipalities served and disposed in the landfill until its two sectors are completely filled. It is from this moment on that the biodegradation process of the waste and the consequent production of biogas and leachate start.
As the landfill is filled with waste, vertical gas venting pipes are installed to enhance the natural flow of air inside the landfill body. According to the Fukuoka method, 56 HDPE perforated pipes with an internal diameter of 30 cm and a medium height of 10 m are distributed at regular intervals every 20 to 40 m and surrounded by a layer of gravel 15 cm thick.

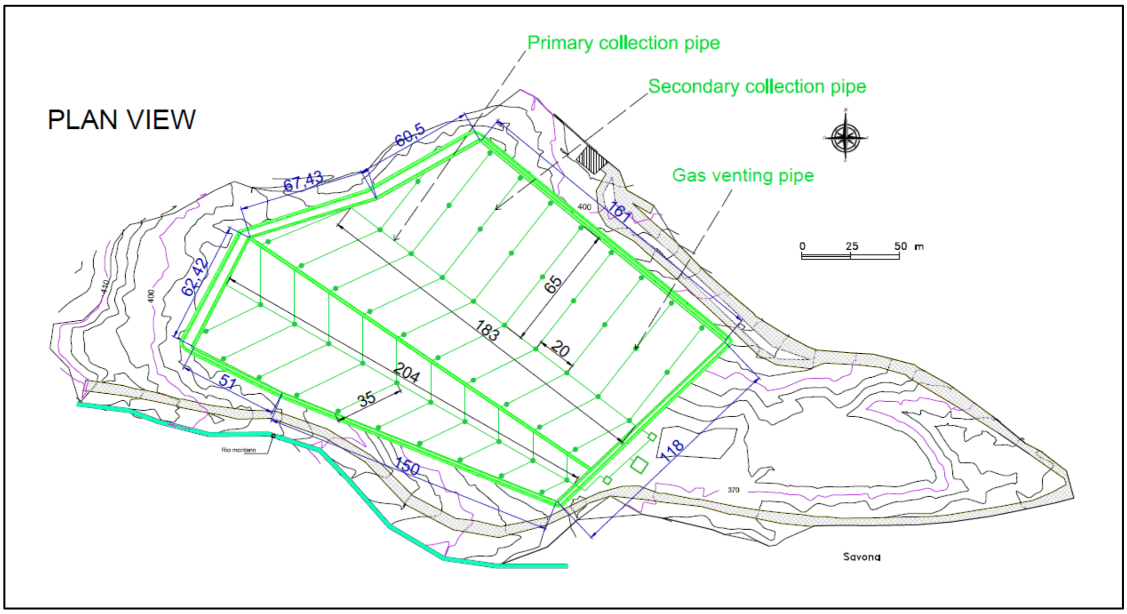


Figure 20. Ventilation system (Lazzarin, 2015/2016).

As the first layers of waste are deposited in the landfill, a daily cover is manually laid to cover the exposed surface, in order to prevent the volatilization of dust and infestation by animals. The daily cover is made of synthetic material with a permeability greater than 10^{-3} m/s and can be reused several times.

After the landfill sectors are completely filled, the daily cover is replaced by the temporary top cover.

The temporary top cover must allow the infiltration of rain and the passage of air to increase the kinetics of waste degradation and the oxidation of the biogas produced.

To accomplish these requirements, the temporary top cover is made up of the following layers (from bottom to top):

- About 20 cm of regularization layer to homogenize the surface of the waste;
- 0.55 m of coarse gravel with high hydraulic conductivity;
- 0.55 m of fine sand and compost obtained from municipal solid waste for the oxidation of the biogas;
- 1.1 m of natural soil (Sciarrone, 2020/2021).

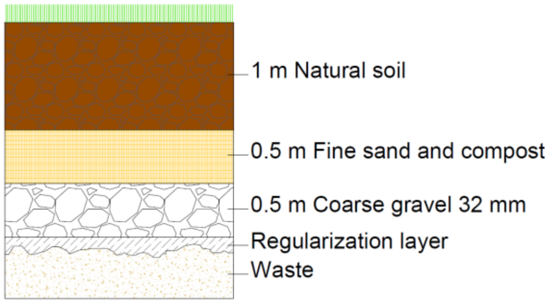


Figure 21. Temporary top cover (Lazzarin, 2015/2016).

During the operational phase, the leachate is treated by the reverse osmosis, phytoremediation and adsorption systems and then discharged into surface water. For details regarding the leachate treatment plant operation, refer to chapter 3.

2.3.3. Landfill aftercare and closure

Following the installation of the temporary top cover, the aftercare phase begins, which extends over a period of 40 years in which the waste continues to be biodegraded until it reaches a sufficient degree of stabilization.

At this stage, the installation of any type of landfill facility is not envisaged; this is a waiting period in which rain is allowed to pass through the top cover and biodegradation takes its course by producing biogas and leachate.

During this phase, just as the biogas is oxidized by passing through the temporary top cover and released into the atmosphere, the leachate is also treated by the phytoremediation and adsorption systems. For details regarding the leachate treatment plant operation, refer to chapter 3.

At the end of the aftercare, when mechanical stability has been achieved, the landfill is closed with an impermeable final top cover; this operation lasts 1 year in the so called "closure" phase.

The final top cover was realized in compliance with the current legislation, to ensure the control of emissions, reduce the erosion phenomena and settlement; it consists of the following layers (from bottom to top):

- A regularization layer;
- 0.5 m of coarse gravel with a hydraulic conductivity higher than 10^{-3} m/s;
- 0.5 m of clay with a hydraulic conductivity lower than 10^{-8} m/s;

- 0.5 m of coarse gravel with a hydraulic conductivity higher than 10^{-3} m/s;
- 1 m of natural soil.

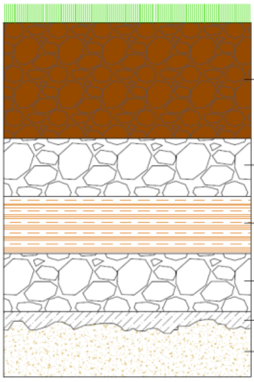


Figure 22. Final top cover (Lazzarin, 2015/2016).

2.3.4. Landfill conversion

The conversion phase starts immediately after the installation of the final top cover; it lasts 39 years and consists in the adaptation of the landfill surface for recreational use. In fact, after 61 years from the beginning of waste disposal, the landfill body has reached a high degree of stability and its surface is ready to be planted with grass using the hydroseeding technique.

During the entire conversion phase and beyond, despite the high degree of stabilization and the impermeability of the top cover, the biodegradation of the waste continues producing biogas and leachate, even if in less quantity and of better quality.

The leachate treatment plant is in fact always functioning and for more information regarding the individual phytoremediation and adsorption units, refer to chapter 3.

2.4. Biogas production

Biogas, together with leachate, is a product of the waste degradation that occurs inside the landfill.

Methane and carbon dioxide are the major biogas components, but other compounds can be found in traces.

The biogas composition depend on a lot of factors but generally the percentage of methane can be linked to the landfill typology; typically the lower the level of aeration of the landfill, the higher the methane concentration.
To calculate the quantity and quality of the biogas produced in the case of a semi aerobic landfill, it is necessary to firstly calculate the quantity of biogas produced in the anaerobic landfill and then use a correction factor to convert the results.

2.4.1. Biogas quantity

The waste composition is the factor that most influences the production of biogas. The fractional composition of the waste described in paragraph 2.2 was used to calculate the total amount of biogas produced.
To do this we consider the stoichiometric formula relating to the microbial conversion of organic carbon to methane; this equation allows to estimate the theoretical yield of landfill gas and calculate the quantity of CH_4 and CO_2.
The biogas production is not influenced only by the organic carbon but also by the biodegradable carbon, which has to be considered to compute the landfill gas specific yield.
In order to calculate the specific biogas production at the passing of time, it has to be considered that each waste fraction has a different degradation velocity; so through a first order kinetic model the decay constant for each waste fraction is calculated.
Figure 23 shows the results related to the specific biogas production for 100 years; to view the calculation procedures step by step, refer to Sciarrone (2020/2021). From the graph it can be observed how the highly biodegradable fraction becomes biogas faster than the other fractions but, since most of the waste consists of slowly biodegradable materials, the slowly biodegradable fraction contributes mostly to the overall biogas production.

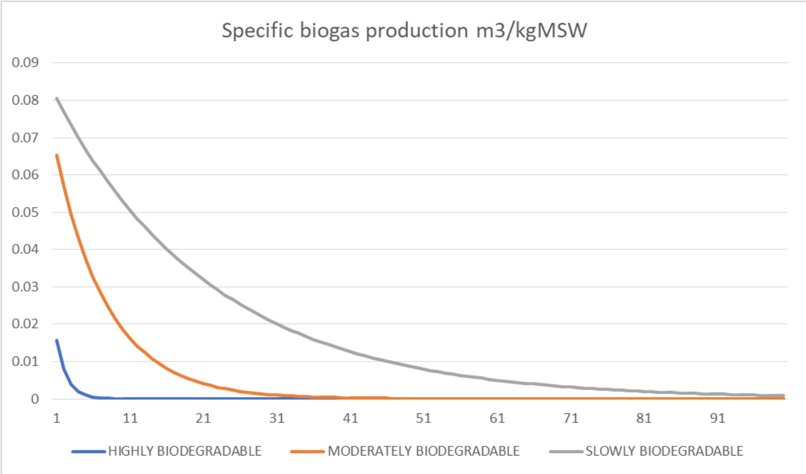


Figure 23. Specific biogas production for 100 years (Sciarrone 2020/2021).

The total quantity of biogas produced for each year is the sum of the contributions from each pile of waste. This means that for the first 20 years the annual production of biogas increases since new waste is disposed regularly, while after the landfill is completely filled the quantity of biogas decreases with time as shown in Figure 24.

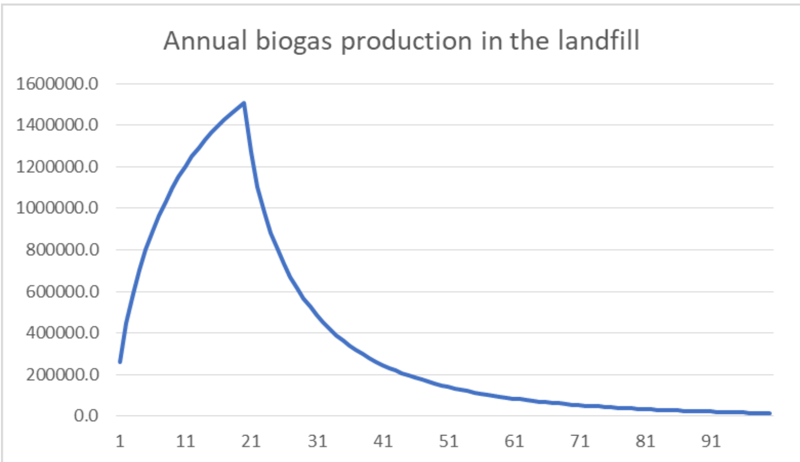


Figure 24. Annual biogas production in the landfill (Sciarrone, 2020/2021).

The following Table 3, according to the calculations of Sciarrone (2020/2021), reports the total volume of biogas produced in the 4 phases. While Figure 25 shows the cumulated biogas quantity.

Table 3. Total biogas produced for each phase (Sciarrone, 2020/2021).

Years	Nm^3
From 1 to 20	21661105
From 21 to 61	14800681
62	84589
From 63 to 100	1466680

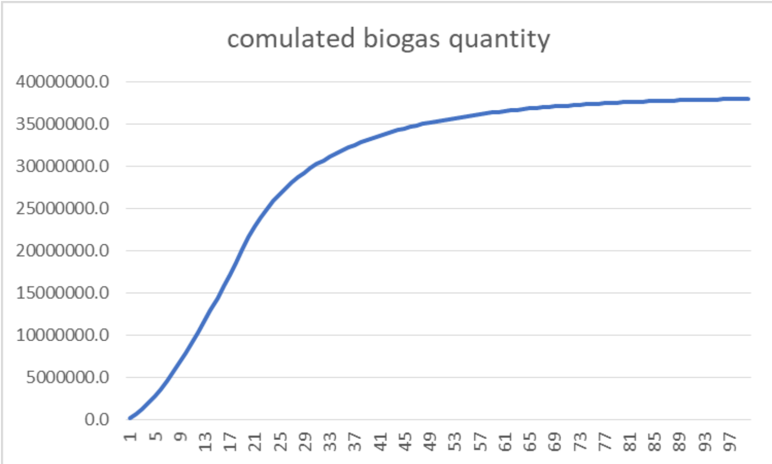


Figure 25. Cumulated biogas production (Sciarrone, 2020/2021).

2.4.2. Biogas quality

Different landfill types produce biogas with different percentages of methane and carbon dioxide.

Inside a semi-aerobic landfill there are both aerobic and anaerobic spots, therefore it seems reasonable to assume that the quantity of methane produced is lower than the anaerobic condition and higher than the aerobic one.

To evaluate the percentage distribution of the aerobic and anaerobic areas in the semi aerobic landfill, the methane correction factor (MCF) is applied.

This parameter is defined by the international panel on climate change guidelines (IPCC, 2006) to evaluate the methane produced and indicates the ratio between the anaerobic and aerobic zones inside the landfill body.

According to the IPCC the MCF for a semi aerobic landfill is equal to 0.5, meaning that half of the waste is degraded under aerobic condition and half under anaerobic condition.

The typical average biogas composition of a semi aerobic landfill consists of 30% methane and 70% carbon dioxide.

Before being released to the atmosphere, part of the biogas generated is oxidized by the top cover installed on the landfill surface.

To take into account the real efficiency of a top cover, considering that fugitive emissions can occur through cracks/fissures or via lateral diffusion, an oxidation factor (OX) equal to 0.1 has been suggested by the IPCC for a covered, well managed landfill. Considering a OX equal to 0.1 means that the CH_4 emitted is the 90% of the generated CH_4 and only the remaining 10% is oxidized.

Only for the operational phase, due to the absence of a top cover, the oxidation factor was considered equal to 0.

The total methane emitted can be derived knowing the methane generated by each waste category, the recovered methane and the oxidation factor for each year; the results of the calculations are reported in Table 4, for the detailed steps refer to Sciarrone (2020/2021).

Table 4. Quantity of biogas, methane and carbon dioxide produced; quantity of methane oxidized and emitted for each phase (Sciarrone, 2020/2021).

	filling	aftercare	clousure	conversion	unit
years	20	40	1	39	y
production	21661105	14800681	84589	1466680	m^3
CH_4 %	30	30	30	30	%
CO_2 %	70	70	70	70	%
CH_4	6498332	4440204	25377	440004	m^3
CO_2	15162774	10360477	59212	1026676	m^3
oxidized CH_4 %	0	10	10	10	%
non oxidized CH_4 %	100	90	90	90	%
non oxidized CH_4	6498332	3996184	22839	396004	m^3
produced CO_2	0	444020	2538	44000	m^3
tot CH_4	6498332	3996184	22839	396004	m^3
tot CO_2	15162774	10804497	61750	1070677	m^3
tot CH_4	3600076	2213886	12653	219386	kg
tot CO_2	23199044	16530880	94477	1638135	kg

To complete the biogas composition, the concentrations of trace compounds were considered from Manfredi and Christensen (Manfredi et al., 2009); the quantity of each compound in kilograms are given by multiplying the concentrations for the volume of produced biogas and are reported in Table 5.

Table 5. Quantity of biogas trace compounds for each phase (Sciarrone, 2020/2021).

	filling	aftercare	clousure	conversion	unit
benzene	152	104	0.59	10	kg
CFC 11	217	148	0.85	15	kg
CFC12	1083	740	4.23	73	kg
Dichloromethane	1083	740	4.23	73	kg
HCFC 21	260	178	1.02	18	kg
HCFC 22	282	192	1.10	19	kg
Hydrogenchloride	130	89	0.51	9	kg
Hydrogenfluoride	43	30	0.17	3	kg
Hydrogen sulphide	2	1	0.01	0.147	kg
Propylbenzene	1083	740	4.23	73	kg
Tetrachloroethene	585	400	2.28	40	kg
Toluene	3466	2368	13.53	235	kg
Trichloroethylene	347	237	1.35	23	kg
Vinylchloride	455	74	0	0	kg
VOCs	4982	3404	19.46	337	kg
Xylenes	1300	888	5.08	88	kg

2.5. Leachate production

The leachate is produced by the infiltration of rain into the landfill, where it comes into contact with the waste and dissolves the soluble components.

Estimating the quantity and quality of the leachate is very important for sizing the plants dedicated to its treatment.

2.5.1. Leachate quantity

The amount of leachate produced essentially depends on the amount of rain that is able to infiltrate through the top cover.

The properties of the top cover and the waste type play a fundamental role in regulating the amount of water that percolates into the landfill. While the efficiency of the leachate collection system determines how much leachate is extracted out of the total produced.

In this project it is assumed, for simplification, that all infiltrated rain is converted into leachate and that all the leachate is collected without leakages.

A simplified hydrological mass balance of the landfill was applied to calculate the leachate quantity.

During the operational phase, the quantity of leachate produced (L) is given by the difference between precipitation (P) and evaporation (E):

$$L = P - E$$

The equation is solved by knowing the precipitation regime of Cairo Montenotte and the evaporation rate. The evaporation phenomenon of part of the infiltrated water is due to the absence of a top cover and is calculated according to specific parameters linked to the average rainfall and solar radiation of the site.
Refer to Sciarrone (2020/2021) to view the calculations in detail. Table 6 reports the results of the mass balance for the operation phase.

Table 6. Leachate production during operation phase (Sciarrone, 2020/2021).

Month	**L=P-E (mm/month)**
January	45.82
February	40.94
March	37.56
April	45.48
May	31.03
June	17.60
July	11.48
August	17.72
September	44.00
October	64.25
November	95.02
December	49.03

During the aftercare phase, the quantity of leachate produced (L) is given by the difference between precipitation (P), run off (R) and evapotranspiration (ET):

$$L = P - R - ET$$

The equation is solved by knowing the precipitation regime of Cairo Montenotte, the run off and the evapotranspiration rate.
Run off is defined as the part of rain, which in the presence of a semipermeable top cover and due to the morphology of the landfill, is diverted to the surrounding environment (and is collected by the special rainwater collection system).

The run off is calculated according to specific parameters that consider the precipitation regime, the type of soil and the materials used for the top cover, the landfill slope and the soil moisture content.

Evapotranspiration is another phenomenon that occurs only starting from the aftercare phase. It considers the combination of evaporation of water from the soil and transpiration of the plants covering the landfill surface.

The potential evapotransiration is calculated as a function of the average monthly temperature, the annual thermal index, the hours of solar exposure and the latitude. For the wet season the evapotranspiration coincides with the potential evapotranspiration; while for the dry season a correction factor is introduced which takes into account the moisture content of the top cover and the field capacity.

Refer to Sciarrone (2020/2021) to view the calculations in detail. Table 7 reports the results of the hydrological mass balance for the aftercare phase.

Table 7. Leachate production during aftercare and closure phases (Sciarrone, 2020/2021).

Month	L=P-E (mm/month)
January	47.0
February	40.5
March	36.5
April	42.1
May	2.6
June	1.3
July	0.0
August	0.0
September	26.5
October	56.6
November	93.4
December	49.0

The leachate produced during the conversion phase was calculated considering that only 5% of the water can infiltrate trough the final impermeable top cover. Table 8 reports the total leachate production and collection for the conversion phase.

Table 8. Leachate production during conversion phase (Sciarrone, 2020/2021).

Month	Conversion (mm/month)
January	2.35
February	2.03
March	1.82
April	2.11
May	0.13
June	0.06
July	0.00
August	0.00
September	1.32
October	2.83
November	4.67
December	2.45

The filling sequence of the 2 sectors that make up the landfill was considered to calculate the volume of leachate produced during the operation phase. The incoming waste is divided into 5 piles and as the sectors are filled, the surface covered by the waste grows linearly and so does the produced leachate.

While starting from the aftercare, when the filling is completed and the surface covered by the waste remains always the same (as well as the value of the rainfall assumed), the leachate produced is constant over the years.

The graph in Figure 26 shows the trend in leachate production during the first 61 years of the landfill's life.

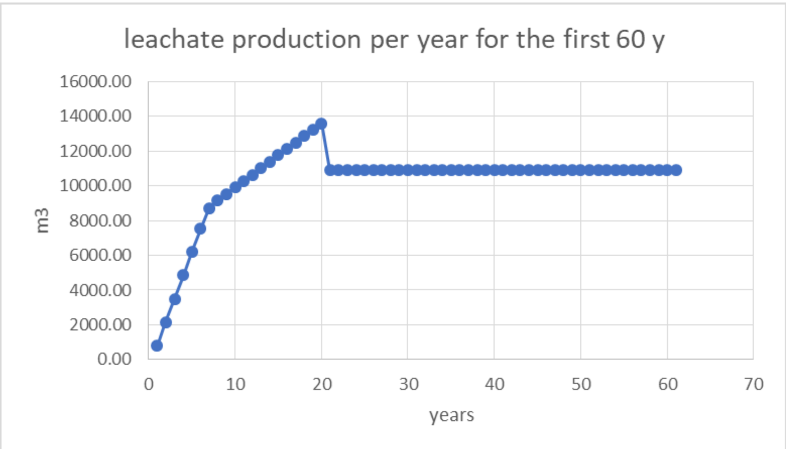


Figure 26. leachate production per year (Sciarrone, 2020/2021).

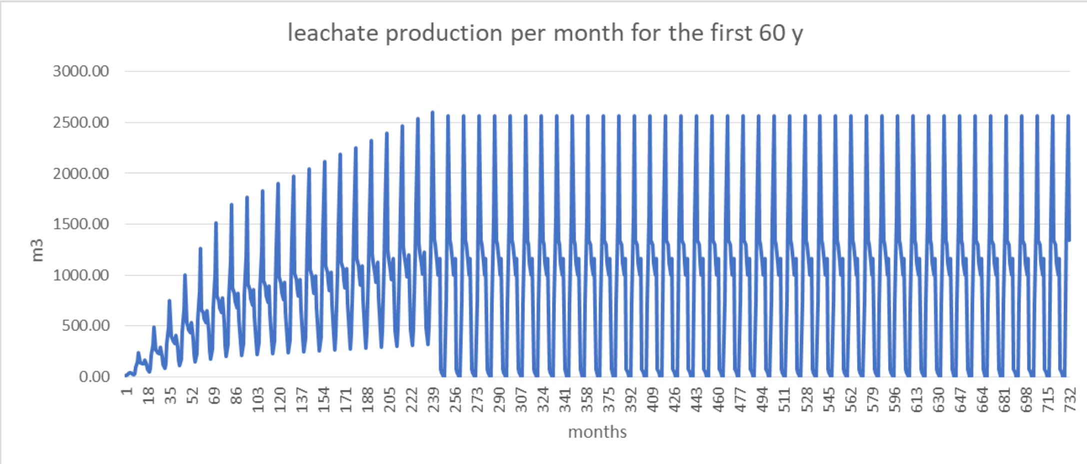


Figure 27. Leachate production per month (Sciarrone, 2020/2021).

The total quantities of leachate produced and collected in each phase are reported in Table 9.

Table 9. Total quantities of leachate (Sciarrone, 2020/2021).

	Operation	**Aftercare**	**Closure**	**Conversion**	**Unit**
Years	20	1	40	39	y
Leachate production	181587	10878	435114	21212	m^3

2.5.2. Leachate quality

Leachate is a wastewater rich in a wide variety of compounds. Its quality is influenced by several factors, first of all the state of waste degradation, the water content, the waste composition and the type of landfill.

In a semi-aerobic landfill the leachate quality is better than in the case of an anaerobic landfill thanks to the higher capability of ammonia removal and the faster degradation kinetics.

For this project the mean values of pollutants concentration for each phase of the landfill were taken from Manfredi and Christensen (Manfredi et al., 2009). The values reported by the article were in compliance with the laboratory experiment performed by Cossu on waste columns subjected to different degradation conditions (anaerobic, aerobic and semi aerobic).

The pollutants concentration values implemented in the model are shown in Table 10.

Table 10. Pollutants concentration in the leachate (personal elaboration).

	Filling (mg/l)	Aftercare (mg/l)	Closure (mg/l)	Conversion (mg/l)
bod	16000	10000	1000	40
cod	20000	15000	5000	400
ammonia	1000	700	500	400
chloride	2500	2000	1500	980
sodium	700	500	400	200
phospate	14	14	14	14
toluene	0.16	0.16	0.02	0.02
bromine	0.5	0.3	0.2	0.16
cadmium	0.012	0.01	0.008	0.006
arsenic	0.03	0.025	0.02	0.02
zinc	4	2.2	1.5	0.7

Multiplying the pollutants concentration for the volume of leachate produced in each phase it is possible to compute the pollutants quantities in kilograms, as shown in Table 11.

Table 11. Pollutants quantities in the leachate (personal elaboration).

	Filling (kg)	Aftercare (kg)	Closure (kg)	Conversion (kg)
bod	2905387.9	4351139.2	10877.8	848.5
cod	3631734.9	6526708.8	54389.2	8484.7
ammonia	181586.7	304579.7	5438.9	8484.7
chloride	453966.9	870227.8	16316.8	20787.6
sodium	127110.7	217557.0	4351.1	4242.4
phospate	2542.2	6091.6	152.3	297.0
toluene	29.1	69.6	0.2	0.4
bromine	90.8	130.5	2.2	3.4
cadmium	2.2	4.4	0.1	0.1
arsenic	5.4	10.9	0.2	0.4
zinc	726.3	957.3	16.3	14.8

3. Leachate treatment plant

3.1. Leachate treatment plant description

The leachate produced during the operation of the landfill is subjected to a treatment that includes the following phases: reverse osmosis and solar evaporation, phytoremediation, adsorption by granular activated carbon. While in the aftercare, closure and conversion phases, the quality of the leachate to be treated makes reverse osmosis unnecessary, allowing only the combination of phytoremediation and adsorption to be exploited (see Table 12). The plants were sized taking into account the average value of leachate produced daily over the entire life cycle of the landfill. To simplify, the extracted leachate was assumed to be equal to the quantity produced. Table 13 shows the maximum and minimum values of leachate extracted in the various phases, as well as the average value taken into consideration in the sizing of the plants.

Table 12. Combination of the leachate treatment stages applied to each phase of the landfill. Filling phase: reverse osmosis, followed by phytoremediation and adsorption as last step. Aftercare, closure and conversion: phytoremediation and adsorption (personal elaboration).

	FILLING	AFTERCARE	CLOSURE	CONVERSION
1) Reverse osmosis and solar evaporation	√	X	X	X
2) Phytoremediation	√	√	√	√
3) Adsorption	√	√	√	√

Table 13. Total leachate produced, maximum, minimum and average flow rate produced in the landfill for each phase (personal elaboration).

	FILLING	AFTERCARE	CLOSURE	CONVERSION
Total leachate produced (m^3)	181587	435114	10878	21212
Max. flow rate (m^3/d)	87	86	86	4
Min. flow rate (m^3/d)	0.34	0	0	0
Average flow rate (m^3/d)	44	43	43	2

Leachate leaving the landfill is collected in cylindrical fibreglass storage tanks. Three units with a capacity of 18 cubic metres are used.

Figure 28. Fibreglass storage tank for leachate (Varem LR).

The length of a single tank measures 6 m, while the outer diameter is 2 m. By subtracting the thickness of the walls (2 cm) from the external diameter, it is possible to calculate the internal diameter. From here it is easy to calculate the external and internal volume of the tank.

$$External\ volume = \pi \cdot 1 \cdot 6 = 18.8\ m^3$$

$$Internal\ volume = \pi \cdot (1 - 0.02)^2 \cdot (6 - 2 \cdot 0.02) = 18.1\ m^3$$

The density of fibreglass is 1.5 t/m^3, therefore the weight of tree tanks is:

$$Tanks\ weight = (18.8 - 18.1) \cdot 1.5 \cdot 3 = 3.9\ ton$$

3.2. Leachate treatment plant design

3.2.1. Reverse osmosis design

3.2.1.1. Reverse osmosis dimensioning

The reverse osmosis plant was sized to treat an influent flow rate of 44 m^3/d, i.e. the daily average of leachate produced in the filling phase (see Table 13). Four modules of thin film composite polyamide membranes in parallel are required to achieve 85% recovery. This guarantees a permeate flow rate of 37 m^3/d and a concentrate flow rate of 6.7 m^3/d.

$$Recovery, r = 85\%$$

$$Permeate\ flow\ rate, Q_p = Feeding\ flow\ rate \cdot r = 44 \cdot 0.85 = 37\ m^3/d$$

The membranes are of spiral wound type (see Figure 29), with a total diameter of 10 cm and a length of 1 m each. Each membrane weighs 3.2 kg and, with the appropriate maintenance measures, has an average life of 5 years (Hydronautics, Nitto Group Company). Considering that the plant is active for twenty years, 16 membranes are needed, for a total weight of:

$$Membranes\ weight = 3.2 \cdot 4 \cdot \frac{20}{5} = 55.7\ kg$$

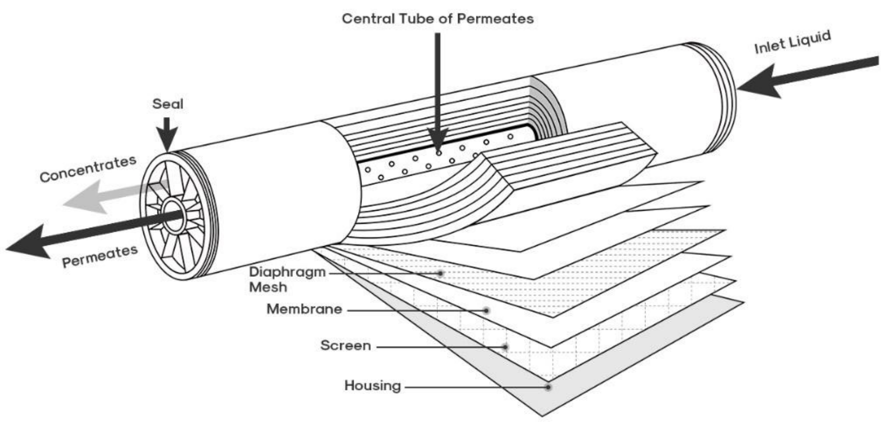


Figure 29. Spiral wound membrane elements (www.delemil.com).

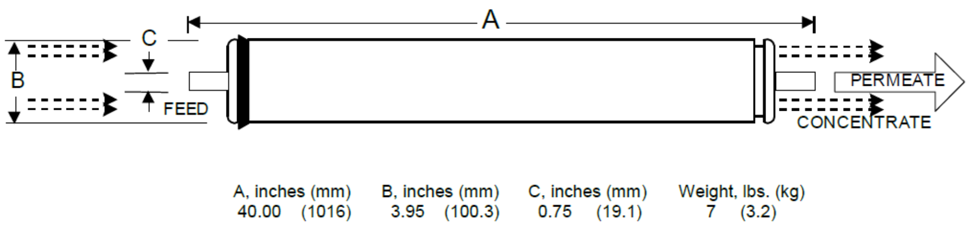


Figure 30. Detail of membrane dimensions (Hydronautics, Nitto Group Company).

The membranes are enclosed in stainless steel vessels (see Figure 31), 10.4 cm in diameter and 1 m long. Knowing that the thickness of the walls is 2 mm, the external and internal volume of each vessel can be calculated:

$$External\ volume = \pi \cdot \left(\frac{0.104}{2}\right)^2 \cdot 1 = 0.0085\ m^3$$

$$Internal\ volume = \pi \cdot \left(\frac{0.104}{2} - 0.002\right)^2 \cdot (1 - 2 \cdot 0.002) = 0.0078\ m^3$$

The density of stainless steel is equal to 7.9 t/m^3, so the weight of four vessels is:

$$Vessels\ weight = (0.0085 - 0.0078) \cdot 7900 \cdot 4 = 23.1\ kg$$

Figure 31. Stainless steel vessels for membranes (Pure Aqua, Inc).

In order to prevent membrane scaling and fouling, an antiscalant solution is used, to be diluted with part of the permeate in a concentration of 8 mg/l. Chemical cleaning takes place once per week. Consequently, the dosage and weight of the mixture are:

$$Antiscalant\ dosage = 8 \cdot \frac{0.0312}{1000} = 0.0003\ kg/week$$

$$Antiscalant\ weight = 0.0003 \cdot \frac{365}{7} \cdot 20 = 0.3\ kg$$

A stainless steel multi-stage pump, whose weight is 79 kg, will provide an average pressure gradient of 2800 kPa, equivalent to the consumption of 18.2 kWh/m^3. Considering a total of 181587 m^3 of leachate treated over a period of twenty years, the electricity demand for reverse osmosis operation is:

$$Electricity = 18.2 \cdot 181587 = 3304883\ kWh$$

Figure 32. Complete reverse osmosis system (Pure Aqua, Inc).

The permeate and the concentrate are stored in cylindrical fibreglass tanks. Permeate storage tanks are 6 m long and with a diameter of 2 m. Since the wall thickness is 2 cm, it is possible to compute the external and internal volumes. To calculate the weight of two tanks, the fibreglass density is multiplied for the volume of material.

$$External\ volume = \pi \cdot 1 \cdot 6 = 18.8\ m^3$$

$$Internal\ volume = \pi \cdot (1 - 0.02)^2 \cdot (6 - 2 \cdot 0.02) = 18.0\ m^3$$

$$Permeate\ tanks\ weight = (18.8 - 18.0) \cdot 1.5 \cdot 2 = 2.6\ ton$$

The same procedure is repeated for the three concentrate storage tanks, but this time are considered 3 m of length, 1 m of diameter and 1 cm of wall thickness.

$$External\ volume = \pi \cdot 0.5^2 \cdot 3 = 2.4\ m^3$$

$$Internal\ volume = \pi \cdot \left(\frac{1}{2} - 0.01\right)^2 \cdot (3 - 2 \cdot 0.01) = 2.2\ m^3$$

$$Permeate\ tanks\ weight = (2.4 - 2.2) \cdot 1.5 \cdot 3 = 0.5\ ton$$

Figure 33. Fibreglass concentrate storage tanks (Pure Aqua, Inc.).

To take into account the connections between the reverse osmosis system and the eight storage tanks of raw leachate, permeate and concentrate, PVC pipes of 5 cm in diameter, 3 mm in thickness and 10 m in length have been adopted.

$$External\ volume = \pi \cdot \left(\frac{0.05}{2}\right)^2 \cdot 10 = 0.020\ m^3$$

$$Internal\ volume = \pi \cdot \left(\frac{0.05}{2} - 0.003\right)^2 \cdot 10 = 0.015\ m^3$$

The density of PVC is equal to 1.3 t/m^3, therefore the weight of the pipes is:

$$Pipes\ weight = (0.020 - 0.015) \cdot 1.3 \cdot 8 = 0.05\ ton$$

3.2.1.2. Reverse osmosis performance

The reverse osmosis plant is able to guarantee the 98% of salts rejection. Knowing the feed concentrations, it is possible to estimate the permeate ones:

$$Permeate\ concentrations, C_p = C_f(1 - Rejection)$$

Whereas the concentrations of the concentrate are derived from the mass balance:

$$Concentrate\ concentrations, C_r = (Q_f C_f - Q_p C_p)/Q_r$$

Table 14 shows the values of the pollutants concentrations found in the feed, permeate and concentrate.

Table 14. Concentration values of contaminants found in leachate, permeate and concentrate (personal elaboration).

Contaminant	Influent leachate concentration (mg/l)	Permeate concentration (mg/l)	Concentrate concentration (mg/l)
BOD	16000	320	102963
COD	20000	400	128704
AMMONIA	1000	20	6435
CHLORIDE	2500	50	16088
SODIUM	700	14	4505
PHOSPHATE	14	0.28	90
TOLUENE	0.16	0.0032	1
BROMIUM	0.5	0.01	3
CADMIUM	0.012	0.0002	0.08
ARSENIC	0.03	0.0006	0.19
ZINC	4	0.08	26

3.2.2. Evaporation pond design

The concentrate from the reverse osmosis treatment is an aqueous solution rich in salts and organic molecules retained by the membranes. This waste material is deposited in a solar evaporation pond until it is completely dehydrated.

The pond was sized assuming an average evaporation rate equal to 4 L/m^2d (Perez-Gonzalez et al., 2011). The surface needed for the complete concentrate evaporation is obtained from the ratio between the concentrate flow rate and the evaporation rate:

$$Pond\ surface\ needed = \frac{6671}{4} = 1668\ m^2$$

$$Length = 56\ m$$

$$Width = 30\ m$$

Since the extension of the surface allows the complete evaporation of 6.67 m^3 of concentrate per day, the capacity of the pond coincides exactly with 6.67 m^3 and the required depth is given by the ratio between volume and surface; 20 cm of freebord for rainfall and waves are added as precaution:

$$Pond\ depth = \frac{6.67}{1668} + 0.20 = 0.204\ m$$

After solar exposure there is a 95% volume reduction of the concentrate, leaving in the pond a solid salts flow rate of 0.33 m^3/d to be removed and stored in HDPE tanks, waiting for the final disposal in a landfill for special or hazardous waste. Two tanks 1 m long and with a diameter of 0.5 m are needed for this purpose. Considering the thickness of the walls equal to 1 cm, the external and internal volume can be computed:

$$External\ volume = \pi \cdot \left(\frac{0.5}{2}\right)^2 \cdot 1 = 0.20\ m^3$$

$$Internal\ volume = \pi \cdot \left(\frac{0.5}{2} - 0.01\right)^2 \cdot (1 - 2 \cdot 0.01) = 0.18\ m^3$$

The density of HDPE is 0.95 t/m^3, therefore the weight of the two tanks is:

$$Tanks\ weight = (0.20 - 0.18) \cdot 0.95 \cdot 2 = 0.036\ ton$$

Figure 34. Tanks for solid residues from concentrate evaporation (Clack Corporation).

For the construction of the pond it is necessary to prepare the area by removing the surface vegetation and a layer of soil to realise the bottom liner.

A total volume of topsoil equal to 2179 m^2 of surface for a depth of 1 m is removed by a skid-steer loader. The specific weight of the natural soil is 1.75 t/m^3; the result is a weight of 3812 tons.

It is assumed that the vegetated area is 20% of the total surface, i.e. 436 m^2. Since each tree occupies a space of 10 m^2 and weighs approximately 12.5 kg, there are 44 trees to be removed for a final weight of 545 kg. A chainsaw is used to cut the tree, for a working time of 440 minutes. For bushes it is assumed that each of them occupies 5 m^2 and weighs 1.5 kg, therefore 131 kg of bushes are removed. The clods with the roots of the plants are removed by a hydraulic digger.

Table 15. Detailed quantities of topsoil removed (personal elaboration).

Surface of topsoil	2179	m^2
Soil depth	1	m
Volume of soil to remove	2179	m^3
Vegetated area	436	m^2
N. of trees to remove (10 m^2 each)	44	-
Chainsaw working time (10 min for each tree)	440	min
Weight of trees (12.5 kg each)	550	kg
N. of bushes to remove (5 m^2 each)	87	-
Weight of bushes (1.5 kg each)	131	kg
Trees clods volume (0.03272492 m^3 each)	1.4	m^3
Bushes clods volume (0.00409062 m^3 each)	0.4	m^3
Total clods volume to remove	1.8	m^3

After land clearance, the area is impermeabilized. For this purpose 1668 m^3 of clay, which consists of three layers of 30 cm of thickness each, are spread and compacted by a pad foot drum compactor. In addition, a further 164 m^3 of clay are destined for the construction of the perimeter embankments (Figure 35). In this project trapezoidal shaped embankments are built with a height of 0.5 m, an external angle of 45 degrees and an internal angle of 18 degrees.

$$Clay\ weight = 1832 \cdot 2.1 = 3847\ ton$$

Table 16. Pad foot drum compactor operational data (personal elaboration).

Distance to cover	1021	m
N. of layers (30 cm thick)	3	-
Total distance to cover	3063	m
Compactor velocity	3.5	km/h
Working hours	0.9	h
Compactor power	111.7	kW
Electricity demand	98	kWh

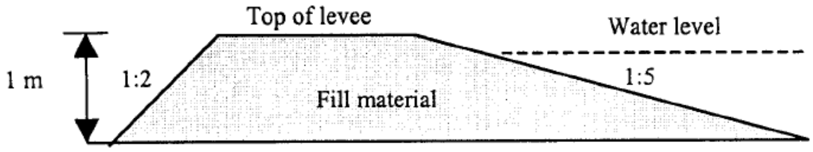


Figure 35. Generalised embankment dimensions (Ahmed et al., 2000).

Subsequently, to complete the bottom liner, 2091 m^2 of 2.5 mm thick HDPE sheet is laid manually and is welded to the clay base with the help of a welding machine. The sheet covers the entire surface of the pond and is anchored to the upper base of the embankments (Figure 36). Rolls of dimensions 70 m x 5.1 m are used. Considering the covered area and known the density of HDPE, it is possible to calculate the volume of sheet required and the corresponding weight:

$$HDPE\ volume = 2091 \cdot 0.0025 = 5\ m^3$$

$$HDPE\ weight = 5 \cdot 0.95 = 4.96\ ton$$

Table 17. HDPE welding machine operational data (personal elaboration).

Number of rolls	6	-
Welding distance	451	m
Welding machine velocity	1.5	m/min
Welding time	5	h
Welding machine power	700	W
Electricity demand	3.5	kWh

Figure 36. Evaporation pond (Source: unknown).

3.2.3. Phytoremediation design

3.2.3.1. Phytoremediation dimensioning

The phytoremediation basin was sized in accordance with the national ISPRA guidelines, according to which it is estimated that for each people equivalent, from 3 to 5 m^2 of vegetated surface are required in order to ensure a quality of treated leachate such as to satisfy the limit concentrations of discharge into surface waters. The concept of people equivalent refers to the average quantity of water consumed per day by an inhabitant, or to the quantity of potentially contaminating substances released daily into the water flow by the same (in terms of BOD_5, COD, ammonia, etc.).

In this project, the average amount of BOD_5 consumed per day by an inhabitant was considered a people equivalent, as is commonly done in the design of constructed wetlands for urban wastewater.

Since 1 people equivalent is equal to 60 g/d of BOD_5, it is possible to estimate the number of people equivalents corresponding to the BOD_5 flow rate of incoming leachate during the operating, aftercare, closure and conversion phases. Known the value of the total BOD concentration from the composition of the leachate, the biochemical oxygen demand in a 5-days incubation test (BOD_5) can be estimated with the following formula:

$$BOD_5(mg/l) = BOD_{tot}(1 - e^{-kt})$$

Where:

$$k = K_{ref}\ \theta^{(T-T_{ref})}$$

For polluted water and wastewater a typical value of K_{ref} (at reference temperature of 20°C) is 0.23 days. The value of θ is assumed equal to 1.135, as it is often quoted in the literature within the temperature range between 4°C and 20°C (Wastewater engineering, 4th Edition, Metcalf & Eddy).

After that it is easy to compute the BOD_5 flow rate:

$$BOD_5\ flow\ rate\ \left(\frac{g}{d}\right) = BOD_5\ \left(\frac{g}{m^3}\right) \cdot Leachate\ flow\ rate\ \left(\frac{m^3}{d}\right)$$

Multiplying the people equivalents for 5 m^2, instead, we obtain the area necessary for the treatment. Table 18 shows the plant potential in terms of people equivalents and corresponding area necessary for each phase of the landfill life. The surface adopted was obtained by rounding the value of the required surface in order to obtain a ratio between length and width equal to 2 (generally this ratio can vary from 0.5 to a maximum of 3). The total surface is further subdivided into a network of smaller rectangular sectors.

$$People\ equivalents, PE = \frac{Leachate\ BOD\ flow\ rate\ (g/d)}{60\ (g/d)}$$

$$Surface\ needed = PE \cdot 5\ (m^2)$$

Table 18. Design parameters for the phytoremediation plant (personal elaboration).

Phase	**Incoming BOD_5 flow rate (g/d)**	**People equivalents (-)**	**Surface required (m^2)**	**Surface adopted (m^2)**	**Number of sectors**	**Length (m) x Width (m)**
Filling	4042	67	337	450	1	30 x 15
Aftercare	146783	2446	12232	12800	4	80 x 40
Closure	14678	245	1223	1250	1	50 x 25
Conversion	27	0.5	2	8	1	4 x 2

It was decided to adopt a horizontal flow (HF) system. The treatment scheme provides for the presence of two HF systems placed in parallel, each of them composed of two HF modules placed in series. This arrangement facilitates maintenance operations and allows to obtain higher purification yields, as well as it is easier to resize the vegetated surface during the transitions of organic load that occurs during the life cycle of the landfill. The result is therefore a network of four adjacent basins (see Figure 37). In the aftercare phase, the surface required for optimal purification makes it necessary to use all four of them; in the filling and closure phases it is possible to use only one module; while in the conversion phase a small portion of a single basin is used.

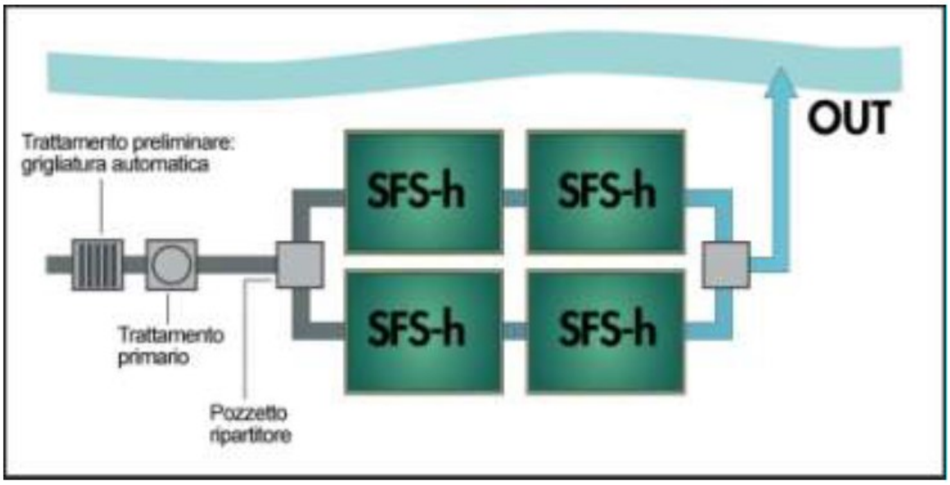


Figure 37. Scheme of an HF constructed wetland plant for urban wastewater (Manuali e Linee Guida 81/2012, ISPRA). In this leachate treatment project, the scheme remains the same as that shown in the figure, while preliminary and primary treatment are to be excluded.

The first step in building the plant is to remove 10240 m^3 of soil where the vegetated modules are installed. It is a total area of 12800 m^2 divided into four identical rectangular compartments with dimensions of 80 x 40 m^2 each and a depth of 0.8 m to take into account the downward development of the plant roots. The ground will be excavated to create a slope of the bottom of the bed of 3%. The soil is removed by a skid-steer loader; the weight of the soil is 17920 tons (1.75 t/m^3). As already done, it is considered that 20% of the total area to be removed is covered by plants. A chainsaw cuts the trees and the bushes, while a hydraulic digger removes the clods with the roots.

Table 19. Detailed quantities of topsoil removed (personal elaboration).

Surface of topsoil	12800	m^2
Soil depth	0.8	m
Volume of soil to remove	10240	m^3
Vegetated area	2096	m^2
N. of trees to remove (10 m^2 each)	210	-
Chainsaw working time (10 min for each tree)	35	h
Weight of trees (12.5 kg each)	2620	kg
N. of bushes to remove (5 m^2 each)	419	-
Weight of bushes (1.5 kg each)	629	kg
Trees clods volume (0.03272492 m^3 each)	6.9	m^3
Bushes clods volume (0.00409062 m^3 each)	1.7	m^3
Total clods volume to remove	8.6	m^3

Once the rectangular compartments have been excavated, the bottom of each of them is impermeabilized by laying 14048 m^2 of a 2.5 mm thick HDPE sheet with the help of a welding machine. The sheet covers the bottom and lateral surface of the ponds extending to the ground level, where it is anchored. Rolls of dimensions 70 m x 5.1 m are used. Considering the covered area and known the density of HDPE, it is possible to calculate the volume of sheet required and the corresponding weight:

$$HDPE\ volume = 14048 \cdot 0.0025 = 35\ m^3$$

$$HDPE\ weight = 35 \cdot 0.95 = 33.3\ ton$$

Table 20. HDPE welding machine operational data (personal elaboration).

Number of rolls	39	-
Welding distance	2932	m
Welding machine velocity	1.5	m/min
Welding time	32.6	h
Welding machine power	700	W
Electricity demand	22.8	kWh

The next step is to fill the ponds with the appropriate substrate. In horizontal submerged flow systems a hydraulic conductivity of at least 100 m/d must be ensured; the use of topsoil is therefore not recommended, while gravel of variable grain size, cleaned and washed, is commonly used. This project uses gravel with an average diameter between 4 and 16 mm; furthermore, crushed stone with a diameter of 80-120 mm is placed for a length of 1 m from the inlet and outlet section, to avoid clogging phenomena. A skid-steer loader fill the basins with 10240 m^3 of gravel.

Table 21. Amount of substrate required to fill the phytoremediation basins (personal elaboration).

Substrate	**Volume (m^3)**	**Density (t/m^3)**	**Weight (t)**
Gravel φ=4-16 mm	9984	1.56	15575
Crushed stones φ=80-120mm	256	1.42	363

Thanks to the slope of the bottom of each compartment, the leachate distribution is continuous and governed by gravity. The irrigation system is located on the surface and consists of perforated pipes with T-shaped distribution elements, as shown in Figure 38. The outlet system consists of a drainage pipe placed on the bottom, at the foot of the basin in the discharge section for its entire width, and connected with a pipe to a manhole. The manhole represents the connection between the two basins in series from which the irrigation piping branches off to the basin at the lower level. The pipes are in PVC, whose specific weight is 1.3 t/m^3, for a diameter of 10 cm, 3 mm of thickness and a total length, which includes all the pipes, equal to 410 m. The weight of the pipes to be placed manually is:

$$Pipes\ external\ volume = \pi \cdot \left(\frac{0.1}{2}\right)^2 \cdot 410 = 3.22\ m^3$$

$$Pipes\ internal\ volume = \pi \cdot \left(\frac{0.1}{2} - 0.003\right)^2 \cdot 410 = 2.84\ m^3$$

$$Irrigation\ pipes\ weight = (3.22 - 2.84) \cdot 1.3 = 0.49\ ton$$

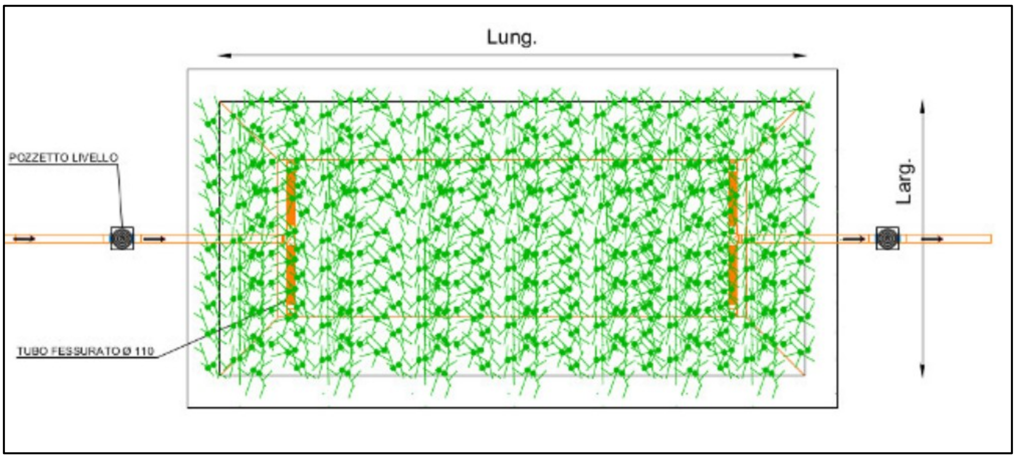


Figure 38. Planimetry of a rectangular phytodepuration basin. Detail of the configuration of the irrigation system. The level well at the outlet collects the leachate to be treated in the secondary basin connected in series at the lower level (Source: unknown).

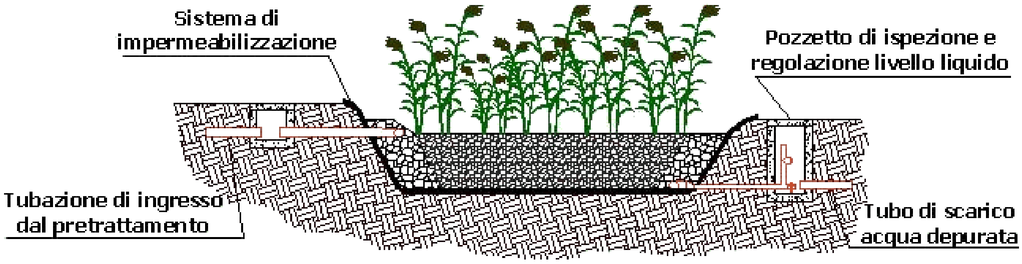


Figure 39. Longitudinal section of a phytoremediation basin. Detail of the impermeabilization and irrigation system; distribution of the substrate (gravel of coarse-medium size)(Source: unknown).

The plant chosen for the treatment is the "Phragmites australis", a herbaceous, perennial, rhizomatous species that can reach up to 4 m in height (Figure 40). It is part of the emerging rooted macrophytes, terrestrial plants that over time have adapted to life on soils that are partially or completely saturated with water. They are usually present in swamps and on the shores of lakes and are increasingly used in constructed wetlands systems due to numerous advantages, such as low maintenance required and increased speed of accretion.

Figure 40. Left: planting scheme of phragmites australis species. Right: aerial development of Phragmites australis species (Source: unknown).

The planting technique is represented by the manual transplanting in spring of already developed seedlings with a density of 4 seedlings/m^2 (Manuali e Linee Guida 81/2012, ISPRA). The plants take about 2 years to reach full development and for the root system to reach maximum depth. The development of the horizontal rhizomes allows the total coverage of the phytodepuration plant starting from the second vegetative year. In the operational phase, the area required for planting is 450 m^2, so the number of seedlings required is:

$$Number\ of\ plants\ (filling\ phase) = 450 \cdot 4 = 1800$$

Assuming that a 50 cm high seedling weighs 20 g, it is possible to calculate the total weight of the vegetation by multiplying the unit weight by the number of seedlings to be grown.

$$Weight\ of\ the\ plants\ (filling\ phase) = 1800 \cdot \frac{20}{1000} = 36\ kg$$

In the aftercare phase it is necessary to expand the cultivated area in the face of a high organic load due to the absence of the reverse osmosis pretreatment. All four basins are used to their full capacity for a total of 12800 m^2. The number and weight of seedlings to add to those previously planted are:

$$Number\ of\ plants\ (aftercare\ phase) = (12800 - 450) \cdot 4 = 49400$$

$$Weight\ of\ the\ plants\ (aftercare\ phase) = 49400 \cdot \frac{20}{1000} = 988\ kg$$

For the rest of the life of the landfill it is not necessary to plant other plants as only one basin out of four already vegetated is used for phytodepuration.

Guaranteed the correct functioning of the system with the appropriate controls (hydraulic and/or pollutant overload, clogging of pipes or the filling medium), maintenance is limited to cutting the aerial part of the plants every three years during the winter period and to removal of plant material from the bed. Therefore, for each life phase of the landfill it is possible to estimate the wasted phytomass produced by the mowing and the energy consumption of the mechanical mower, with a power of 10.3 kW, used for this purpose. Considering that the mower removes 3.5 m of plant in height, each plant provides 140 g of wasted phytomass and the total weight of wasted phytomass is:

$$Wasted\ phytomass\ (for\ each\ landfill\ stage), kg = Number\ of\ plants \cdot 0.140\ kg \cdot Mowing\ occurrences$$

Table 22. Mowing operation details for each phase of the landfill life (personal elaboration).

	Filling	**Aftercare**	**Closure**	**Conversion**
Vegetated surface (m^2)	**450**	**12800**	**1250**	**8**
Working width (m)	0.18	0.18	0.18	0.18
Distance to cover (m)	2500	71111	-	-
Working velocity (m/min)	133	133	-	-
Working time (min)	19	533	-	-
Wasted phytomass (kg)	1680	7111	-	58
Electricity demand (kWh)	3	92	-	-

As shown in Table 22, the closure phase, which includes only one year, does not foresee mowing as this occurs with a regularity of once every three years. While in the conversion phase, given the small service area, the mowing takes place manually and therefore no energy consumption is expected.

3.2.3.2. Phytoremediation performance

In general, the operating model of horizontal submerged flow systems approximates an adherent biomass plug-flow reactor in which pollutants are degraded according to kinetics of the first order (ISPRA, Manuals and Guidelines 81/2012).

Generally, in the literature, good yields are found in terms of pollutant removal. In particular, horizontal flow schemes represent an excellent compromise between plant simplicity and efficiency. It is estimated a reduction of organic contaminants (in terms of COD, BOD parameters) around 85-90%, and of nutrients (ammonia nitrogen and phosphorus) between 60-70% (ISPRA, Manuals and Guidelines 81/2012). Significant evapo-transpiration is also observed, promoting removal of up to 80% of the inlet irrigation volume (Garbo et al., 2016).

Tables 23 and 24 list the concentrations of contaminants entering and leaving the phytodepuration plant for each life phase of the landfill. The quality of the effluent was considered to comply with legal limits. In particular, a percentage of removal of individual contaminants was considered such as to obtain the concentrations at the outlet of the treatment equal to the limits for discharge into surface waters specified in Legislative Decree 152/2006 (Table 25). The pollutants concentrations that were already compliant on entry were not modified.

Table 23. Contaminants influent concentrations to the phytoremediation plant for each phase of the landfill life (personal elaboration).

Contaminant	FILLING Influent Concentrations (mg/l)	AFTERCARE Influent Concentrations (mg/l)	CLOSURE Influent Concentrations (mg/l)	CONVERSION Influent Concentrations (mg/l)
BOD	320	10000	1000	40
COD	400	15000	5000	400
AMMONIA	20	700	500	400
CHLORIDE	50	2000	1500	980
SODIUM	14	500	400	200
PHOSPHATE	0.28	14	14	14
TOLUENE	0.003	0.16	0.02	0.02
BROMIUM	0.01	0.3	0.2	0.16
CADMIUM	0.0002	0.01	0.008	0.006
ARSENIC	0.001	0.025	0.02	0.02
ZINC	0.1	2.2	1.5	0.7

Table 24. Contaminants effluent concentrations from the phytoremediation plant for each phase of the landfill life (personal elaboration).

Contaminant	FILLING Effluent Concentrations (mg/l)	AFTERCARE Effluent Concentrations (mg/l)	CLOSURE Effluent Concentrations (mg/l)	CONVERSION Effluent Concentrations (mg/l)
BOD	40	40	40	40
COD	160	160	160	160
AMMONIA	15	15	15	15
CHLORIDE	50	1200	1200	980
SODIUM	0.7	0.7	0.7	0.7
PHOSPHATE	0.28	10	10	10
TOLUENE	0.003	0.16	0.02	0.02
BROMIUM	0.01	0.3	0.2	0.16
CADMIUM	0.0002	0.01	0.008	0.006
ARSENIC	0.001	0.025	0.02	0.02
ZINC	0.1	0.5	0.5	0.5

Table 25. Concentration limits for discharge of leachate in water bodies (D.Lgs. 152/2006).

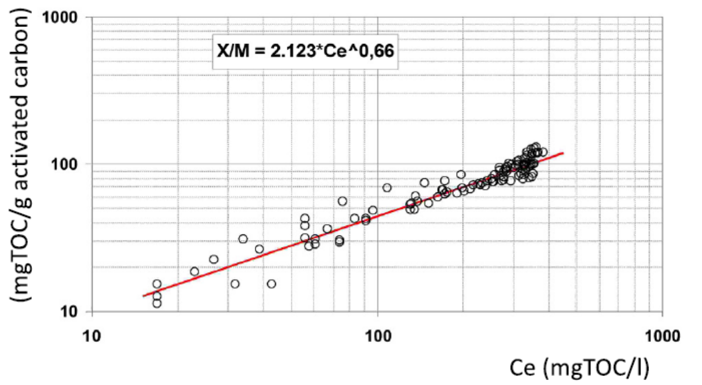
Contaminant	D.Lgs. 152/2006 Concentrations (mg/l)
BOD	40
COD	160
AMMONIA	15
CHLORIDE	1200
SODIUM	0.7
PHOSPHATE	10
TOLUENE	0.16
BROMIUM	0.5
CADMIUM	0.02
ARSENIC	0.5
ZINC	0.5

3.2.4. Adsorption with granular activated carbon (GAC) design

3.2.4.1. Adsorption with GAC dimensioning

To close the leachate management cycle, a final purification by adsorption with granular activated carbon (GAC) is forseen. The need to include an additional stage of treatment, before discharge into surface waters, is due to precautionary reasons. First of all, we want to ensure optimal performance even in the event of any malfunctions in the previous treatment steps (i.e. reverse osmosis and phytoremediation). Furthermore, today, landfills come into contact with waste containing countless emerging contaminants, such us drugs, PFAS and a wide spectrum of organics (i.e. aromatic solvents, PCBs, pesticides and herbicides, hydrocarbons) which are hardly detected by laboratory analyses as they are often not sought after. Activated carbon is able to neutralise all this remaining dissolved organic matter.

The plant was sized in such a way as to obtain a concentration of COD in the effluent of 10 mg/l, starting from 160 mg/l of incoming COD (at the end of the phytoremediation). From here it is possible to calculate the activated carbon load X/M (mg COD or TOC/g activated carbon) by means of the equation obtained from the Freundlich isotherm (Figure 41).



Freundlich isotherm:

$X/M = K * Ce^n$

X/M = load of organics per weight of activated carbon (e.g. mg COD or TOC / g activated carbon)

Ce = Equilibrium concentration in the solution = remaining concentration after adsorption (e.g. mg COD or TOC /l).

K and n are the characteristic parameters of the isotherm

Figure 41. Relationship between effluent values Ce [COD or TOC (mg/L)] and activated carbon load X/M (mg COD or TOC/g activated carbon), (Solid Waste Landfilling, Cossu & Stegmann, 2019).

Then, the GAC usage rate (g of carbon/litres of leachate) is given by the ratio between the removed concentration and the carbon load:

$$GAC\ usage\ rate\ \left(\frac{gCarbon}{l}\right) = \frac{Influent\ COD\ \left(\frac{mg}{l}\right) - Effluent\ COD\ \left(\frac{mg}{l}\right)}{\frac{X}{M}\left(\frac{mgCOD}{gCarbon}\right)}$$

Knowing the incoming leachate flow rate for each phase, it is easy to compute the carbon required per day:

$$Carbon\ required\ per\ day\ \left(\frac{gCarbon}{d}\right) = GAC\ usage\ rate\ \left(\frac{gCarbon}{l}\right) \cdot Leachate\ to\ treat\ \left(\frac{l}{d}\right)$$

Table 26 shows the results of the previous calculations for each phase of the landfill life.

Table 26. Amount of carbon required for adsorption (personal elaboration).

	Filling	**Aftercare**	**Closure**	**Conversion**
Influent COD (mg/l)	160	160	160	160
Effluent COD (mg/l)	10	10	10	10
X/M (mgCOD/gCarbon)	9.7	9.7	9.7	9.7
GAC usage rate (gCarbon/l)	15.4	15.4	15.4	15.4
Treated leachate (l/d)	7400	8600	8600	400
Carbon required per day (gCarbon/d)	114386	132935	132935	6183

The density of activated carbon is 0.44 t/m^3, so the volume of carbon used in each landfill phase can be estimated as:

$$Carbon\ volume\ (m^3) = \frac{Carbon\ required\ per\ day\ \left(\frac{tonCarbon}{d}\right) \cdot 365 \cdot Phase\ duration\ (years)}{Carbon\ density\ \left(\frac{ton}{m^3}\right)}$$

Hence the weight:

$$Carbon\ weight\ (ton) = Carbon\ volume\ (m^3) \cdot Density\ \left(\frac{ton}{m^3}\right)$$

It is estimated that the bed life is 365 days, and that the carbon at the end of its life undergoes 10 steam regeneration cycles before being discarded. Taking this into account, the weight and volume of carbon really needed in each life phase of the landfill is:

$$Effective\ carbon\ weight\ (ton) = Carbon\ required\ per\ day\ \left(\frac{tonCarbon}{d}\right) \cdot 365 \cdot \frac{Phase\ duration\ (years)}{10}$$

$$Effective\ carbon\ volume\ (m^3) = \frac{Effective\ carbon\ weight\ (ton)}{Density\ \left(\frac{ton}{m^3}\right)}$$

Table 27 lists the results of the above calculations for each life stage of the landfill.

Table 27. Amount of filter media used for each life phase of the landfill (personal elaboration).

	Filling	**Aftercare**	**Closure**	**Conversion**
GAC density (t/m^3)	0.44	0.44	0.44	0.44
GAC volume (m^3)	1898	4411	110	200
GAC weight (t)	835	1941	48.5	88
Bed life (days)	365	365	365	365
Regeneration cycles (-)	10	10	10	10
Phase duration (years)	20	40	1	39
Effective GAC weight (t)	83.5	194.1	4.8	8.8
Effective GAC volume (m^3)	190	441	11	20

The contact between activated carbon and leachate coming out of phytoremediation takes place in an open rectangular fibreglass tank downstream of the vegetated basin, with the dimensions specified in Table 28. The estimated contact time is about 30 minutes. The activated carbon, enclosed in fine mesh nets, is left to float inside the tank and easily removed manually at the time of replacement.

Table 28. Dimensions of the tank for leachate-GAC contact (personal elaboration).

Number of units	-	1
Material	-	Fibreglass
Density	ton/m^3	1.5
Height	m	1.5
Width	m	2
Length	m	4
Wells thickness	m	0.02
Internal volume	m^3	11.5
External volume	m^3	12
Material volume	m^3	0.51
Material weight	ton	0.77

At the end of the adsorption process, the purified leachate is stored in four cylindrical fibreglass tanks, the dimensions of which are shown in Table 29.

Table 29. Dimensions of storage tanks for clean water (personal elaboration).

Number of units	-	4
Material	-	Fibreglass
Density	ton/m^3	1.5
Diameter	m	1
Wells thickness	m	0.01
Internal volume	m^3	2.25
External volume	m^3	2.36
Material volume	m^3	0.11
Material weight	ton	0.65

The containers just described receive the purified leachate coming from the adsorption process through a connection pipe in PVC between the tanks, with an average length of 10 m and 3 mm of thickness.

Table 30. PVC pipe dimensions. The pipe connects the tank in which the adsorption process takes place and the container for the storage of purified leachate (personal elaboration).

Material	-	PVC
Density	ton/m^3	1.3
Length	m	10
Diameter	m	0.05
Wells thickness	m	0.003
Internal volume	m^3	0.0152
External volume	m^3	0.0196
Material volume	m^3	0.0044
Material weight	ton	0.0058

3.2.4.2. Adsorption with GAC performance

Through adsorption with activated carbon it is possible to reach concentrations of COD and BOD of 10 mg/l and 7 mg/l respectively in the effluent (Wastewater engineering, 4th Edition, 2003, Metcalf & Eddy). With regard to the removal efficiency relative to other substances, the literature cases vary considerably as a function of the sizing parameters, origin of the filter media and initial quality of the wastewater. Therefore, in the absence of a study with parameters similar to those of this project, most of the concentrations of the contaminants in question were kept unaltered (i.e. identical to the quality of the phytoremediation effluent), while we were limited to considering only a reduction of COD and BOD. Tables 31 and 32 show the concentrations of the contaminants of concern before and after adsorption respectively.

Table 31. Contaminants influent concentrations to the adsorption process for each phase of the landfill life (personal elaboration).

Contaminant	FILLING Influent Concentrations (mg/l)	AFTERCARE Influent Concentrations (mg/l)	CLOSURE Influent Concentrations (mg/l)	CONVERSION Influent Concentrations (mg/l)
BOD	40	40	40	40
COD	160	160	160	160
AMMONIA	15	15	15	15
CHLORIDE	50	1200	1200	980
SODIUM	0.7	1	0.7	0.7
PHOSPHATE	0.28	10	10	10
TOLUENE	0.003	0.2	0.02	0.02
BROMIUM	0.01	0.3	0.2	0.16
CADMIUM	0.0002	0.01	0.01	0.006
ARSENIC	0.001	0.03	0.02	0.02
ZINC	0.1	0.5	0.5	0.5

Table 32. Contaminants effluent concentrations from the adsorption process for each phase of the landfill life (personal elaboration).

Contaminant	FILLING Effluent Concentrations (mg/l)	AFTERCARE Effluent Concentrations (mg/l)	CLOSURE Effluent Concentrations (mg/l)	CONVERSION Effluent Concentrations (mg/l)
BOD	7	7	7	7
COD	10	10	10	10
AMMONIA	15	15	15	15
CHLORIDE	50	1200	1200	980
SODIUM	0.7	0.7	0.7	0.7
PHOSPHATE	0.28	10	10	10
TOLUENE	0.003	0.2	0.02	0.02
BROMIUM	0.01	0.3	0.2	0.16
CADMIUM	0.0002	0.01	0.01	0.006
ARSENIC	0.001	0.03	0.02	0.02
ZINC	0.1	0.5	0.5	0.5

3.3. Quality of the effluent from the leachate treatment plant

Once the leachate treatment cycle is completed, the purified wastewater is discharged into surface waters (i.e. rivers, seas). The purpose of the designed plants is to limit as much as possible the amount of potentially contaminating emissions to the environmental matrices. By guaranteeing the correct functioning of the leachate purification system, it is estimated that the emissions released into water are in compliance with the limits established by Legislative Decree 152/2006 and, in some cases, well below these critical concentrations.

Table 33 lists the quantity of leachate produced for each life phase of the landfill. Assuming the losses to be zero, the amount of leachate collected coincides with that produced, as explained in the previous paragraphs.

Table 33. Amount of leachate produced and collected in each phase of the landfill life (Sciarrone,2020/2021 modified).

	Filling	Aftercare	Closure	Conversion
Phase duration (years)	20	40	1	39
Leachate production (m^3)	181587	435114	10878	21212
Leakages (m^3)	0	0	0	0
Leachate collected (m^3)	181587	435114	10878	21212
Leachate collected (liters)	181586743	435113919	10877848	21211804

By multiplying the concentration released in the water bodies of each contaminant for the volume of leachate collected in each life phase of the landfill, it is possible to estimate the mass of each contaminant released into surface water. The mass values are reported in Table 34.

$$Residual\ mass\ of\ contaminant\ (kg) = \frac{Contaminant\ concentration\ \left(\frac{mg}{l}\right) \cdot Volume\ of\ collected\ leachate\ (l)}{10^6}$$

Table 34. Mass of contaminants discharged to surface water in each phase of the landfill (personal elaboration).

Contaminant	FILLING Mass of contaminant (kg)	AFTERCARE Mass of contaminant (kg)	CLOSURE Mass of contaminant (kg)	CONVERSION Mass of contaminant (kg)
BOD	1271	3046	76	148
COD	1816	4351	109	212
AMMONIA	2724	6527	163	318
CHLORIDE	9079	522137	13053	20788
SODIUM	127	305	8	15
PHOSPHATE	51	4351	109	212
TOLUENE	1	70	0.2	0.4
BROMIUM	2	131	2	3
CADMIUM	0.04	4	0.1	0.1
ARSENIC	0.2	11	0.2	0.4
ZINC	18	218	5	11

Knowing the initial quantity of contaminants in unit mass (Table 35), the amount of pollutants removed from the leachate treatment plants (Table 36) is calculated by difference:

$$
\begin{aligned}
&Mass\ of\ contaminant\ removed\ (kg) \\
&\qquad = Initial\ mass\ of\ contaminant\ (kg) \\
&\qquad - Residual\ mass\ of\ contaminant (kg)
\end{aligned}
$$

Table 35. Leachate initial mass of contaminants (personal elaboration).

Contaminant	FILLING Mass of contaminant (kg)	AFTERCARE Mass of contaminant (kg)	CLOSURE Mass of contaminant (kg)	CONVERSION Mass of contaminant (kg)
BOD	2905388	4351139	10878	848
COD	3631735	6526709	54389	8485
AMMONIA	181587	304580	5439	8485
CHLORIDE	453967	870228	16317	20788
SODIUM	127111	217557	4351	4242
PHOSPHATE	2542	6092	152	297
TOLUENE	29	70	0	0
BROMIUM	91	131	2	3
CADMIUM	2	4	0	0
ARSENIC	5	11	0	0
ZINC	726	957	16	15

Table 36. Mass of contaminants removed from the leachate through reverse osmosis, phytoremediation and adsorption (personal elaboration).

Contaminant	FILLING Mass of contaminant (kg)	AFTERCARE Mass of contaminant (kg)	CLOSURE Mass of contaminant (kg)	CONVERSION Mass of contaminant (kg)
BOD	2904117	4348093	10802	700
COD	3629919	6522358	54280	8273
AMMONIA	178863	298053	5276	8167
CHLORIDE	444888	348091	3263	0
SODIUM	126984	217252	4344	4228
PHOSPHATE	2491	1740	44	85
TOLUENE	29	0	0	0
BROMIUM	89	0	0	0
CADMIUM	2	0	0	0
ARSENIC	5	0	0	0
ZINC	708	740	11	4

The mass of contaminants removed is concentrated in the waste produced by each treatment unit: solid salts from evaporation of the reverse osmosis concentrate, phytomass eliminated by mowing and spent activated carbon.

4. Goal and scope definition and inventory analysis

This study was carried out in compliance with the LCA standards: ISO 14040 and ISO 14044 (ISO, 2020a).

The first paragraph of this chapter concerns the goal and scope definition; it presents the purpose and characteristics of the study.

Then follows the life cycle inventory, which describes the model used for the study and lists the data collected and entered in SimaPro in easy-to-consult tables.

4.1. Goal and scope definition

The first phase of the LCA is the goal and scope definition; it includes the intended use of the assessment and the characteristics of the study (ISO, 2020a).

This project aims to evaluate the potential environmental impacts of a leachate treatment plant used to purify the leachate produced over the entire life of a semi aerobic landfill; moreover, the role of leachate treatment in improving the environmental performance of the landfill will be highlighted. The impacts derive from the contribution of construction materials, management activities and waste by products that characterise the life of the treatment plant.

The system boundaries of the model include the entire life of the leachate treatment plant starting from its construction and including all operation and maintenance activities.

The functional unit of the study was defined as "landfilling of 1 ton of wet unsorted waste in a semi aerobic landfill with a mean depth of 10 metres for 100 years"; where the landfilling of unsorted waste was defined as the system function. This functional unit was chosen to underline the function of the treatment plant as a tool for managing the leachate produced specifically by a semi aerobic landfill. The characteristics of the plant are modelled in relation to the quality of the leachate produced in each phase of the landfill life; therefore the configuration and function of the treatment plant are strictly correlated to the waste disposed of in the landfill, since the composition of the leachate to be treated is the result of the temporal evolution of the degradation of the deposited waste.

To assess the overall impact of the plant, the contribution of each individual treatment unit was estimated. In this way it was possible to find out which of the plant construction or operation during the different life stages of the landfill was the most impactful.

In the literature, in fact, the LCAs applied to leachate treatment are few and their objective is to compare the environmental impacts deriving from different treatment technologies, rather than analysing the life stages of a single plant. Furthermore, the construction operations of the infrastructures are rarely considered, when they could often lead to a large contribution on environmental impacts.

It is also noted that in most of the case studies concerning landfills LCA it is common practice to estimate the impacts in terms of leachate and biogas production, without examining the equipment set up to treat these emissions (see, for example, the case studies published by Manfredi et al. and Sauve et al..); therefore this study represents an important source of information to cover the gaps in the literature.

The LCA was performed using the SimaPro software.

4.1.1. Data collection and quantification

Primary and secondary data were collected to model the system.

Primary data are the result of design and sizing of the treatment units, such as number of membrane modules, electricity needed, phytoremediation basins volume, amount of activated carbon required etc.

Among the secondary data, taken from literature, there are the specific weight of the various materials and the performance of the individual treatment units, for which it was not possible to trace laboratory samples.

Ecoinvent 3 database was the source of secondary data; in particular, not knowing the production specifications of the suppliers of single materials, market processes were selected to take into account the average global production's impact.

To solve multifunctional processes, the allocation at point of substitution "APOS, S" was chosen for this project; this assumption uses the expansion of a product system to avoid allocating (Ecoinvent).

4.1.2. Model definition

The model developed in SimaPro consists in the definition of the construction and operation processes of the leachate treatment plant within the different phases of the landfill life. The choice of considering the leachate treatment units within the life stages of the landfill has the dual function of allowing the assessment of the impacts relating

exclusively to the treatment plant, and secondarily to understand to what extent the leachate treatment modifies the environmental performance of the landfill.
The boundaries of the system include the five stages into which the life of the landfill has been divided.
A flow diagram (Figure 37) shows the processes belonging to each phase; the needed materials, as well as fuel and electricity, are connected to the respective processes, from which emissions and waste are highlighted as outgoing flows.
The construction phase includes the processes necessary to prepare the area to be converted to landfill and the processes of lining the bottom, building the drainage layer and the leachate treatment modules. For each process, the incoming flow of electricity and the fuel for transporting the materials required to complete the processes, and any outgoing waste flows (i.e. felled trees, bushes) were considered.
The second phase is that of filling, which consists in the creation of sectors capable of hosting the waste which is now entering the landfill. Other processes that take place in this phase are the realisation of the top covers (i.e. daily top cover and temporary top cover) and the ventilation system. In addition to electricity, the flows of materials connected to the various processes and the relative transport to the site of use are highlighted. Starting from the filling phase, the rainwater, indicated in the diagram as an incoming flow, infiltrates the landfill body and is responsible for the production of leachate. The leachate is subjected to a treatment process, which releases the purified fraction into surface waters. Biogas is also produced from the biodegradation processes and directly released to the atmosphere.
The part of the waste that does not leave the landfill in the form of leachate or biogas is indicated as "waste 1" and is an input of the following phase, in which it will undergo further degradation. This is a recurrent concept applied for the other phases too; in fact, waste biodegradation never stops to occur.
After the landfill is completely filled, the aftercare begins. Here the only input is the rainwater, which infiltrates the waste and produces leachate which, once treated (as occurs for biogas), comes out in the form of emission. Biogas, after being partially oxidised through the temporary top cover, is released as an emission into the atmosphere in the form of methane, carbon dioxide and traces of other compounds.

The biodegradation of waste continues until a good degree of stabilisation has been achieved.
We then come to the closure phase, in which the final top cover will be installed. Biogas and leachate are still produced, collected and treated.
The fifth and final phase consists in converting the landfill to a new destination. For this purpose, grass seeds are planted over the entire surface; the diagram highlights the materials (such as seeds, water, fertiliser etc.) necessary to complete the cultivation process. Electricity and fuel for transport are also highlighted. During this phase the amount of infiltrating rainwater is reduced due to the low permeability of the previously installed final top cover, therefore leachate is still produced but in lower quantity. The leachate treatment plant is still in operation and releases the purified product into surface waters. Also the biogas is still produced, albeit in minimal quantities too, and is partially oxidised by the final top cover.

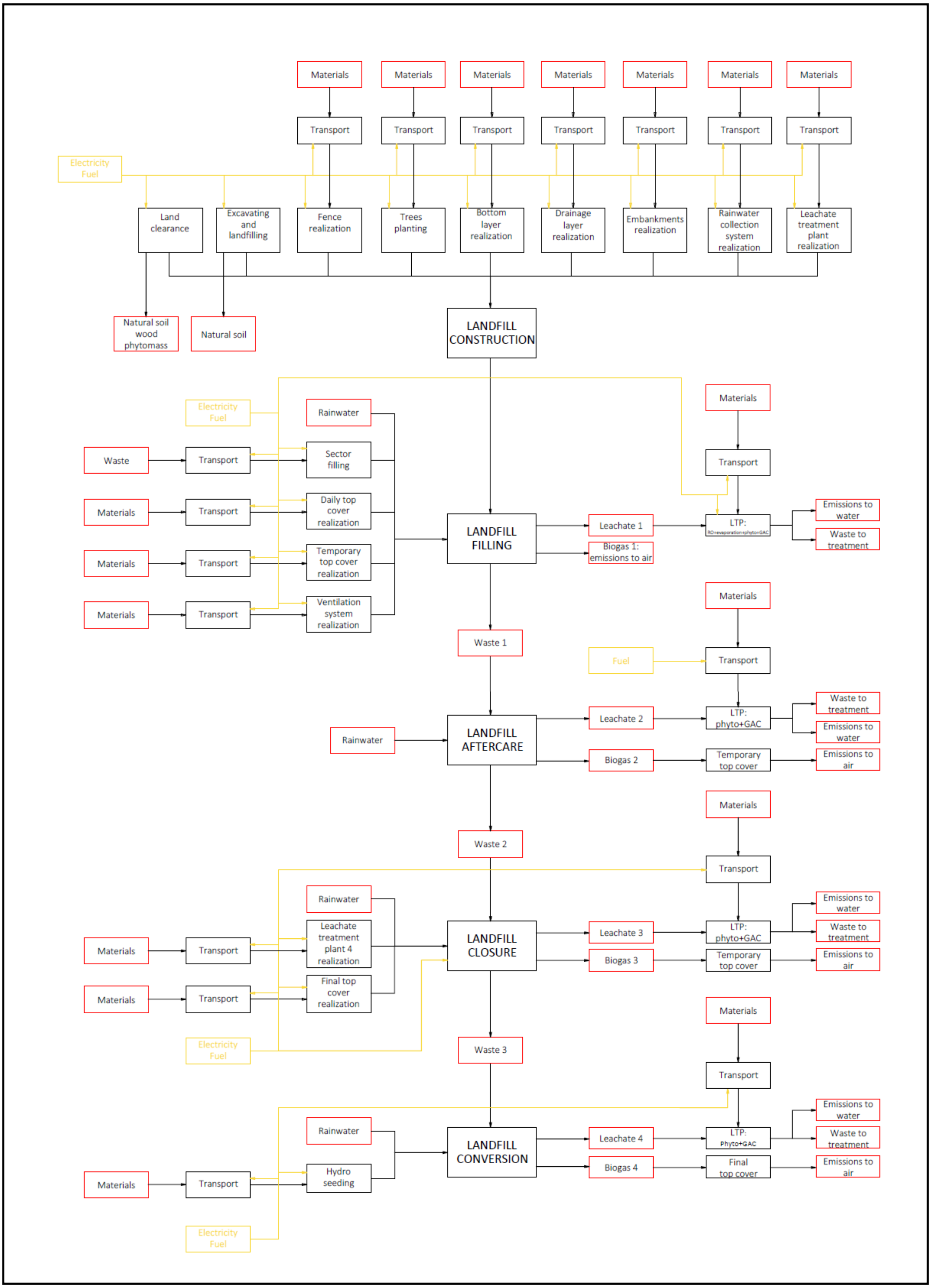


Figure 37. Landfill model graphical representation (personal elaboration).

4.2. Life Cycle Inventory

The life cycle inventory phase is an iterative procedure that involves the collection of data and the calculations to quantify the input/output of the system (ISO, 2020a).

After defining the model, the previously collected data can be entered into the SimaPro software to calculate the impacts.

The model consists of several processes, each one characterised by specific inputs and outputs.

The data are selected from Ecoinvent 3 database and are entered in the right entry on SimaPro according to their type. The data that can be entered are classified as:

- Known output to technosphere, product and coproduct;
- Known output to technosphere, avoided products;
- Known input from nature (resources);
- Known output to technosphere (materials/fuels);
- Known output to technosphere (electricity/heat);
- Emissions to water;
- Emissions to air;
- Final waste flow;
- Non-material emissions;
- Social issues;
- Economic issues;
- Known output to technosphere, waste and emission to treatment.

The entire life cycle of the leachate treatment plant is represented by the "life cycle assembly", as it consists of the five phases of plant construction and operation described above. Each phase in turn includes a series of processes with inputs and outputs, therefore each phase can also be considered as an assembly of as many processes.

The method selected to evaluate the impacts is ReCiPe 2016.

Once the input and output data has been entered, the results of the inventory analysis are displayed in the program window in the form of a process tree. In this representation it is easy to identify the flows that enter and exit the individual processes and which of these is the most critical.

The following paragraphs show the assemblies and subassemblies, which contain the different inputs and outputs, created for building the model of the treatment plant in SimaPro.

4.2.1. Construction phase

The landfill construction phase is the assembly of 9 processes; each of them includes materials and energy used.

Table 42 describes the construction assembly.

Table 42. SimaPro elaboration for CONSTRUCTION assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
CONSTRUCTION	1	p
Materials/fuels		
Land clearance	1	p
Excavation and filling	1	p
Fence realization	1	p
Tree planting	120	p
Bottom layer	1	p
Drainage layer	1	p
Embankment	1	p
Rainfall water collection	1	p
Leachate treatment plant construction	1	p

Here, only the construction and operation processes of the leachate treatment plant are reported. As regards the remaining processes, please refer to Sciarrone (2020/2021).

The infrastructures that make up the leachate treatment plant are produced and installed during the construction phase of the landfill. They include the reverse osmosis equipment, the construction of the evaporation pond, the preparation of the phytoremediation basin and the contact bed for the adsorption with activated carbon.

Table 43. SimaPro elaboration for LEACHATE TREATMENT PLANT CONSTRUCTION assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Leachate treatment plant construction	1	p
Materials/fuels		
Reverse osmosis equipment	1	p
Evaporation pond	1	p
Phytoremediation basin	1	p
Adsorption equipment	1	p

Table 44 shows the reverse osmosis equipment block.

The reverse osmosis equipment is composed of the spiral wound membranes contained in stainless steel vessels and a multi-stage pump in stainless steel. Fibreglass storage tanks for raw leachate, RO permeate and concentrate have also been included in this section. Liquids are conveyed to and from the reverse osmosis module via PVC pipes. The materials were transported by light vehicle for a standard distance of 100 km.

Table 44. SimaPro elaboration for REVERSE OSMOSIS EQUIPMENT assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Reverse osmosis equipment	1	p
Materials/fuels		
Fibreglass tank	7	ton
Seawater reverse osmosis module {GLO}| market for | APOS, S	26.3	m^2
Stainless steel vessels	0.023	ton
Reverse osmosis pump	72	kg
PVC pipes	0.046	ton
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	714.3	tkm

Since some units of the RO equipment were not present in the ecoinvent database, specific assemblies were created according to the average production methods of these items. Tables 45, 46, 47 and 48 report the assemblies relating to fibreglass tank, stainless steel vessels, RO pump and PVC pipes, respectively.

Table 45. SimaPro elaboration for 1 ton of FIBREGLASS TANK assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Fibreglass tank	1	ton
Materials/fuels		
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | APOS, S	991.1	kg
Steel, unalloyed {GLO}| market for | APOS, S	8.9	kg
Metal working, average for steel product manufacturing {GLO}| market for | APOS, S	8.9	kg

Table 46. SimaPro elaboration for 1 ton of STAINLESS STEEL VESSELS assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Stainless steel vessels	1	ton
Materials/fuels		
Steel, chromium steel 18/8 {GLO}| market for | APOS, S	1	ton
Metal working, average for chromium steel product manufacturing {GLO}| market for | APOS, S	1	ton

Table 47. SimaPro elaboration for 1 kg of MULTI-STAGE PUMP assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Reverse osmosis pump	1	kg
Materials/fuels		
Cast iron {GLO}| market for | APOS, S	0.73	kg
Steel, unalloyed {GLO}| market for | APOS, S	0.12	kg
Copper {GLO}| market for | APOS, S	0.044	kg
Synthetic rubber {GLO}| market for | APOS, S	0.041	kg
Aluminium, primary, liquid {GLO}| market for | APOS, S	0.033	kg
Steel, chromium steel 18/8 {GLO}| market for | APOS, S	0.015	kg
Bronze {GLO}| market for | APOS, S	0.002	kg
Petrol, two-stroke blend {GLO}| market for | APOS, S	0.012	kg
Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	0.95	kg

Table 48. SimaPro elaboration for 1 ton of PVC PIPES assembly (personal elaboration on the SimaPro software).

	quantity	unit
Products		
PVC pipes	1	ton
Materials/fuels		
Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S	1	ton
Extrusion, plastic pipes {GLO}| market for | APOS, S	1	ton

Table 49 shows the evaporation pond block.

The construction of the evaporation pond involves first cleaning the ground from trees and bushes using a chainsaw and an excavator to remove the roots and the top layer of soil.

A quantity of compacted clay is needed to make the bottom liner of the pond and to erect the perimeter embankments; the clay will be laid with a skid-steer loader and compacted by a pad foot drum compactor.

An HDPE geomembrane will be anchored by a diesel-electric welding machine to the clay layer to complete the lining of the bottom.

The HDPE tanks to contain the residual salts of the evaporation process were also included in the assembly shown in Table 49.

A light vehicle was selected to transport the light materials like HDPE rolls and tanks, while a heavy vehicle was used to transport the clay. The average transport distance considered is still 100 km.

From this process, specifically from the removal of tree species, the wood comes out as a waste stream to be treated.

Table 49. SimaPro elaboration for EVAPORATION POND assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Evaporation pond	1	p
Materials/fuels		
Power sawing, without catalytic converter {GLO}| market for | APOS, S	440	min
Excavation, hydraulic digger {GLO}| market for | APOS, S	1.8	m^3
Excavation, skid-steer loader {GLO}| market for | APOS, S	2178	m^3
Clay {RoW}| market for clay | APOS, S	3846.4	ton
Diesel, burned in building machine {GLO}| market for | APOS, S	98	kWh
Excavation, skid-steer loader {GLO}| market for | APOS, S	1832	m^3
HDPE geomembrane	5	ton
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	4	kWh
HDPE tank	0.036	ton
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, S	384642	tkm
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	500	tkm
Waste to treatment		
Waste wood, untreated {IT}| market for waste wood, untreated | APOS, S	0.68	ton

Since some units needed to the evaporation process were not present in the ecoinvent database, specific assemblies were created according to the average production methods of these items. Tables 50 and 51 report the assemblies relating to HDPE geomembrane and HDPE tank, respectively.

Table 50. SimaPro elaboration for 1 ton of HDPE GEOMEMBRANE assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
HDPE geomembrane	1	ton
Materials/fuels		
Polyethylene high density granulate (PE-HD), production mix, at plant RER	1	ton
Carbon black {GLO}| market for | APOS, S	0.02	ton
Electricity/heat		
Extrusion, plastic film {GLO}| market for | APOS, S	1	ton
Thermoforming, with calendering {GLO}| market for | APOS, S	1	ton

Table 51. SimaPro elaboration for 1 ton of HDPE TANK assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
HDPE tank	1	ton
Materials/fuels		
Polyethylene, high density, granulate {GLO}| market for | APOS, S	1	ton
Injection moulding {GLO}| market for | APOS, S	1	ton

Table 52 shows the phytoremediation basin block.

To prepare the phytoremediation basin, as a first step it is necessary to clean the ground from trees and bushes using a chainsaw; the roots are removed by a hydraulic digger. Once the holes have been dug by a skid-steer loader, an HDPE geomembrane is anchored over the entire surface by a welding machine to impermeabilize the area. Subsequently, a skid-steer loader fills the ponds with a gravel substrate. The PVC pipes for irrigation and drainage are distributed manually. The rhizomes of the plants are also planted manually at regular intervals. A light vehicle was selected to transport light materials like PVC pipes and plants rhizomes, while a heavy vehicle was chosen to transport the gravel and HDPE rolls.

The land clearance produces wooden phytomass as waste stream to be treated.

Table 52. SimaPro elaboration for PHYTOREMEDIATION BASIN assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Phytoremediation basin	1	p
Materials/fuels		
Power sawing, without catalytic converter {GLO}| market for | APOS, S	2096	min
Excavation, hydraulic digger {GLO}| market for | APOS, S	8.6	m^3
Excavation, skid-steer loader {GLO}| market for | APOS, S	10240	m^3
HDPE geomembrane	33.4	ton
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	23	kWh
Gravel, crushed {RoW}| market for gravel, crushed | APOS, S	15938.6	ton
Excavation, skid-steer loader {GLO}| market for | APOS, S	10240	m^3
PVC pipes	0.49	ton
Miscanthus rhizome, for planting {GLO}| market for | APOS, S	1800	p
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, S	1593856	tkm
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	3389	tkm
Waste to treatment		
Waste wood, untreated {IT}| market for waste wood, untreated | APOS, S	3.2	ton

Table 53 shows the adsorption equipment block.

The leachate exiting the phytoremediation basin comes into contact with the activated carbon in a fibreglass tank. PVC pipes convey the purified wastewater to a fibreglass storage tank for clean water, which has to be subsequently discharged to water bodies. The transport of materials is carried out by a light vehicle for 100 km.

Table 53. SimaPro elaboration for ADSORPTION EQUIPMENT assembly (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Adsorption equipment	1	p
Materials/fuels		
Fiberglass tank	0.77	ton
PVC pipes	0.006	ton
Fiberglass tank	0.65	ton
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	143	tkm

4.2.2. Operation phase

After completion of construction, the landfill goes into operation. Over a total period of 20 years, the landfill will be filled with 220000 tons of waste collected and transported from the municipalities served. Again, it is emphasised that, according to the zero burden assumption, the waste is not associated with any environmental impact.

The assembly block of the operation phase includes as inputs the entire amount of waste entering the landfill ("waste 1"), the vertical ventilation system, the daily and temporary cover, the rainwater and the leachate treatment plant materials necessary for its optimal operation.

During this phase the biodegradation of disposed waste begins, promoted by the infiltration of rain and the recirculation of air. The products of biodegradation are biogas, which is released directly into the atmosphere considering an MCF = 0.5, and the leachate.

It is assumed that the rainwater penetrating the waste is entirely converted into leachate, which is collected and subsequently purified by means of a specific treatment. The leachate components (and the rainwater) are released into the surface water bodies at the end of the treatment in the form of emissions to water.

Waste 2 is the product of the biodegradation to which entering waste 1 is subjected, and is equal to the difference between waste 1 and the quantities of biogas and leachate exiting the landfill. It should be emphasised that waste 2 is an intermediate product of the biodegradation process of waste that takes place in the landfill, therefore it continues to be associated with no additional impact, nor is it subject to transport as it remains confined to the landfill.

Table 54. SimaPro elaboration for FILLING block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
FILLING	1	p
waste 2	185882.2	ton
Resources		
Water, rain	181586.7	m^3
Materials/fuels		
temporary top cover	1	p
daily cover	6.6	ton
vertical ventilation	1	p
waste 1	220000	ton
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	660	tkm
Leachate treatment plant operation 1	1	p
Emissions to air		
Methane	3600075.7	kg
Carbon dioxide	23199044	kg
Benzene	152	kg
Methane, trichlorofluoro-, CFC-11	217	kg
Methane, dichlorodifluoro-, CFC-12	1083	kg
Methane, dichloro-, HCC-30	1083	kg
Methane, dichlorofluoro-, HCFC-21	260	kg
Methane, chlorodifluoro-, HCFC-22	282	kg
Hydrogen chloride	130	kg
Hydrogen fluoride	43	kg
Hydrogen sulfide	2	kg
Propylbenzene	1083	kg
Ethane, tetrachloro-	585	kg
Toluene	3466	kg
Ethane, 1,1,2-trichloro-	347	kg
Ethene, chloro-	455	kg
VOC, volatile organic compounds as C	4982	kg
Xylene	1300	kg
Emissions to water		
bod	1271	kg
cod	1816	kg
ammonia	2724	kg
chloride	9079	kg

sodium	127	kg
phospate	51	kg
toluene	0.5	kg
bromine	1.8	kg
cadmium	0.04	kg
arsenic	0.2	kg
zinc	18	kg
rainwater	181586743	kg

Here, only the blocks related to the operation of the leachate treatment plant ("Leachate treatment plant operation 1") are explained in detail; while as regards the remaining processes, please refer to Sciarrone (2020/2021).

In the operation phase, the collected leachate passes through a series of treatment units. A first stage of reverse osmosis produces a separation between concentrate, whose volume is reduced by solar evaporation, and permeate, which is further refined by phytoremediation. The last step, before discharging into surface water, is adsorption with activated carbon.

Table 55. SimaPro elaboration for LEACHATE TREATMENT PLANT OPERATION 1 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Leachate treatment plant operation 1	1	p
Materials/fuels		
Reverse osmosis 1	1	p
Evaporation pond 1	1	p
Phytoremediation 1	1	p
Adsorption 1	1	p

Table 56 reports the SimaPro elaboration for the reverse osmosis block. To ensure the optimal functioning of the membranes it is necessary to clean them with chemical agents regularly, therefore an antiscalant is used. RO membranes generally have a maximum life of 5 years, due to persistent corrosion; the reverse osmosis block includes the membranes supplied for replacement. The spent membranes are considered as waste to treatment.

Electricity is used to apply the required pressure gradient.

Light vehicles are responsible for transporting the material to the landfill site (100 km distance).

Table 56. SimaPro elaboration for REVERSE OSMOSIS 1 block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Reverse osmosis 1	1	p
Materials/fuels		
Seawater reverse osmosis module {GLO}| market for | APOS, S	78.9	m^2
Hydrochloric acid, without water, in 30% solution state {RER}| market for | APOS, S	0.0003	ton
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	4.2	tkm
Electricity/heat		
Electricity, medium voltage {IT}| market for | APOS, S	3304883	kWh
Waste to treatment		
Waste, unspecified (wfr)/RER	55.7	kg

Table 57 reports the SimaPro elaboration for the evaporation pond block.
The laying in the pond of the concentrate takes place by means of a skid-steer loader. The collection of residual salts after evaporation occurs in the same way. The volume of residual solid salts is considered as waste to be treated.

Table 57. SimaPro elaboration for EVAPORATION POND 1 block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Evaporation pond 1	1	p
Materials/fuels		
Excavation, skid-steer loader {GLO}| market for | APOS, S	48691	m^3
Excavation, skid-steer loader {GLO}| market for | APOS, S	2435	m^3
Waste to treatment		
Salts	5283	ton

Table 58 reports the SimaPro elaboration for the phytoremediation block.

Over time, plants irrigated with leachate increase their mass until they reach up to 4 m. Every three years the plants are mechanically mowed; the residual phytomass is entered as biowaste to be treated.

Table 58. SimaPro elaboration for PHYTOREMEDIATION 1 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Phytoremediation 1	1	p
Materials/fuels		
Mowing, by motor mower {GLO}| market for | APOS, S	3000	m^2
Waste to treatment		
Biowaste {RoW}| market for | APOS, S	1.68	ton

Table 59 reports the SimaPro elaboration for the adsorption block.

The granular activated carbon used for the adsorption reaches complete saturation within a year, therefore the quantity of GAC for replacement is considered in the block, also taking into account the regeneration cycles. Spent carbon is treated as a waste stream.

Table 59. SimaPro elaboration for ADSORPTION 1 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Adsorption 1	1	p
Materials/fuels		
Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, S	83.5	ton
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, S	8350	tkm
Waste to treatment		
Spent GAC	83.5	ton

4.2.3. Aftercare phase

The aftercare starts after the landfill is completely filled and the temporary top cover is installed.

Waste 2 is now the input subjected to further biodegradation, which will produce waste 3, biogas 3 and leachate 3. Biogas and leachate are considered as emissions to air and water respectively.

As in the previous phase, the rainwater entering the landfill exits as leachate, which is sent to treatment prior to discharge. The biogas emissions are still referred to a MCF of 0.5.

Table 60. SimaPro elaboration for AFTERCARE block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
AFTERCARE	1	p
waste 3	154849.7	ton
Resources		
Water, rain	435113.9	m^3
Materials/fuels		
waste 2	185882.2	ton
Leachate treatment plant operation 2	1	p
Emissions to air		
Methane	2213886	kg
Carbon dioxide	16530880	kg
Benzene	104	kg
Methane, trichlorofluoro-, CFC-11	148	kg
Methane, dichlorodifluoro-, CFC-12	740	kg
Methane, dichloro-, HCC-30	740	kg
Methane, dichlorofluoro-, HCFC-21	178	kg
Methane, chlorodifluoro-, HCFC-22	192	kg
Hydrogen chloride	89	kg
Hydrogen fluoride	30	kg
Hydrogen sulfide	1	kg
Propylbenzene	740	kg
Ethane, tetrachloro-	400	kg
Toluene	2368	kg
Ethane, 1,1,2-trichloro-	237	kg
Ethene, chloro-	74	kg
VOC, volatile organic compounds as C	3404	kg
Xylene	888	kg
Emissions to water		
bod	3046	kg
cod	4351	kg
ammonia	6527	kg
chloride	522137	kg

sodium	305	kg
phospate	4351	kg
toluene	69.6	kg
bromine	130.5	kg
cadmium	4.35	kg
arsenic	10.9	kg
zinc	218	kg
rainwater	435113919	kg

Here, only the blocks related to the operation of the leachate treatment plant ("Leachate treatment plant operation 2") are explained in detail; while as regards the remaining processes, please refer to Sciarrone (2020/2021).

In the operation phase, the collected leachate is treated by phytoremediation and adsorption with activated carbon.

Table 61. SimaPro elaboration for LEACHATE TREATMENT PLANT OPERATION 2 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Leachate treatment plant operation 2	1	p
Materials/fuels		
Phytoremediation 2	1	p
Adsorption 2	1	p

Table 62 reports the SimaPro elaboration for the phytoremediation block.

During the aftercare the quality of the incoming leachate requires the expansion of the vegetated surface. So the manual planting of a further quantity of rhizomes takes place. The transport of the necessary rhizomes is accomplished with a light vehicle. As in the previous phase, mowing takes place every 3 years with a mechanical mower and the residual phytomass is considered biowaste to be treated.

Table 62. SimaPro elaboration for PHYTOREMEDIATION 2 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Phytoremediation 2	1	p
Materials/fuels		
Miscanthus rhizome, for planting {GLO}| market for | APOS, S	49400	p
Mowing, by motor mower {GLO}| market for | APOS, S	170667	m^2
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | APOS, S	99	tkm
Waste to treatment		
Biowaste {RoW}| market for | APOS, S	95.6	ton

Table 63 reports the SimaPro elaboration for the adsorption block.

The same considerations made for the filling phase apply to the aftercare phase. In the block appears the GAC used as filter media for the adsorption, and its transport by light vehicle. The spent carbon is treated as waste stream.

Table 63. SimaPro elaboration for ADSORPTION 2 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Adsorption 2	1	p
Materials/fuels		
Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, S	194	ton
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, S	19409	tkm
Waste to treatment		
Spent GAC	194	ton

4.2.4. Closure phase

The landfill closure consists of the installation of the final top cover over the entire surface of the landfill.

Waste 3 is now the input subjected to further biodegradation, which will produce waste 4, biogas 4 and leachate 4. Biogas and leachate are considered as emissions to air and water respectively.
As in the previous phases, the rainwater entering the landfill exits as leachate, which is sent to treatment prior to discharge. The biogas emissions are still referred to a MCF of 0.5.

Table 64. SimaPro elaboration for CLOSURE block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
CLOSURE	1	p
waste 4	154650.9	ton
Resources		
Water, rain	10878	m^3
Materials/fuels		
final top cover	1	p
waste 3	154849.7	ton
Leachate treatment plant operation 3	1	p
Emissions to air		
Methane	12653	kg
Carbon dioxide	94477	kg
Benzene	0.59	kg
Methane, trichlorofluoro-, CFC-11	0.85	kg
Methane, dichlorodifluoro-, CFC-12	4.23	kg
Methane, dichloro-, HCC-30	4.23	kg
Methane, dichlorofluoro-, HCFC-21	1.02	kg
Methane, chlorodifluoro-, HCFC-22	1.10	kg
Hydrogen chloride	0.51	kg
Hydrogen fluoride	0.17	kg
Hydrogen sulfide	0.01	kg
Propylbenzene	4.23	kg
Ethane, tetrachloro-	2.28	kg
Toluene	13.53	kg
Ethane, 1,1,2-trichloro-	1.35	kg
Ethene, chloro-	0.00	kg
VOC, volatile organic compounds as C	19.46	kg
Xylene	5.08	kg
Emissions to water		
bod	76	kg
cod	109	kg
ammonia	163	kg

chloride	13053	kg
sodium	8	kg
phospate	109	kg
toluene	0.2	kg
bromine	2.2	kg
cadmium	0.09	kg
arsenic	0.2	kg
zinc	5	kg
rainwater	10877848	kg

Here, only the blocks related to the operation of the leachate treatment plant ("Leachate treatment plant operation 3") are explained in detail; while as regards the remaining processes, please refer to Sciarrone (2020/2021).

In the closure phase, the collected leachate is treated by phytoremediation and adsorption with activated carbon.

Table 65. SimaPro elaboration for LEACHATE TREATMENT PLANT OPERATION 3 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Leachate treatment plant operation 3	1	p
Materials/fuels		
Phytoremediation 3	1	p
Adsorption 3	1	p

During the closure phase, which lasts only one year, no mowing of the plants used for phytodepuration is foreseen. Therefore the block related to phytoremediation will have null inputs and outputs.

As for adsorption, the inputs that appear are always the GAC used as filter medium and its transport. While spent carbon is seen as a waste stream.

Table 66 reports the SimaPro elaboration for the adsorption block.

Table 66. SimaPro elaboration for ADSORPTION 3 block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Adsorption 3	1	p
Materials/fuels		
Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, S	4.85	ton
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, S	485	tkm
Waste to treatment		
Spent GAC	4.85	ton

4.2.5. Conversion phase

After the final top cover is installed, the landfill is converted to a new destination. The purpose is to create a lawn on the landfill surface using a hydroseeding technique.

Waste 4 is now the input subjected to further biodegradation, which will produce waste 5, biogas 5 and leachate 5. Due to the low permeability of the top cover, the leachate and biogas are produced in reduced quantities compared to the other phases, and also have a better quality given by the high degree of waste stabilisation achieved over 60 years. Biogas and leachate are considered as emissions to air and water respectively.

As in the previous phases, the rainwater entering the landfill exits as leachate, which is sent to treatment prior to discharge. The biogas emissions are still referred to a MCF of 0.5.

Table 67. SimaPro elaboration for CONVERSION block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
CONVERSION	1	p
waste 5	152749.2	ton
Resources		
Water, rain	21212	m^3
Materials/fuels		
waste 4	154650.9	ton
lawn	1	p
Leachate treatment plant operation 4	1	p
Emissions to air		
Methane	219386	kg
Carbon dioxide	1638135	kg
Benzene	10	kg
Methane, trichlorofluoro-, CFC-11	15	kg
Methane, dichlorodifluoro-, CFC-12	73	kg
Methane, dichloro-, HCC-30	73	kg
Methane, dichlorofluoro-, HCFC-21	18	kg
Methane, chlorodifluoro-, HCFC-22	19	kg
Hydrogen chloride	9	kg
Hydrogen fluoride	3	kg
Hydrogen sulfide	0.147	kg
Propylbenzene	73	kg
Ethane, tetrachloro-	40	kg
Toluene	235	kg
Ethane, 1,1,2-trichloro-	23	kg
Ethene, chloro-	0	kg
VOC, volatile organic compounds as C	337	kg
Xylene	88	kg
Emissions to water		
bod	148	kg
cod	212	kg
ammonia	318	kg
chloride	20788	kg
sodium	15	kg
phospate	212	kg
toluene	0.4	kg
bromine	3.4	kg
cadmium	0.1	kg
arsenic	0.4	kg
zinc	11	kg
rainwater	21211804	kg

Here, only the blocks related to the operation of the leachate treatment plant ("Leachate treatment plant operation 4") are explained in detail; while as regards the remaining processes, please refer to Sciarrone (2020/2021).
In the conversion phase, the collected leachate is treated by phytoremediation and adsorption with activated carbon.

Table 68. SimaPro elaboration for LEACHATE TREATMENT PLANT OPERATION 4 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Leachate treatment plant operation 4	1	p
Materials/fuels		
Phytoremediation 4	1	p
Adsorption 4	1	p

Table 69 reports the SimaPro elaboration for the phytoremediation block.
In the conversion phase, the surface used for phytoremediation purposes is not very extensive, thanks to the good quality of the leachate leaving the landfill. Therefore the mowing operations are carried out manually without the use of a mechanical mower. The residual phytomass is always considered as biowaste to be treated.

Table 69. SimaPro elaboration for PHYTOREMEDIATION 4 block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
Phytoremediation 4	1	p
Waste to treatment		
Biowaste {RoW}| market for | APOS, S	0.058	ton

Table 70 reports the SimaPro elaboration for the adsorption block.
The inputs include, as in the previous phases, the GAC used as filter medium and its transport. While spent carbon is considered as a waste stream to be treated.

Table 70. SimaPro elaboration for ADSORPTION 4 block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Adsorption 4	1	p
Materials/fuels		
Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, S	8.8	ton
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, S	880	tkm
Waste to treatment		
Spent GAC	8.8	ton

4.2.6. Leachate treatment plant assembly

To evaluate the total potential environmental impact of the leachate treatment plant, the impacts of the individual phases must be added together. To do this, a plant "life cycle" assembly has been created. "Leachate treatment plant operation 1, 2, 3 and 4" refer respectively to the treatment plant operation during landfill filling, aftercare, closure and conversion phases.

Table 71. SimaPro elaboration for leachate treatment plant assembly block (personal elaboration on the SimaPro software).

	quantity	unit
Products		
Leachate treatment plant	1	p
Processes		
Leachate treatment plant construction	1	p
Leachate treatment plant operation 1	1	p
Leachate treatment plant operation 2	1	p
Leachate treatment plant operation 3	1	p
Leachate treatment plant operation 4	1	p

Similarly, to measure the impact of leachate treatment on the entire life cycle of the landfill, it is possible to build a "landfill assembly", which includes all the life stages of the landfill complete with a treatment plant for the leachate. This is useful to evaluate the overall performance of the landfill and, in particular, to highlight how a better quality of the purified leachate is capable of reducing the impacts associated to a landfill.

Table 72. SimaPro elaboration for landfill assembly block (personal elaboration on the SimaPro software).

	quantity	**unit**
Products		
LANDFILL	1	p
Processes		
FILLING	1	p
CONSTRUCTION	1	p
AFTERCARE	1	p
CLOSURE	1	p
CONVERSION	1	p

5. Life cycle impact assessment

In this phase of the LCA, the results of the life cycle inventory are processed to assess the environmental impacts with respect to specific impact categories, each characterised by an indicator.

The LCIA must be performed in compliance with the goal and scope definition; since LCA is an iterative process, the scope and the goal of the study may be modified in case the objective can't be achieved.

According to the standard ISO 14044:2020, the impact assessment phase includes mandatory and optional steps. The mandatory ones are:

- Selection of impact categories, category indicators and characterization models;
- Classification: assignment of LCI results to the selected impact categories;
- Characterization: calculation of category indicator results (ISO, 2020b).

While the optional steps, whose performance depends on the context of the study, are:

- Normalisation, to calculate the magnitude of the category indicator respect to a reference information;
- Grouping, to sort and rank the impact categories;
- Weighting, to convert and aggregate indicators results;
- Data quality analysis, to understand the reliability of the collection of indicator results (ISO, 2020b).

The selection of impact categories, category indicators and characterization models have to be justified and consistent with the goal of the study, and shall reflect a comprehensive set of environmental issues related to the product system being studied (ISO, 2020b).

In the classification stage, LCI results may be assigned to one or more impact categories.

The characterization multiplies the LCI results for characterization factors to obtain common units; then the results with homogeneous units are added up to compute the impact category indicator result.

Even if optional, the normalisation is almost always applied to the characterization results for a better comprehensibility of the magnitude of the impacts in relation to a reference information. The characterization values are normalised dividing them by a reference value.

5.1. Impact assessment method

The impact assessment was performed using the ReCiPe 2016 method. This is a characterization model that transforms emissions and resource extraction into a limited number of environmental impact scores, which express the relative severity into an also limited number of indicators (Prè Sustainability, 2016).

Through ReCiPe 2016, the indicators can be determined at two levels. The impact assessment results are first expressed at midpoint level estimating 18 impact indicators with their own units.

Each impact category is defined by a different indicator and a reference substance represents the total impact of the category. Dimensionless characterization factors (CF) were introduced to express the magnitude of the impact of different substances with respect to the reference substance.

The endpoint level considers the 18 midpoint categories contributing, through various damage pathways, to 3 endpoint categories or "areas of protection".

In this case endpoint characterization factors are obtained from the ones used at midpoint level considering a constant midpoint to endpoint factor (National Institute for Public health and the Environment, 2016).

Since endpoint assessment may lead to subjective results, it is preferable to report the results at midpoint level.

Impact category	Indicator	Unit	CF_m	Abbr.	Unit
climate change	Infra-red radiative forcing increase	W×yr/m^2	global warming potential	GWP	kg CO_2 to air
ozone depletion	stratospheric ozone decrease	ppt×yr	ozone depletion potential	ODP	kg CFC-11 to air
ionizing radiation	absorbed dose increase	man×Sv	ionizing radiation potential	IRP	kBq Co-60 to air
fine particulate matter formation	PM2.5 population intake increase	kg	particulate matter formation potential	PMFP	kg PM2.5 to air
Photochemical oxidant formation: ecosystem quality	tropospheric ozone increase (AOT40)	ppb.yr	Photo-chemical oxidant formation potential: ecosystems	EOFP	kg NOx to air
Photochemical oxidant formation: human health	tropospheric ozone population intake increase (M6M)	kg	Photo-chemical oxidant formation potential: humans	HOFP	kg NOx to air
terrestrial acidification	proton increase in natural soils	yr×m^2×mol/l	terrestrial acidification potential	TAP	kg SO_2 to air
freshwater eutrophication	phosphorus increase in fresh water	yr×m^3	freshwater eutrophication potential	FEP	kg P to fresh water
human toxicity: cancer	risk increase of cancer disease incidence	-	human toxicity potential	HTPc	kg 1,4-DCB to urban air
human toxicity: non-cancer	risk increase of non-cancer disease incidence	-	human toxicity potential	HTPnc	kg 1,4-DCB to urban air
terrestrial ecotoxicity	hazard-weighted increase in natural soils	yr×m^2	terrestrial ecotoxicity potential	TETP	kg 1,4-DCB to industrial soil
freshwater ecotoxicity	hazard-weighted increase in fresh waters	yr×m^3	freshwater ecotoxicity potential	FETP	kg 1,4-DCB to fresh water
marine ecotoxicity	hazard-weighted increase in marine water	yr×m^3	marine ecotoxicity potential	METP	kg 1,4-DCB to marine water
land use	occupation and time-integrated transformation	yr×m^2	agricultural land occupation potential	LOP	m^2×yr annual crop land
water use	increase of water consumed	m^3	water consumption potential	WCP	m^3 water consumed
mineral resource scarcity	ore grade decrease	kg	surplus ore potential	SOP	kg Cu
fossil resource scarcity	upper heating value	MJ	fossil fuel potential	FFP	kg oil

Figure 38. Overview of the midpoint categories and related impact indicators (National Institute for the Public Health and the Environment, 2016).

Area of protection	Endpoint	Abbr.	Name	Unit
human health	damage to human health	HH	disability-adjusted loss of life years	year
natural environment	damage to ecosystem quality	ED	time-integrated species loss	species ×yr
resource scarcity	damage to resource availability	RA	surplus cost	Dollar

Figure 39. Overview of the endpoint categories and related impact indicators (National Institute for the Public Health and the Environment, 2016).

5.2. Impact assessment results

The following paragraphs report the impact assessment results (from characterization and normalisation steps) and the LCI results.

First of all, each treatment unit is studied individually to understand which of the processes involved impact the most. Then, the result is analysed by examining the contribution of the leachate treatment plant to each phase of the landfill life.

The life cycle inventory results are graphically represented by a tree diagram, which is the result of the input-output analysis, where only mass and energy contributions of the singular processes are shown without any reference to the extent of the resulting impacts. The different thickness of the arrows connecting the blocks of the diagram represent the quantity of materials entering and exiting the system boundaries.

The ReCiPe 2016 midpoint method was applied to obtain the characterization and normalisation results, which are reported as a histogram representing a different impact category per each column.

Focusing on the details of the characterization of the leachate treatment plant, it is possible to identify the percentage contribution of each process with respect to the different impact categories. Normalization, instead, makes it possible to identify the impact categories of highest concern and the resulting hotspots in the system.

To complete the analysis, the endpoint results are also discussed.

5.2.1. Life cycle inventory results for the entire leachate treatment plant life

Each of the five phases of the leachate treatment plant contributes in a different way to the entire life cycle, based on the environmental load deriving from the materials and processes that define it. Figure 40 represents the treatment phases contribution and highlights that treatment plant operation during filling and aftercare phases, as well as plant construction are the processes that contribute the most to the entire plant life.

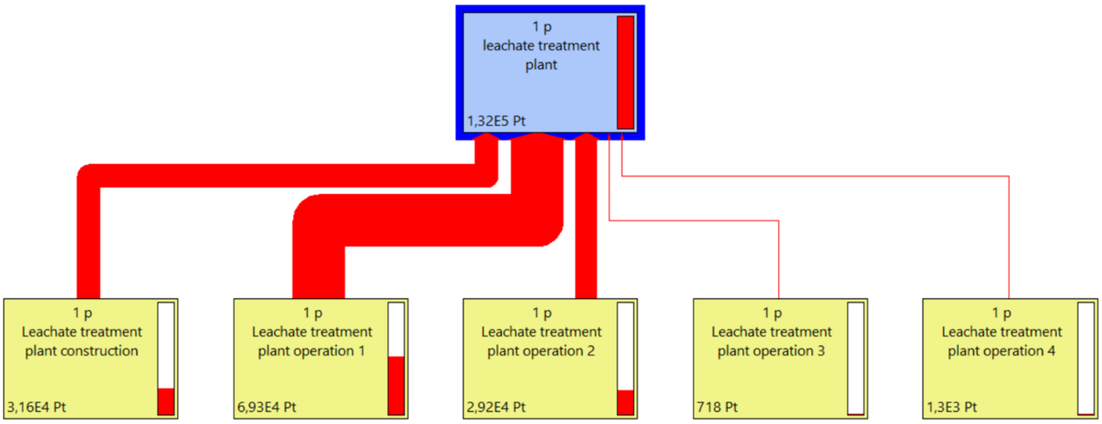


Figure 40. Leachate treatment plant life input/output analysis (personal elaboration from SimaPro software).

5.2.2. Characterization and normalisation of the results for the entire leachate treatment plant life

Table 73 reports the results of the characterization phase of the LCA; in particular, it shows the value of the category indicator for each impact category, both as a result of the entire life cycle of the treatment plant and for each phase.

Table 73. Characterization phase results obtained with ReCiPe 2016 method (personal elaboration from SimaPro).

Impact category	unit	total	plant construction	operation during filling	operation during aftercare	operation during closure	operation during conversion
Global warming	kg CO_2 eq	3239828.5	703504.2	1811321.3	678399.4	16553.7	30050.0
Stratospheric ozone depletion	kg CFC 11 eq	2.8	0.6	1.9	0.2	0.0	0.0
Ionising radiation	kBq Co-60 eq	251853.1	45725.6	180176.8	24234.5	609.8	1106.5
Ozone formation, human health	kg NOx eq	8138.7	2771.5	3722.1	1537.0	38.4	69.7

Fine particulate matter formation	kg PM2.5 eq	4832.8	1162.0	2358.2	1226.7	30.5	55.4
Ozone formation, terrestrial ecotoxicity	kg NOx eq	8291.4	2852.3	3777.8	1552.2	38.8	70.3
Terrestrial acidification	kg SO2 eq	12727.8	2558.0	6720.2	3225.8	79.5	144.2
Freshwater eutrophication	kg P eq	1012.9	172.3	543.2	278.1	6.8	12.4
Marine eutrophication	kg N eq	129.2	31.4	50.0	46.5	0.4	0.8
Terrestrial ecotoxicity	kg 1,4-DCB	9568208.9	6856756.7	2017332.5	644501.1	17628.3	31990.3
Freshwater ecotoxicity	kg 1,4-DCB	89941.2	28720.6	47811.8	12556.2	302.8	549.8
Marine ecotoxicity	kg 1,4-DCB	121458.3	40436.2	62584.8	17262.3	417.3	757.8
Human carcinogenic toxicity	kg 1,4-DCB	110637.6	41950.3	45538.8	21640.4	535.8	972.4
Human non-carcinogenic toxicity	kg 1,4-DCB	2302851.1	639519.2	1097082.6	530275.7	12775.8	23197.8
Land use	m2a crop eq	798613.8	104139.1	587353.9	101613.0	1956.9	3551.0
Mineral resource scarcity	kg Cu eq	46612.0	44452.7	1801.6	332.0	9.1	16.5
Fossil resource scarcity	kg oil eq	962572.7	250064.8	533348.9	167274.7	4222.5	7661.9
Water consumption	m3	45947.2	12346.3	31669.3	1804.8	45.1	81.8

The bar graph in figure 41 shows the percentage contribution of each life phase of the treatment plant for each impact category. It can be seen that each phase contributes to a greater or lesser extent on every impact category.

It can be observed that the impact is more or less uniformly divided between the contribution of plant construction and plant operation during filling and aftercare phases; while plant operation during closure and conversion impacts negligibly on almost every category. Mineral resource scarcity seems to be affected totally by the plant construction phase due to the large amount of natural material required to build the infrastructures.

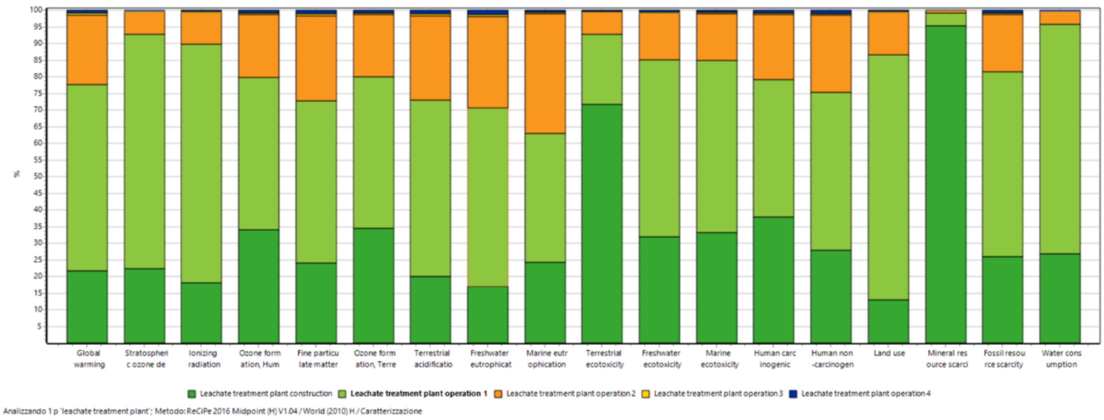


Figure 41. Graphical representation of characterization results through ReCiPe 2016 method for the entire leachate treatment plant life (personal elaboration from SimaPro software).

Global warming

The global warming impact category counts a total of 3 x 10^6 kg of CO_2 equivalent.

The most impacting phase is the plant operation during filling with 1.8 x 10^6 kg of CO_2 equivalent; reverse osmosis with its intensive use of electricity is the main responsible process.

Follows the plant construction phase reaching 7 x 10^5 kg of CO_2 equivalent especially due to the significant amount of natural materials and transport involved.

The third most contributing phase is plant operation during the aftercare with 6.8 x 10^5 kg of CO_2 equivalent almost completely related to the production of the activated carbon used as adsorbent.

While leachate treatment during landfill closure and conversion cover together less than 5% of global warming; indeed, after a good degree of waste stabilization the leachate produced does not need an intensive purification.

Stratospheric ozone depletion

This impact category reaches a total of 2.8 kg CFC11 equivalent.

During the entire life of the leachate treatment plant, the phase which impacts the most on the stratospheric ozone depletion is the operation during landfill filling, responsible for more than 60%. Reverse osmosis plays again an important role caused by the intensive exploitation of electricity.

Plant construction covers slightly more than 20% of ozone depletion and leachate treatment during aftercare shares the 8% of the impact.

The other phases are negligible.

Ionising radiation

The most significant contribution to ionising radiation is given by the plant operation during landfill filling with 1.8 x 10^5 kBq Co-60 eq., which covers more than 70% of the total impact.

Plant construction accounts for about 18% of the total impact with 4.5 x 10^4 kBq Co-60 eq.; while leachate treatment during the aftercare reaches 2.4 x 10^4 kBq Co-60 eq., that is approximately 10% of the total impact. The remaining 2% is split between plant operation in the closure and the conversion phases.

Ozone formation, human health

Ozone formation accounts for 8.1 x 10^3 kg NOx eq. for the entire leachate treatment plant life.

Plant operation during landfill filling is the most impacting phase with 3.7 x 10^3 kg Nox eq. and contributes for over 45% of the total impact. Plant construction and operation in the aftercare account approximately for 35% and 18% of the total impact, being 2.7 x 10^3 and 1.5 x 10^3 kg NOx eq. respectively.

Plant operation in the closure and conversion phases are the least contributing processes.

Fine particulate matter formation

The total impact related to fine PM formation is 4.8 x 10^3 kg PM2.5 eq..

Leachate treatment during landfill filling is responsible for more than 45% of the total impact, reaching 2.3 x 10^3 kg PM2.5 eq.

Plant construction and operation during the aftercare contribute individually for the 25% of the total impact; their values are 1.1 x 10^3 and 1.2 x 10^3 kg PM2.5 eq.

The other phases are negligible.

Ozone formation, Terrestrial ecosystems

This category reaches a total of 8.2 x 10^3 kg NOx eq. for the entire leachate treatment plant life.

Plant operation during the filling phase makes up for the 45% of the total ozone formation, being about 3.7 x 10^3 kg NOx eq..

Plant construction and operation during landfill aftercare contribute respectively for 35% and 20% of the impact with 2.8 x 10^3 and 1.5 x 10^3 kg NOx eq.

The other phases are negligible.

Terrestrial acidification

Terrestrial acidification accounts for 1.2 x 10^4 kg SO^2 eq. for the entire leachate treatment plant life.

Leachate treatment during landfill filling is the most impacting phase sharing 50% of the total impact with 6.7 x 10^3 kg SO_2 eq.

The plant construction and operation in the aftercare cover respectively 20% and 25% of the total impact, counting 2.5 x 10^3 and 3.2 x 10^3 kg SO_2 eq.

Plant operation during closure and conversion share no more than 5% of terrestrial acidification, being respectively 7.9 x 10^1 and 1.4 x 10^2 kg SO_2 eq.

Freshwater eutrophication

This impact category reaches a total of 1.0 x 10^3 kg P eq.

The most contributing phase is the plant operation during landfill filling, being responsible for the 55% of the total impact with 5.4 x 10^2 kg P eq.

Plant construction and operation in the aftercare now cover respectively 15% and 25% of the impact, with 1.7 x 10^2 and 2.7 x 10^2 kg P eq.

The remaining 5% of the impact is distributed between plant operation during closure and conversion phases counting respectively 6.8 and 1.2 x 10^1 kg P eq.

Marine eutrophication

The total impact related to this category counts up to 1.2 x 10^2 kg N eq. for the entire leachate treatment plant life.

Plant operation during landfill filling and aftercare share individually 35% of the impact, being respectively 5.0 x 10^1 and 4.6 x 10^1 kg N eq.

The other phase of considerable importance for marine eutrophication is that of plant construction, with 3.1 x 10^1 kg N eq., which is 25% of the total impact.
Plant operation in the closure and conversion phases show similar contributions and the remaining 5% of the total is shared evenly among them.

Terrestrial ecotoxicity

The total impact related to this category is 9.5 x 10^6 kg 1,4-DCB.
Plant construction dominates among all the leachate treatment life phases reaching 6.8 x 10^3 kg 1,4-DCB.
Plant operation in the filling and aftercare totalize respectively 2.0 x 10^6 and 6.4 x 10^5 kg 1,4-DCB.
The contribution of leachate treatment during landfill closure and conversion is practically absent.

Freshwater ecotoxicity

Freshwater ecotoxicity accounts for 8.9 x 10^4 kg 1,4-DCB for the entire leachate treatment plant life.
The largest contribution is given by the plant operation in the filling phase, which accounts for 4.7 x 10^4 kg 1,4-DCB, that is over 50% of the total impact.
Plant construction and operation in the aftercare cover respectively 30% and 15% of the overall impact, with values equal to 2.8 x 10^4 and 1.2 x 10^4 kg 1,4-DCB.
Plant operation during closure and conversion can be neglected.

Marine ecotoxicity

The total impact related to this category counts up to 1.2 x 10^5 kg 1,4-DCB for the entire leachate treatment plant life.
Plant operation during landfill filling is still the most contributing phase totalizing 6.2 x 10^4 kg 1,4-DCB, sharing 50% of the total impact.
The other phases of considerable importance for marine ecotoxicity are that of plant construction and operation in the aftercare with respectively 4.0 x 10^4 and 1.7 x 10^4 kg 1,4-DCB, which correspond to 30% and 15% of the total impact.
Leachate treatment in the closure and conversion phases do not contribute significantly.

Human carcinogenic toxicity

The score totalized by human carcinogenic toxicity is 1.1×10^5 kg 1,4-DCB for the entire leachate treatment plant life.

Plant operation during landfill filling play a dominant role with 4.5×10^4 kg 1,4-DCB (40% of the total impact).

A similar contribution is given by plant construction, which totalizes 4.1×10^4 kg 1,4-DCB that is over 35% of the total impact.

During landfill aftercare the plant operation accounts for 20% of the entire impact, that is 2.1×10^4 kg 1,4-DCB; while leachate treatment in the closure and conversion phases show a really scarce significance.

Human non-carcinogenic toxicity

Human non-carcinogenic toxicity accounts for 2.3×10^6 kg 1,4-DCB.

More than 45% of the total impact is given by leachate treatment during the filling phase, with 1.1×10^6 kg 1,4-DCB.

The other half of the impact is shared uniformly by plant construction and plant operation in the aftercare, which account individually for 25% with respectively 6.3×10^5 and 5.3×10^5 kg 1,4-DCB.

The remaining 5% of the impact is associated to the plant operation during closure and conversion.

Land use

For the entire leachate treatment plant life the land use category reaches 7.9×10^5 m2a crop eq.

Over 70% of the impact is caused by plant operation in the filling phase. The residual 30% is distributed between plan construction and plant operation during landfill aftercare (15% each); with negligible impact values from the other phases.

Mineral resource scarcity

Mineral resource scarcity category results in a total impact of 4.6×10^4 kg Cu eq.

The impact is almost completely linked to the plant construction due to the exploitation of large amounts of minerals devoted to infrastructures realisation (4.4×10^4 kg Cu eq.).

A small 5% of the impact is covered by plant operation during landfill filling with 1.8×10^3 kg Cu eq.; while the other phases contribution is practically absent.

Fossil resource scarcity

This impact category reaches a total score of 9.6 x 10^5 kg oil eq. for the entire leachate treatment plant life.

In this case plant operation in the filling phase is responsible for 55% of the total impact, due to the intensive use of electricity from non renewable sources.

A 25% is covered by the plant construction while the plant operation during aftercare accounts for 20% of fossil resource scarcity.

Plant operation during closure and conversion do not show a significant contribution.

Water consumption

Water consumption category shows a total impact of 4.5 x 10^4 m^3.

Almost 70% of the total impact is given by leachate treatment in the filling phase; this is again linked to the water used for producing the electricity necessary to run the RO modules.

Follows the plant construction phase, covering 25% of the entire impact, principally as result of the water consumed to produce the HDPE geomembrane and to wash the gravel used for realizing the phytoremediation basin.

Leachate treatment in the aftercare contributes just 5% due to the water consumed for the activated carbon production.

The characterization results described above are shown graphically as a percentage of the total impact for each category, since they have different units of measure.

In this way it seems that all categories have the same importance on the environment.

To improve the interpretation of the characterization results it is useful to express them with respect to a reference information by dividing them by a reference value. The results of normalisation are shown in figure 42.

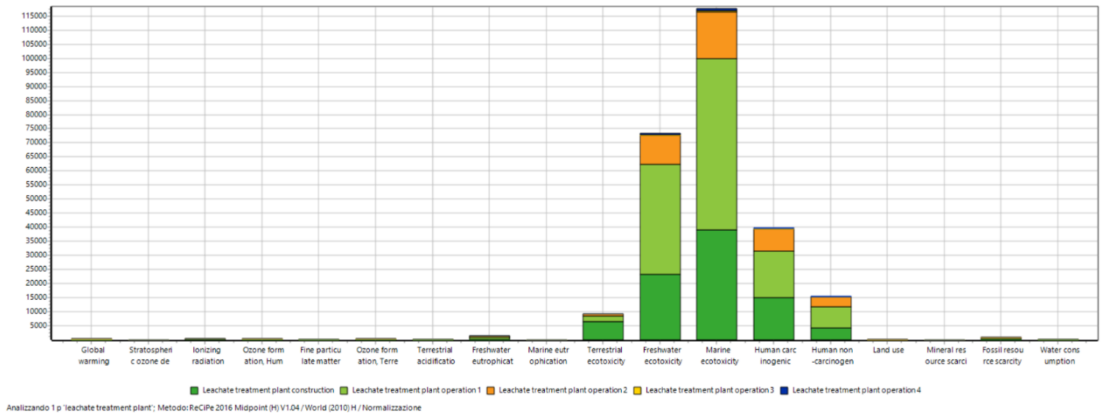


Figure 42. Graphical representation of normalisation results through ReCiPe 2016 method for the entire leachate treatment plant life (personal elaboration from SimaPro software).

Marine ecotoxicity appears as the most important category, followed by freshwater ecotoxicity and land use.

Leachate treatment during landfill filling is responsible of a large part of the score in almost all impact categories of concern; the production of electricity from non renewable resources used to operate the reverse osmosis unit is a crucial issue.

The role of plant construction is also evident from the normalization results; the natural materials involved in the equipment installation (i.e. gravel to fill the phytoremediation basins and clay to line the bottom of the evaporation pond) are the major contributors in this phase.

Plant operation during the aftercare, even if less significant than the aforementioned life phases of the treatment plant, causes anyway a visible impact; the aftercare is quite a long phase (40 years long) and a large amount of materials are required to operate the treatment plant, as well as great amounts of waste by-products are produced.

5.2.3. Life cycle inventory results for the construction phase

Four different processes are involved in the construction phase of the leachate treatment plant. They are added together to estimate the total contribution of the construction phase on the impact related to the entire life of the treatment plant.

The input/output analysis is represented graphically in figure 43.

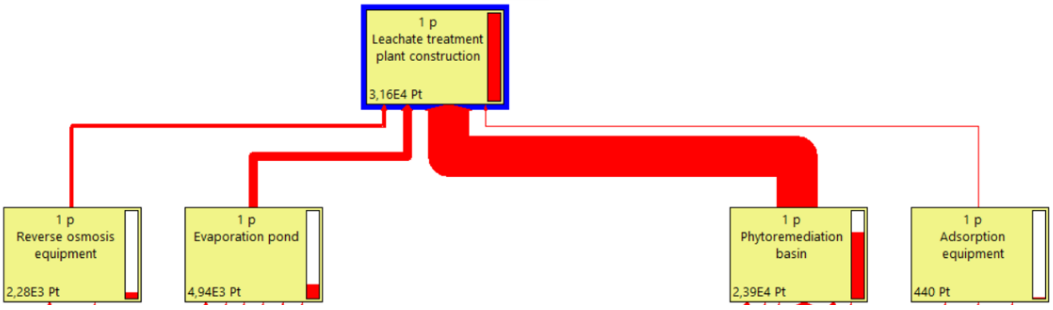


Figure 43. Leachate treatment plant construction input/output analysis (personal elaboration from SimaPro software).

5.2.4. Characterization and normalisation of the results for the construction phase

Each process involved in the construction phase of the leachate treatment plant impacts as much as the sum of the impacts of the materials used to carry it out. In turn, the impact of a phase assembly is obtained by adding together the impacts of all the processes involved.

The characterization results, showing the contribution of the plant construction's processes to the different impact categories, are represented by the graph in figure 44.

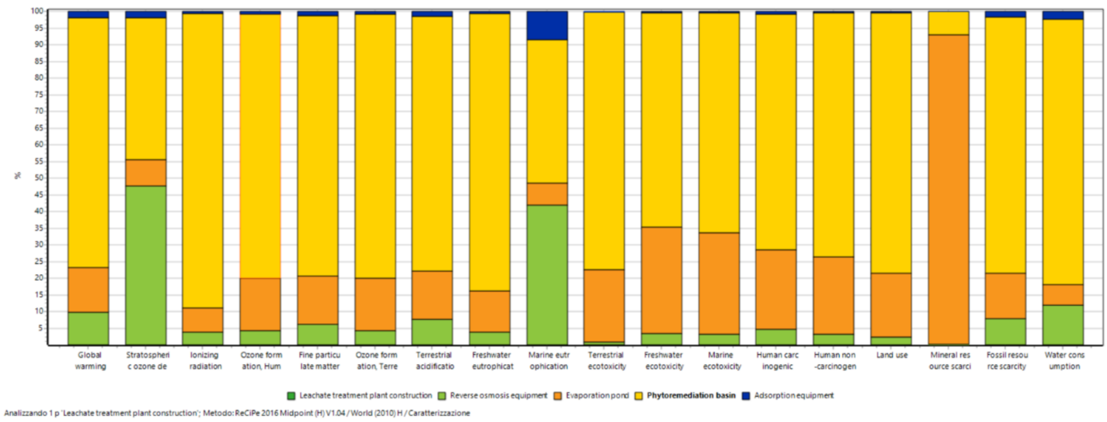


Figure 44. Graphical representation of characterization results through ReCiPe 2016 method for the leachate treatment plant construction (personal elaboration from SimaPro software).

It can be noticed that the preparation of the phytoremediation basin is the element that has the greatest impact. In particular, a large part of the contribution is due to the gravel substrate used to fill the basins and the related transport. HDPE liner is also not negligible. The detailed phytoremediation basin characterization is graphically represented in Figure 45.

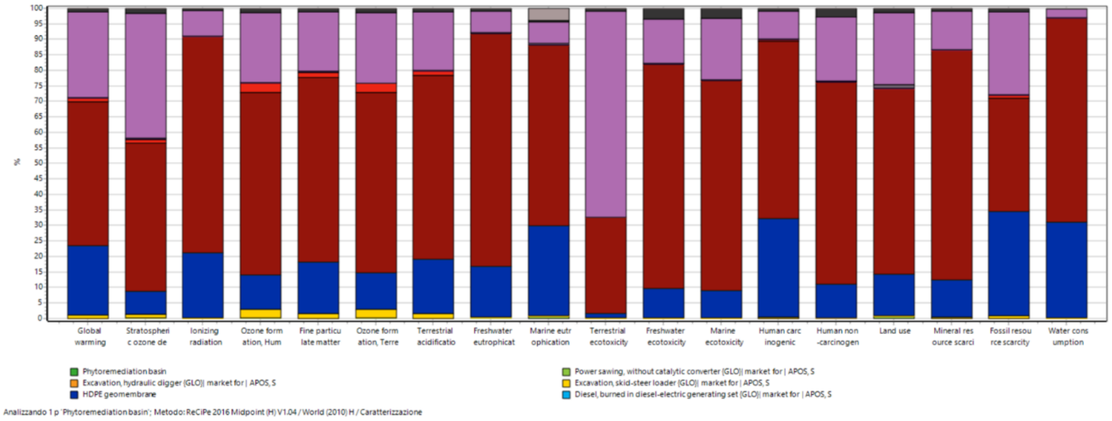


Figure 45. Graphical representation of characterization results through ReCiPe 2016 method for the phytoremediation basin (personal elaboration from SimaPro software).

Also in the case of evaporation pond construction, it is clear that the impermeabilization of the bottom is the most impactful component of the process; the use of the natural material (in this case clay) and its transport and the HDPE liner are responsible for this (Figure 46).

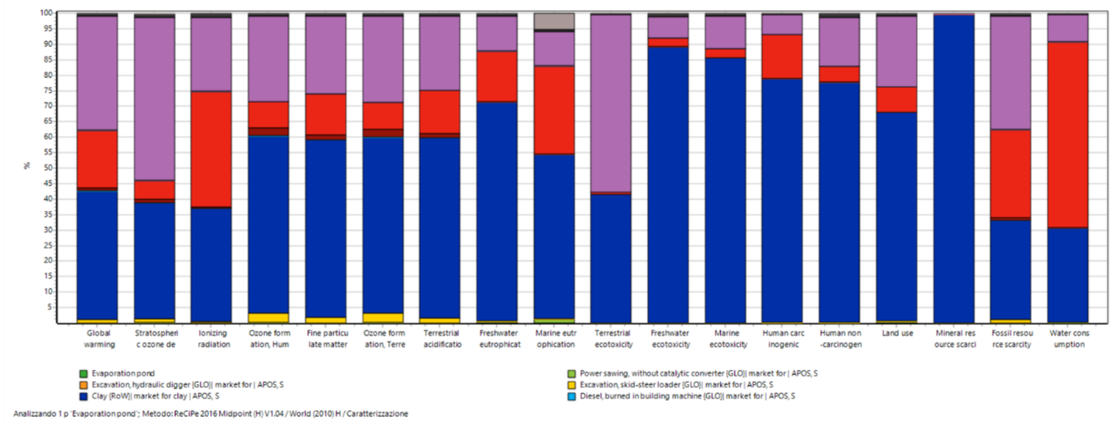


Figure 46. Graphical representation of characterization results through ReCiPe 2016 method for the evaporation pond (personal elaboration from SimaPro software).

As regards the characterization of the reverse osmosis equipment represented by the histogram of figure 47, the RO membranes mainly affect the stratospheric ozone depletion.

The impact of the RO pump and material transport is also evident.

Fibreglass tanks for raw leachate, RO permeate and RO concentrate play the major role in all categories due to the large amount of this material required.

On the other hand, the small stainless steel vessels to contain the RO membranes contribute limitedly.

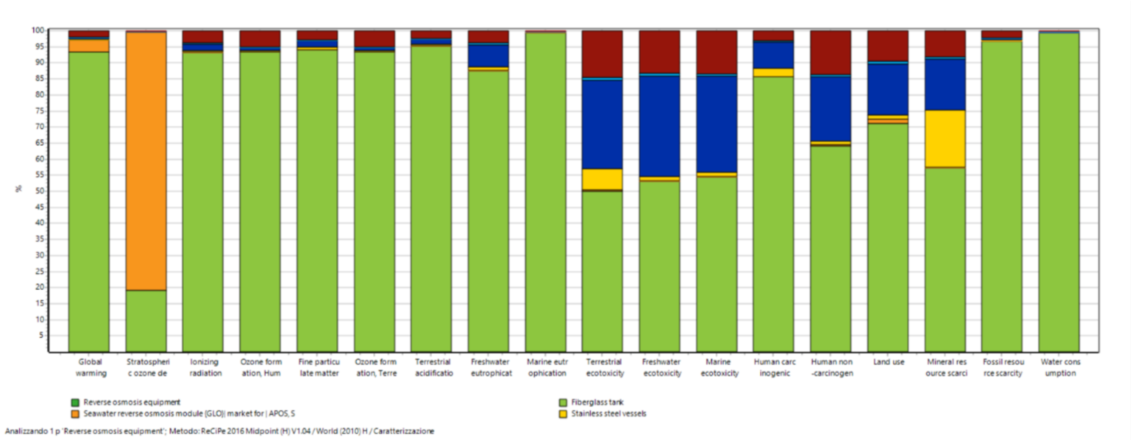


Figure 47. Graphical representation of characterization results through ReCiPe 2016 method for the reverse osmosis equipment (personal elaboration from SimaPro software).

The graph in figure 48 shows the characterization results relating to the realization of the adsorption equipment.

According to the graph of figure 48, here too the contribution given by the fibreglass tanks used as contact bed with the activated carbon and to store the purified leachate are considerable. The transport of the materials is not negligible.

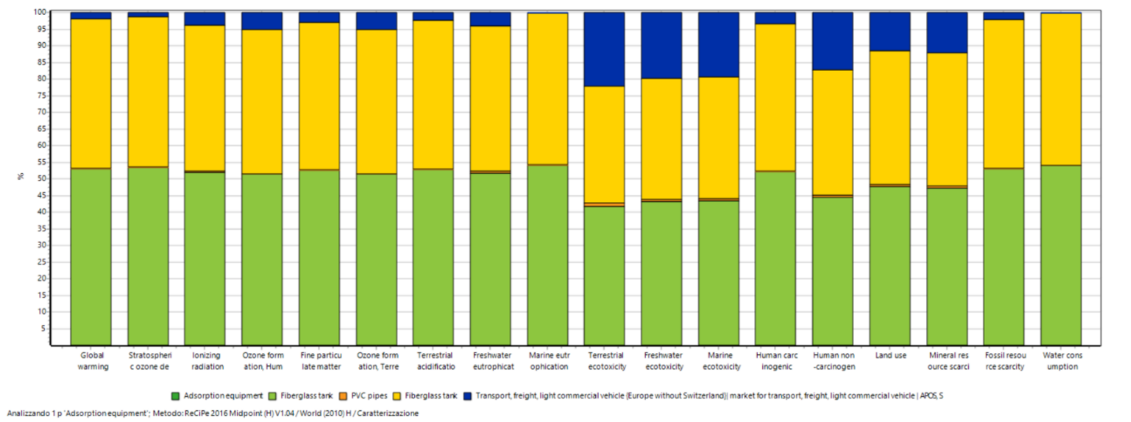


Figure 48. Graphical representation of characterization results through ReCiPe 2016 method for the adsorption equipment (personal elaboration from SimaPro software).

The normalisation results relating to the leachate treatment construction phase are shown in the graph in figure 49. The most impacting categories are marine ecotoxicity, freshwater ecotoxicity and human carcinogenic toxicity. To a lesser extent but still evident there are terrestrial ecotoxicity and human non carcinogenic toxicity.

Construction of the phytoremediation basins and the evaporation pond dominate all the impact categories of concern.

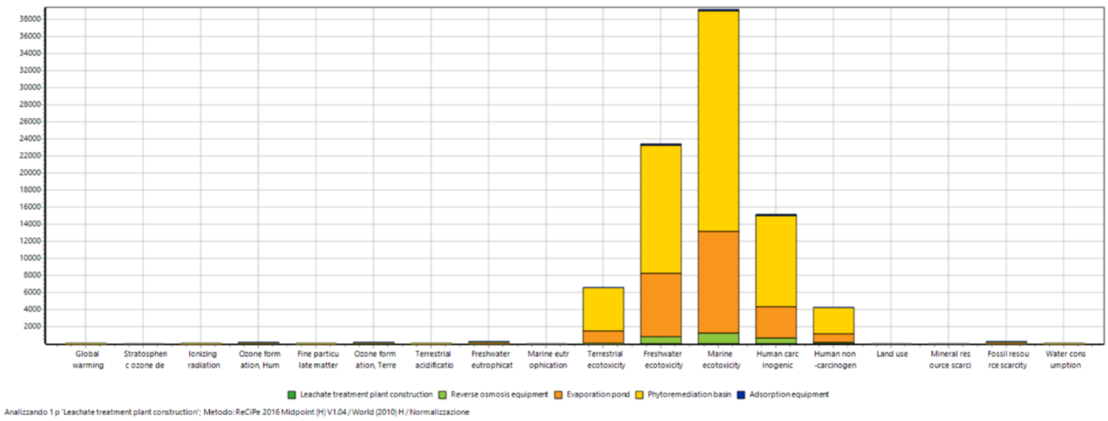


Figure 49. Graphical representation of normalization results through ReCiPe 2016 method for the leachate treatment plant construction (personal elaboration from SimaPro software).

From the point of view of the landfill life cycle, the characterization results shown in the graph of figure 50 demonstrate that leachate treatment plant construction, although to a lesser extent with respect to other processes such as bottom layer realization, has also a significant contribution.

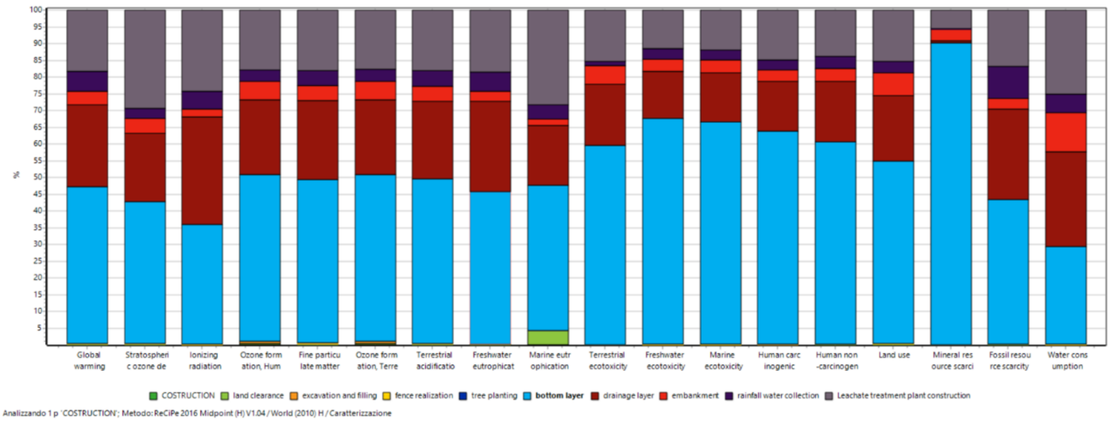


Figure 50. Graphical representation of characterization results through ReCiPe 2016 method for the construction phase (personal elaboration from SimaPro software).

The normalisation results relating to the landfill are shown in the graph in figure 51. The most impacting categories are marine ecotoxicity, freshwater ecotoxicity and human carcinogenic toxicity. To a lesser extent but still evident there are terrestrial ecotoxicity and human non carcinogenic toxicity.

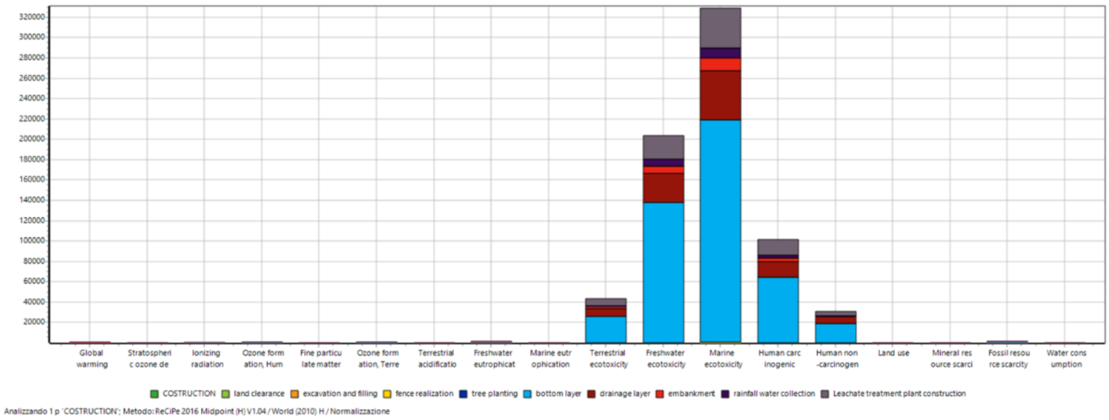


Figure 51. Graphical representation of normalization results through ReCiPe 2016 method for the entire landfill life (personal elaboration from SimaPro software).

5.2.5. Life cycle inventory results for the operation phase

The filling phase covers the first 20 years of the landfill life. In this period the waste is transported and placed in the landfill and, at the end of the disposal operation, it is covered with a semi-permeable top cover.

It is from now that the biodegradation of waste starts the production of leachate and biogas.

The input/output analysis results related to leachate treatment plant are represented in Figure 52, where the great contribution of reverse osmosis can be observed.

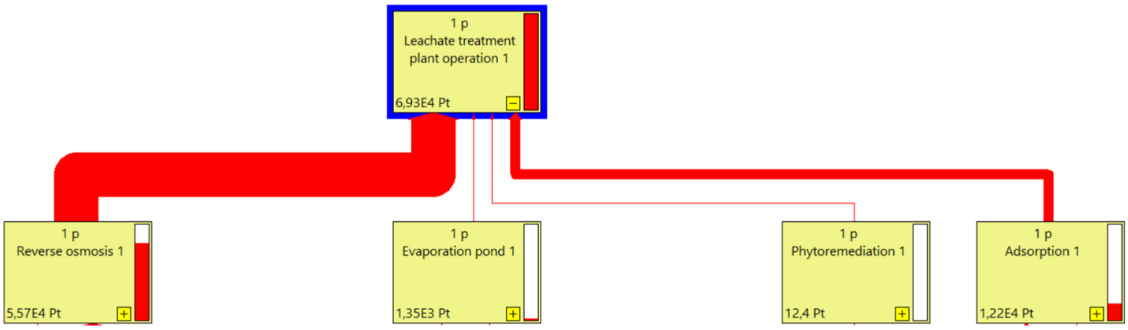


Figure 52. Leachate treatment plant operation during filling input/output analysis (personal elaboration from SimaPro software).

5.2.6. Characterization and normalisation of the results for the operation phase

The impact of the treatment plant operation during the landfill filling phase and the individual processes contribution are calculated and reported in Figure 53.

It is evident that the most impacting process used to treat the leachate in the filling phase is reverse osmosis.

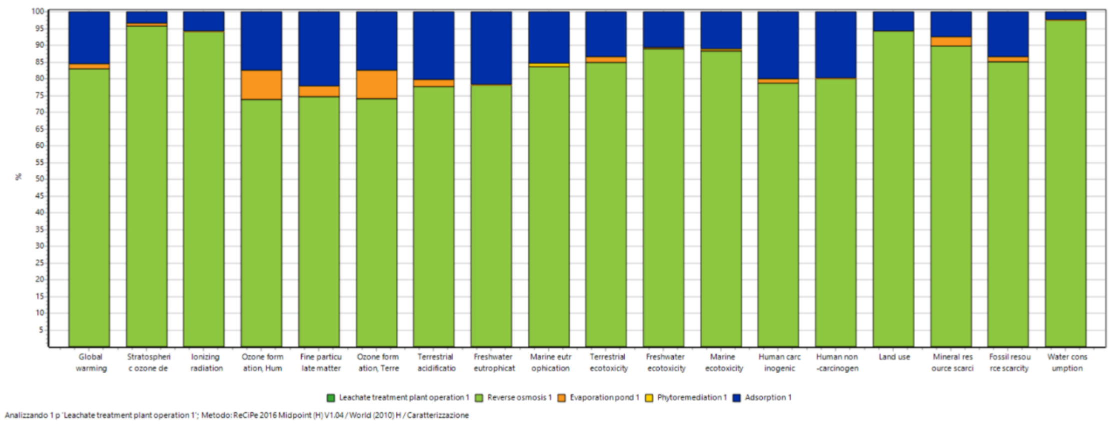


Figure 53. Graphical representation of characterization results through ReCiPe 2016 method for leachate treatment plant operation during the filling phase (personal elaboration from SimaPro software).

Reverse osmosis operation requires a significant amount of electricity to apply the right pressure gradient. As the graph in figure 54 shows, electricity covers the entire impact on all categories; while the RO membranes for replacement at each end of life contribute, as already mentioned, only to the stratospheric ozone depletion.

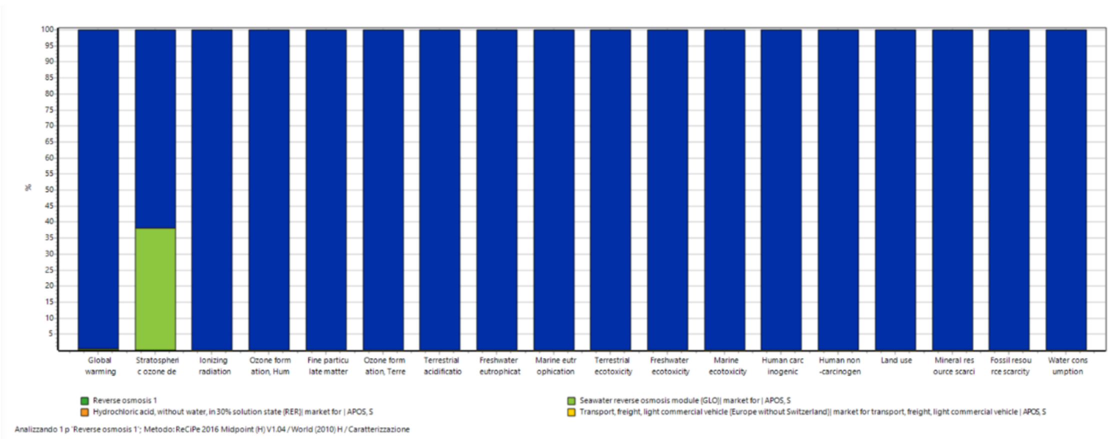


Figure 54. Graphical representation of characterization results through ReCiPe 2016 method for reverse osmosis operation during the filling phase (personal elaboration from SimaPro software).

Solar evaporation contributes to a small extent in all categories; slightly more pronounced impacts are visible in the categories of ozone formation. The activities of laying the concentrate and removing the residual solid salts are the activities responsible for the impacts, as shown in Figure 55.

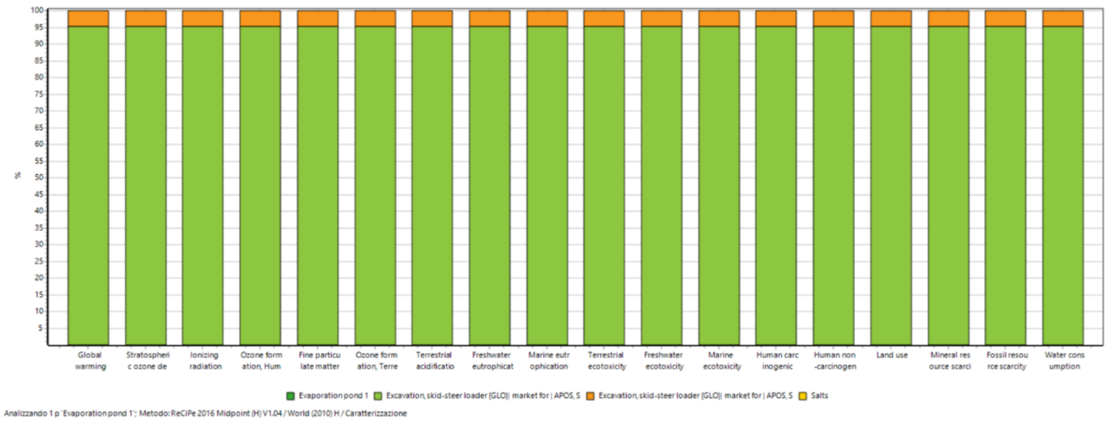


Figure 55. Graphical representation of characterization results through ReCiPe 2016 method for solar evaporation during the filling phase (personal elaboration from SimaPro software).

In the filling phase, phytoremediation has less impact than the other leachate treatment units. The permeate coming out of the reverse osmosis has in fact an excellent quality and requires a minimum improvement before being discharged into surface waters.

The impact from phytoremediation is almost completely due to the residual phytomass obtained by mowing, which is a biowaste that must be subjected to appropriate treatment. Figure 56 shows the characterization results of phytoremediation.

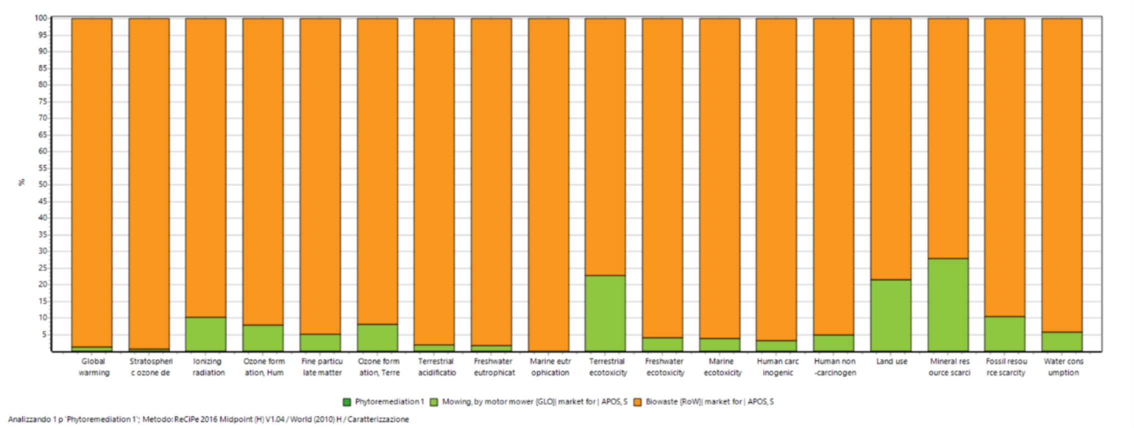


Figure 56. Graphical representation of characterization results through ReCiPe 2016 method for phytoremediation operation during the filling phase (personal elaboration from SimaPro software).

No more than 20% of all impact categories are covered by adsorption; this contribution is due to the granular activated carbon used. The histogram of Figure 57 demonstrates this.

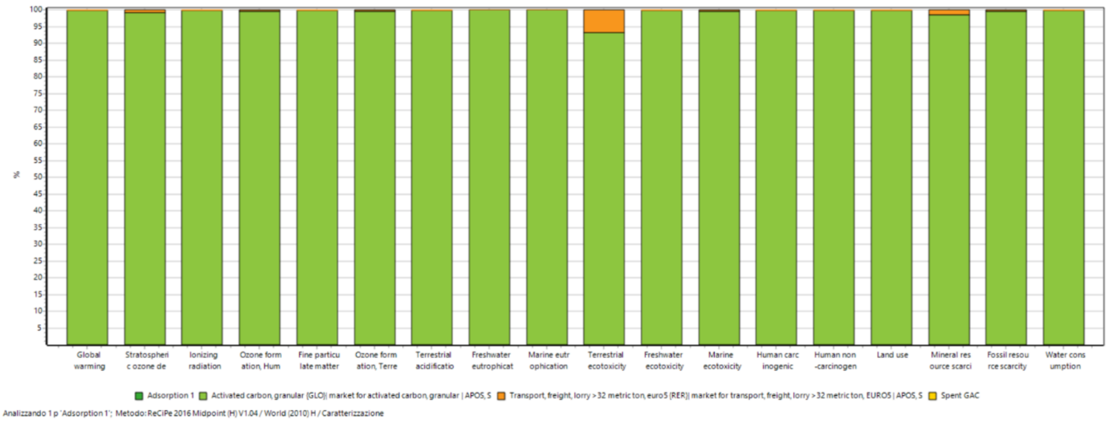


Figure 57. Graphical representation of characterization results through ReCiPe 2016 method for adsorption operation during the filling phase (personal elaboration from SimaPro software).

The characterization results of leachate treatment plant operation during the filling phase are normalised and reported in Figure 58. Marine and freshwater ecotoxicity are the impact categories most affected by leachate treatment; human carcinogenic and non-carcinogenic toxicity are also important in this context.
From the graph, the highest contribution of reverse osmosis to all impact categories of concern can be easily detected, while phytoremediation plays really a negligible role.

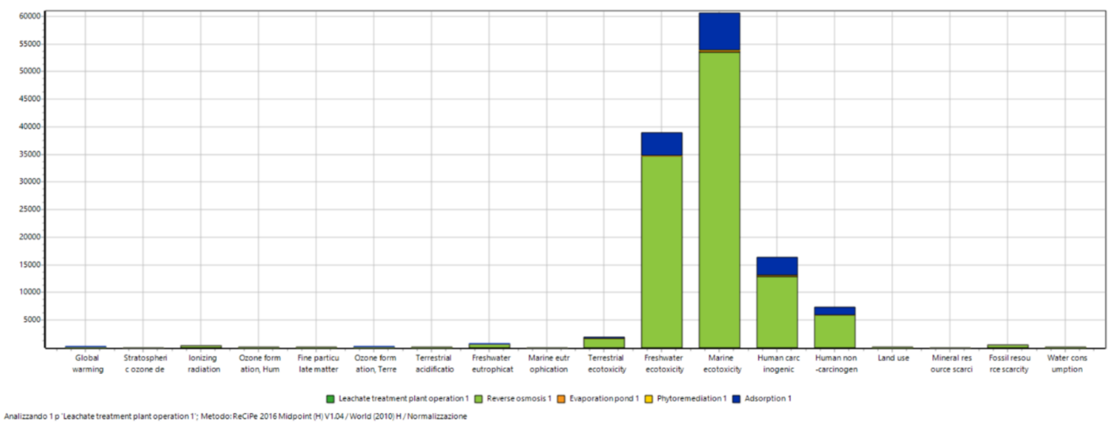


Figure 58. Graphical representation of normalisation results through ReCiPe 2016 method for leachate treatment plant operation during landfill filling (personal elaboration from SimaPro software).

As regards the overall assessment of the landfill filling phase, the characterization results reported in Figure 59 show that the contribution of leachate treatment plant operation is present in most of the categories, with greater evidence as regards ionising radiation and freshwater eutrophication. The impact due to leachate is almost zero for the category of freshwater eutrophication and ecotoxicity, human carcinogenic and non-carcinogenic toxicity, but remains an important component in the case of marine eutrophication.

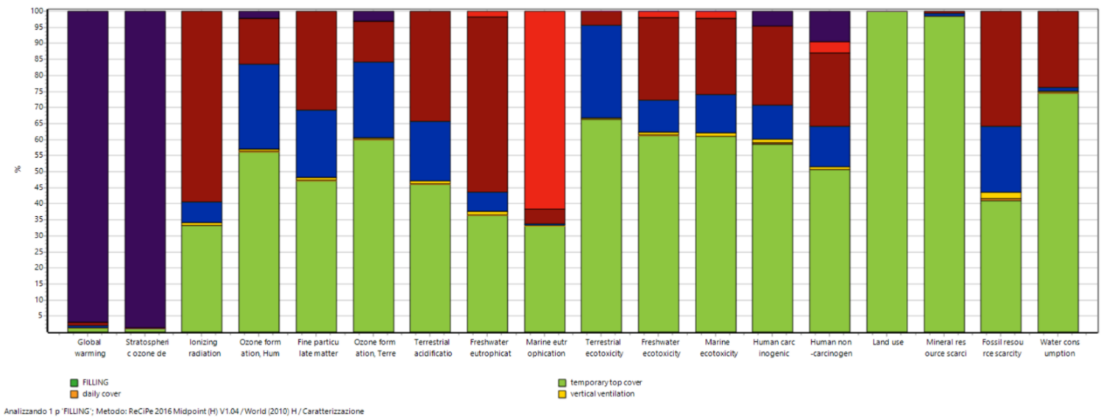


Figure 59. Graphical representation of characterization results through ReCiPe 2016 method for the filling phase (personal elaboration from SimaPro software).

The characterization results for the filling phase are normalised and reported in Figure 60. Land use, marine and freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity, terrestrial ecotoxicity, global warming and stratospheric ozone depletion are the impact categories most affected by landfill filling.

With the introduction of leachate treatment, the contribution of leachate is reduced in all categories; but this reduction is offset by the impacts due to the operation of the treatment units. This entails obtaining normalisation results of the same order of magnitude as those calculated considering a worse leachate quality.

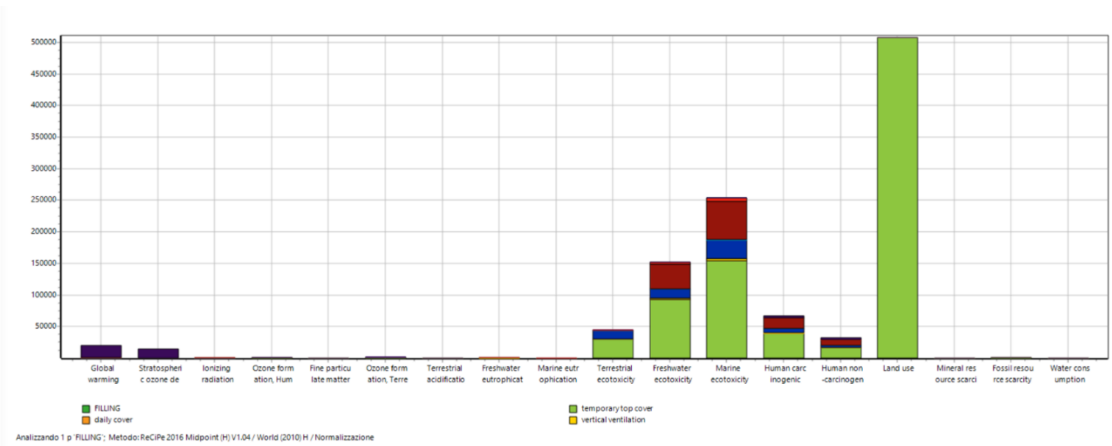


Figure 60. Graphical representation of normalisation results through ReCiPe 2016 method for the landfill filling (personal elaboration from SimaPro software).

5.2.7. Life cycle inventory results for the aftercare phase

After the installation of the temporary top cover, the 40-year aftercare phase starts and the stabilisation process continues thanks to the partial biodegradation of waste into leachate and biogas.

The contribution of each process involved in leachate treatment during the aftercare is shown by the input/output analysis of Figure 61.

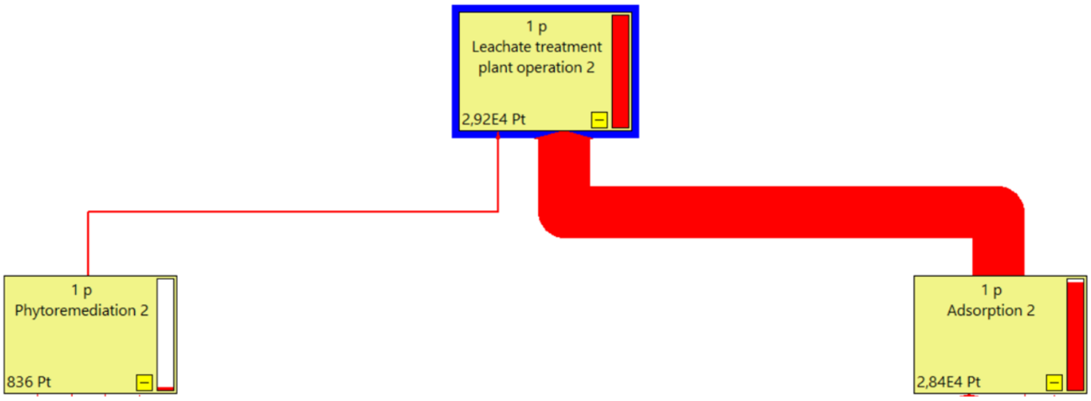


Figure 61. Leachate treatment plant operation during aftercare input/output analysis (personal elaboration from SimaPro software).

During this phase leachate treatment consists of the combination of two units: phytoremediation and adsorption; the adsorption treatment unit is the major contributor.

5.2.8. Characterization and normalisation of the results for the aftercare phase

Analysing the characterization results obtained for leachate treatment in the aftercare phase, it can be deduced that the great contribution is given by adsorption, while phytoremediation plays a minor role except for marine eutrophication (Figure 62).

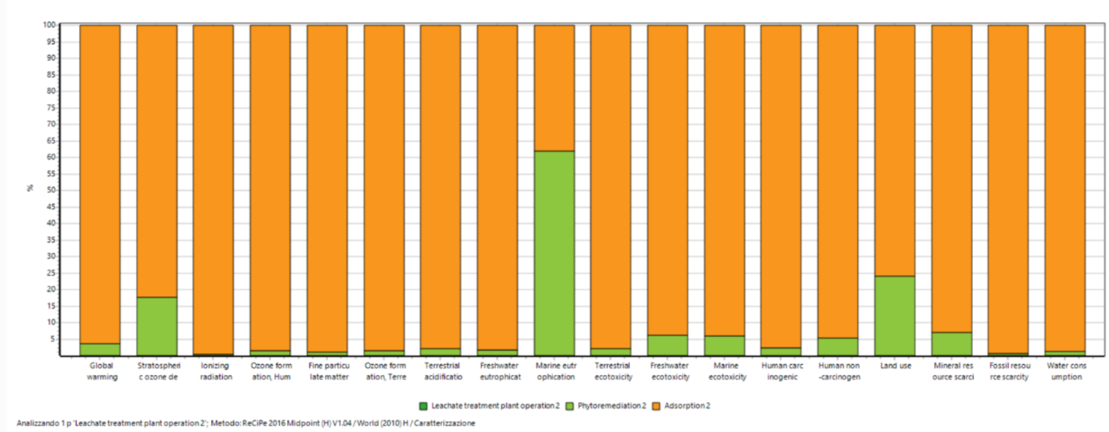


Figure 62. Graphical representation of characterization results through ReCiPe 2016 method for leachate treatment plant operation during the aftercare (personal elaboration from SimaPro software).

Observing the graph in Figure 63 relating to phytodepuration in the aftercare phase, it is possible to note that the residual phytomass obtained as waste from mowing contributes considerably to all impact categories, except in land use in which plant rhizomes predominate.

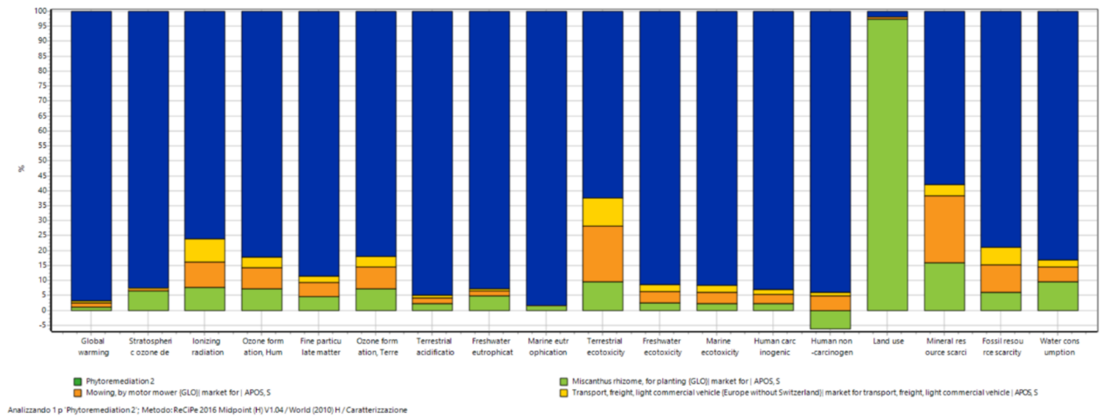


Figure 63. Graphical representation of characterization results through ReCiPe 2016 method for phytoremediation operation during the aftercare (personal elaboration from SimaPro software).

But the greatest contribution among the leachate treatment units, as already mentioned, is due to adsorption. Most of the impact derives from the granular activated carbon used, as the histogram in Figure 64 demonstrates.

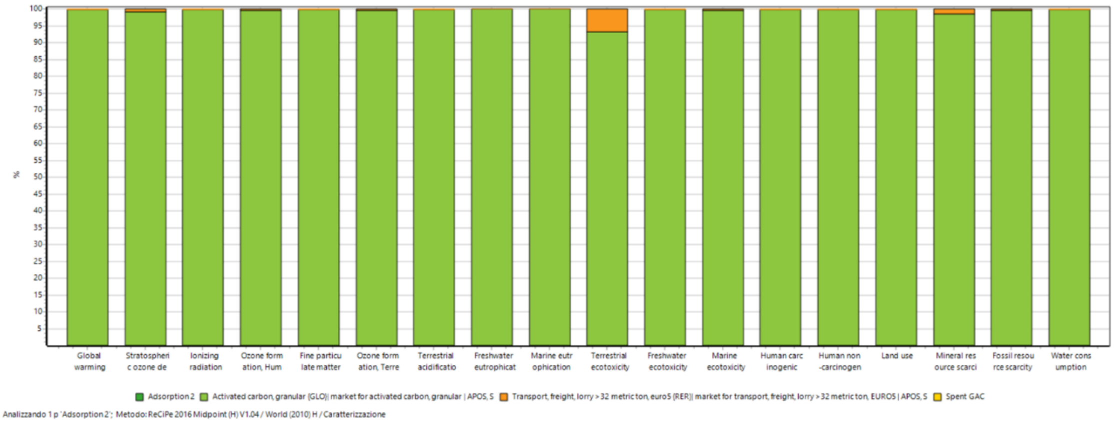


Figure 64. Graphical representation of characterization results through ReCiPe 2016 method for adsorption operation during the aftercare (personal elaboration from SimaPro software).

From the normalisation results related to the leachate treatment plant operation during the aftercare phase it is possible to derive the most significant impact categories. The graph of Figure 65 shows that marine and freshwater ecotoxicity are the most relevant categories; their impact is almost totally caused by the adsorption unit, while phytoremediation contributes to a really low extent. Human carcinogenic and non-carcinogenic toxicity also appear as impact categories of concern.

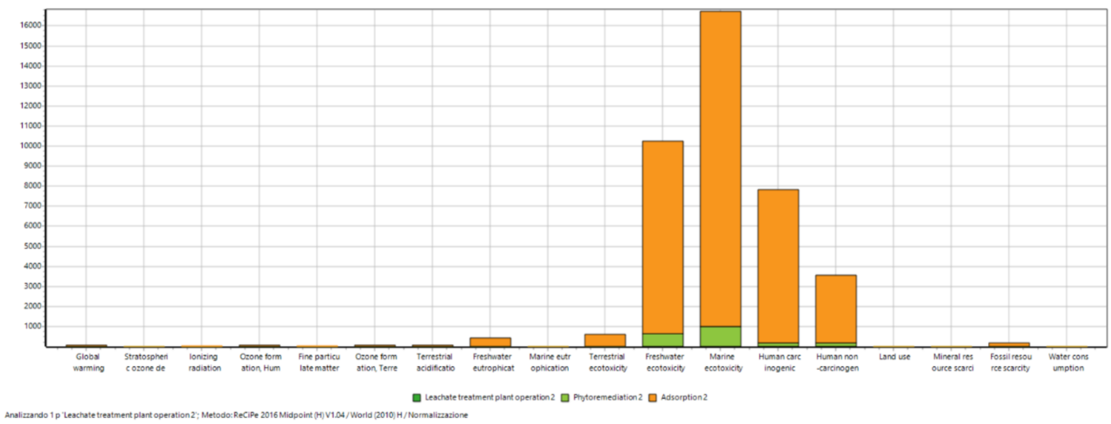


Figure 65. Graphical representation of normalisation results through ReCiPe 2016 method for leachate treatment plant operation during landfill aftercare (personal elaboration from SimaPro software).

The overall impacts of landfill aftercare are characterised and reported in Figure 66; the contribution of the leachate treatment plant operation appears in all impact categories, except for those ones exclusively linked to biogas emissions (i.e. global warming and ozone depletion).

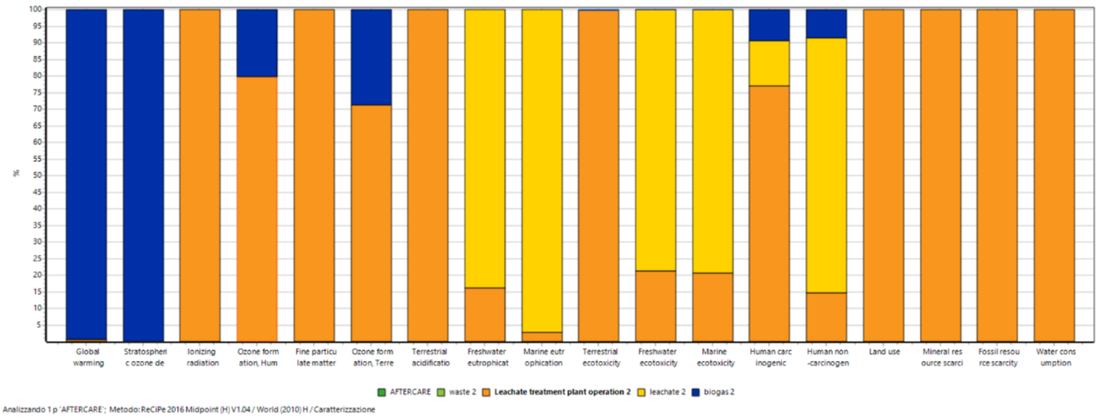


Figure 66. Graphical representation of characterization results through ReCiPe 2016 method for landfill aftercare (personal elaboration from SimaPro software).

From the normalisation of the results for the aftercare phase it is possible to derive the most significant impact categories. The graph of Figure 67 shows that marine and freshwater ecotoxicity are the most relevant categories; their impact is due to the contribution of the leachate treatment plant and the leachate released in surface waters. Despite this, the normalisation shows that with the improvement in the quality of the leachate released, these impact categories totalize a lower score by an order of magnitude compared to the scenario in which an advanced treatment of the leachate is not expected. The same can be said for freshwater and marine eutrophication and human carcinogenic and non-carcinogenic toxicity.

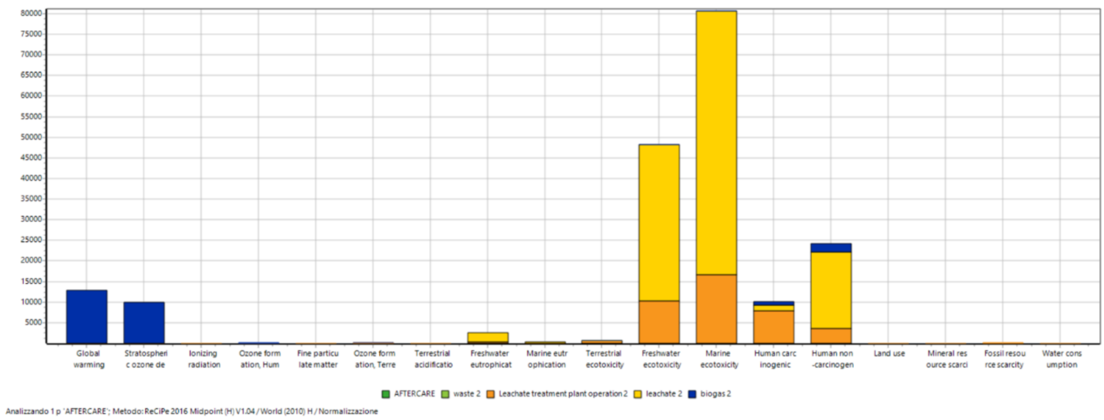


Figure 67. Graphical representation of normalisation results through ReCiPe 2016 method for the landfill aftercare (personal elaboration from SimaPro software).

5.2.9. Life cycle inventory results for the closure phase

Once the landfill has achieved a reasonable degree of stabilisation, the final top cover with low permeability is installed.

Since this phase last only one year, the amounts of biogas and leachate produced are low. Figure 68 reports the input/output flow analysis of the leachate treatment plant operation during closure.

During this phase, phytoremediation and adsorption are still in operation but the contribution comes only from adsorption, since in one year mowing is not performed.

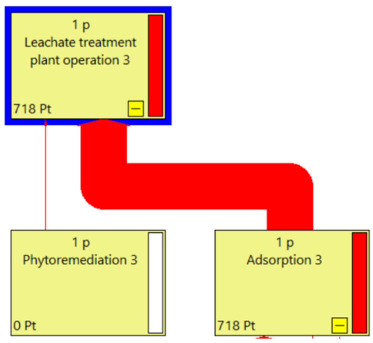


Figure 68. Leachate treatment plant operation during closure input/output analysis (personal elaboration from SimaPro software).

5.2.10. Characterization and normalisation of the results for the closure phase

During landfill closure the contribution of the leachate treatment plant to the environmental impact is totally given by the adsorption stage, which is performed after phytoremediation.

Phytoremediation is not associated with any impacts in this phase, since mowing is not performed and therefore no biowaste is produced. Figure 69 reports the characterization results related to leachate treatment in the closure phase.

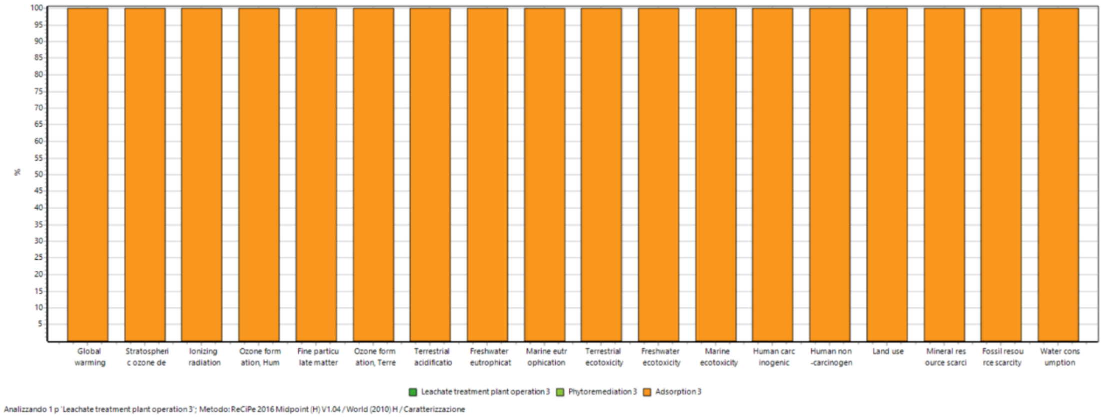


Figure 69. Graphical representation of characterization results through ReCiPe 2016 method for leachate treatment plant operation during landfill closure (personal elaboration from SimaPro software).

As in the other phases, most of the impact related to adsorption is due to the granular activated carbon used, as the histogram in Figure 70 demonstrates.

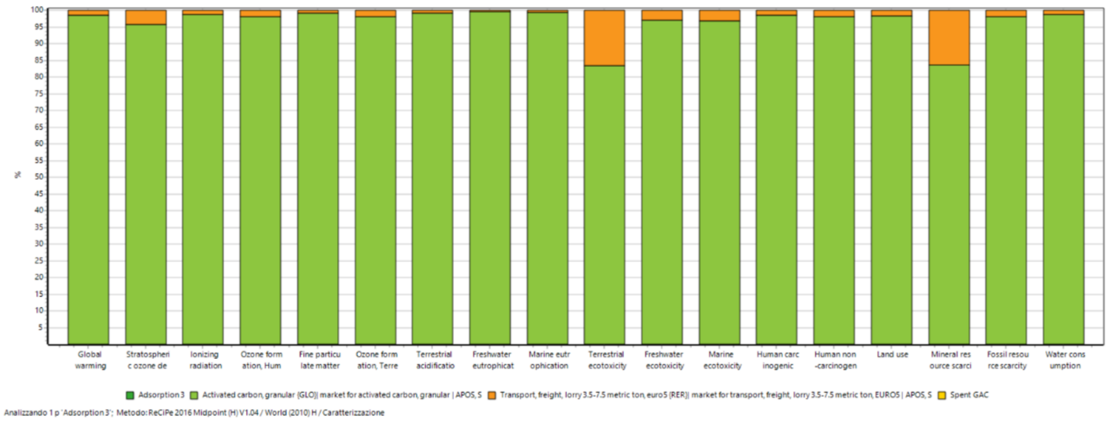


Figure 70. Graphical representation of characterization results through ReCiPe 2016 method for adsorption during landfill closure (personal elaboration from SimaPro software).

The characterization results of leachate treatment plant operation during the closure phase were then normalised to evaluate the most significant impact categories. From the graph in Figure 71 it is clear that adsorption is solely responsible for all impact categories. Adsorption impacts mainly on marine and freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity categories.

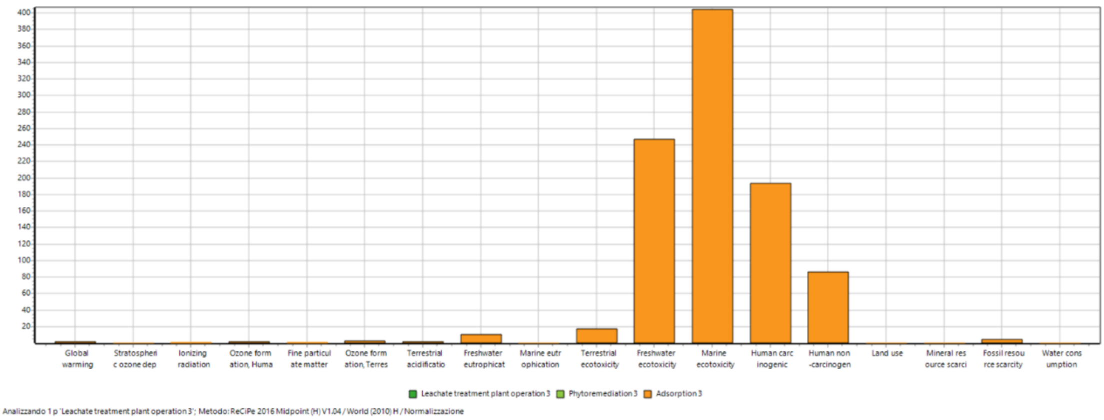


Figure 71. Graphical representation of normalisation results through ReCiPe 2016 method for the leachate treatment plant operation during landfill closure (personal elaboration from SimaPro software).

Analysing the characterization of landfill closure (Figure 72), the leachate treatment plant seems to contribute marginally in each category with respect to the other process taking place in this phase; this is essentially due to the short duration of the closure phase, which involves the absence of important maintenance operations of the treatment plant.

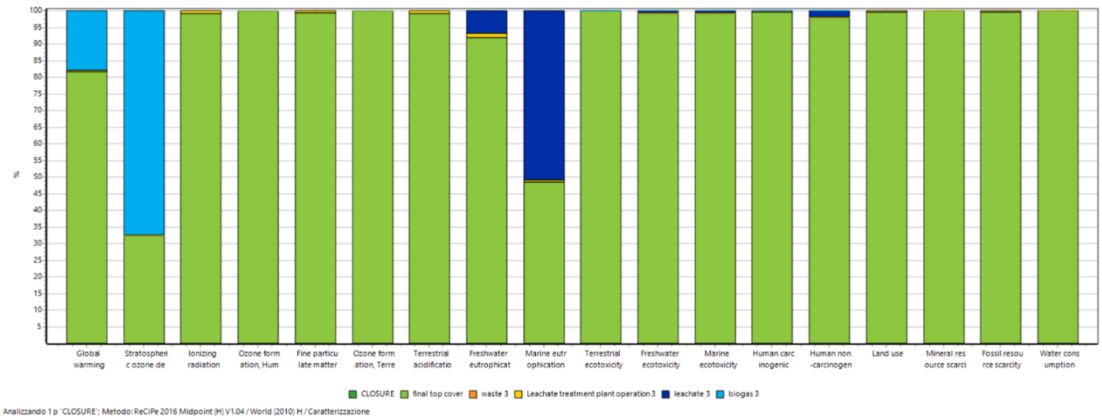


Figure 72. Graphical representation of characterization results through ReCiPe 2016 method for landfill closure (personal elaboration from SimaPro software).

The characterization results of landfill closure were then normalised to evaluate the most significant impact categories. For the closure phase, no noteworthy changes in normalisation results are observed with the introduction of leachate treatment.

From the graph in Figure 73 it is clear that the final top cover is solely responsible for all impact categories; while the contribution of biogas, leachate and related treatment is negligible.

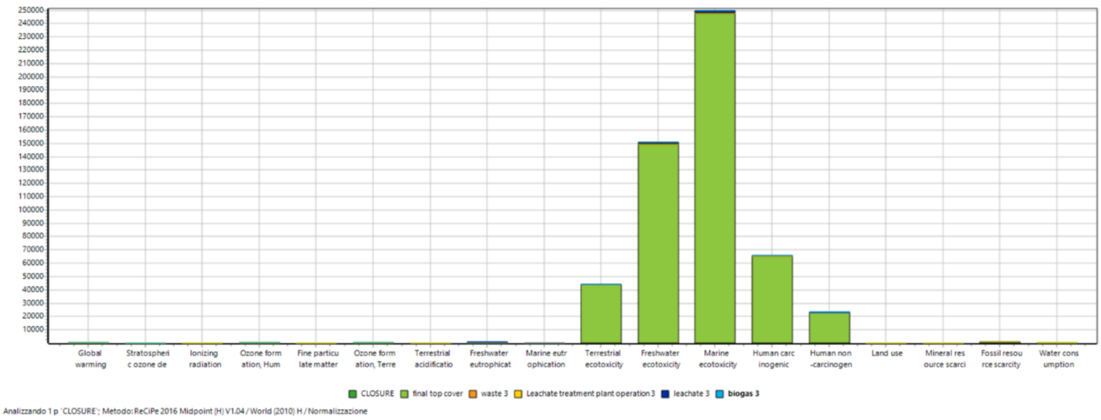


Figure 73. Graphical representation of normalisation results through ReCiPe 2016 method for the landfill closure (personal elaboration from SimaPro software).

5.2.11. Life cycle inventory results for the conversion phase

The last phase of the landfill's life involves its conversion to a future destination, planting grass over the entire surface using the hydroseeding technique.

In this phase the biogas and leachate are always produced, even if of better quality given the high degree of stabilisation of the waste. The leachate treatment plant is always active and consists of the combination of phytoremediation and adsorption.

The input/output analysis of leachate treatment is reported in Figure 74; the biggest contribution is given by the adsorption unit.

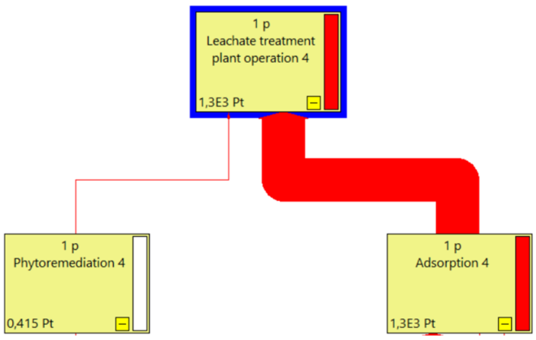


Figure 74. Leachate treatment plant operation during conversion input/output analysis (personal elaboration from SimaPro software).

5.2.12. Characterization and normalisation of the results for the conversion phase

The results of the characterization for leachate treatment plant operation during the conversion phase are reported in Figure 75.

The greatest contribution derives once again from adsorption, while phytoremediation plays a marginal role only in the case of marine eutrophication.

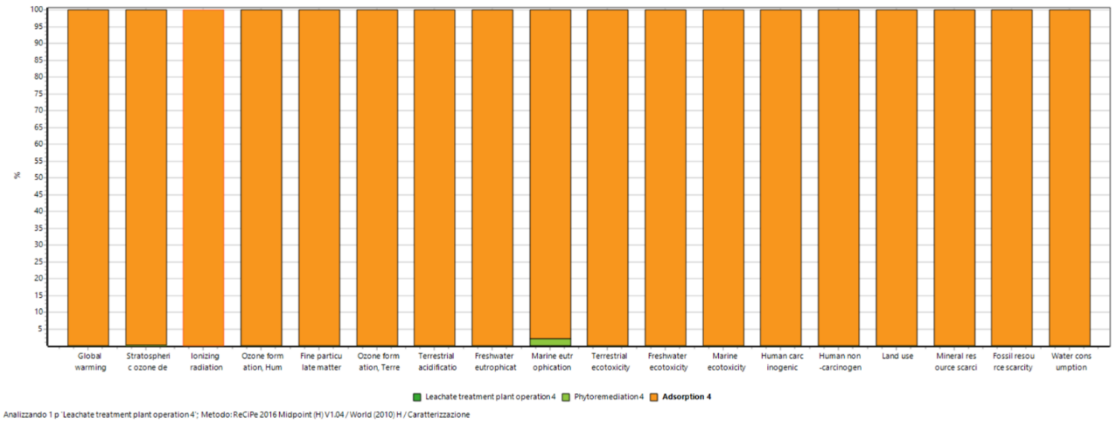


Figure 75. Graphical representation of characterization results through ReCiPe 2016 method for leachate treatment plant operation during landfill conversion (personal elaboration from SimaPro software).

The impact caused by phytoremediation is entirely due to the biowaste produced by manual mowing; while the contribution given by adsorption derives from the granular activated carbon used and its transport (Figures 76 and 77).

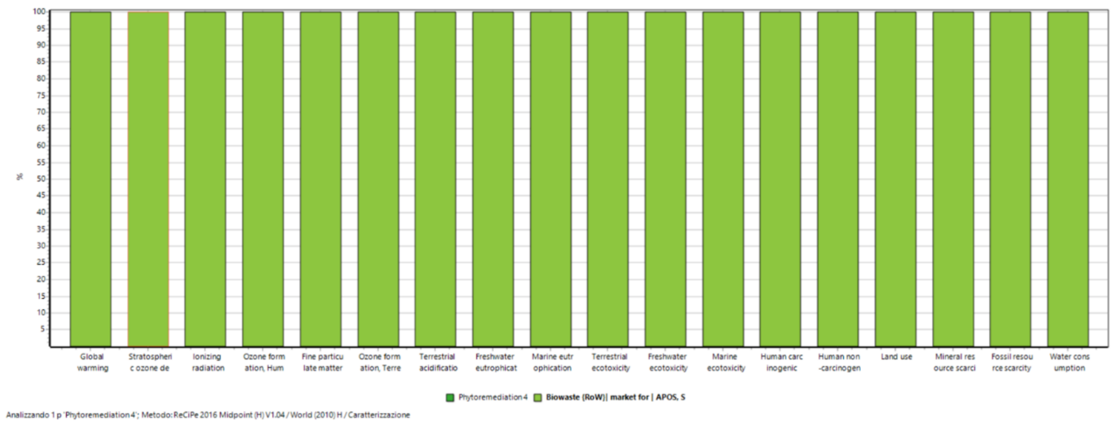


Figure 76. Graphical representation of characterization results through ReCiPe 2016 method for phytoremediation operation during landfill conversion (personal elaboration from SimaPro software).

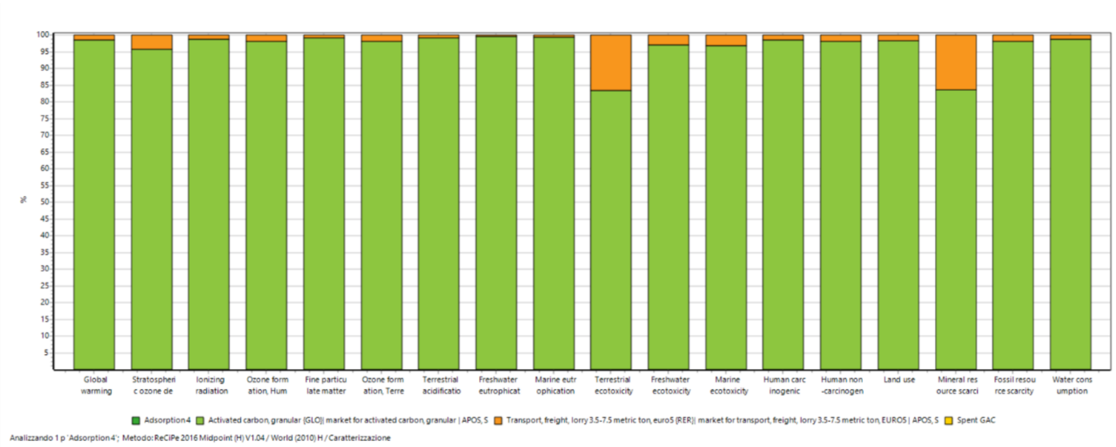


Figure 77. Graphical representation of characterization results through ReCiPe 2016 method for adsorption operation during landfill conversion (personal elaboration from SimaPro software).

From the normalisation results reported in Figure 78, similarly to the previous phases, leachate treatment impact mostly on freshwater and marine ecotoxicity, as well as human carcinogenic and non-carcinogenic toxicity. The greater contribution of adsorption is evident.

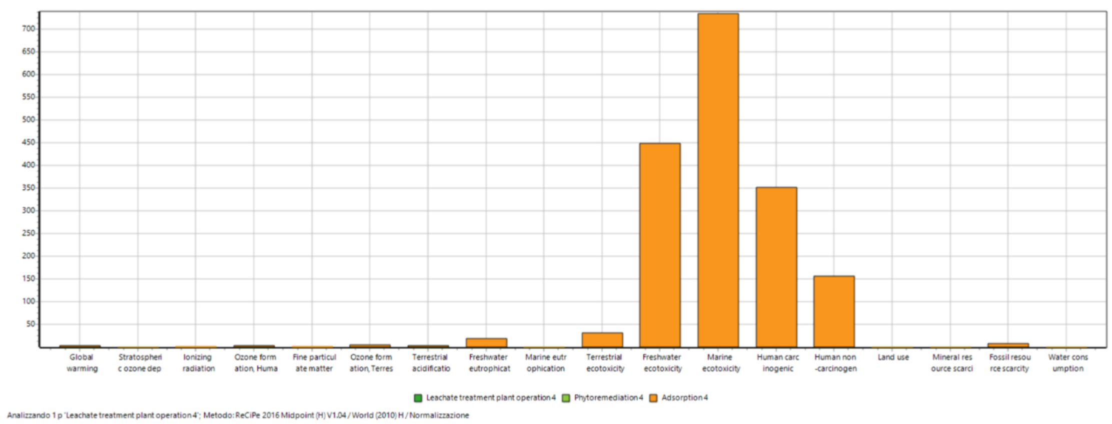


Figure 78. Graphical representation of normalization results through ReCiPe 2016 method for the leachate treatment plant operation during landfill conversion (personal elaboration from SimaPro software).

When it comes to the characterization of the landfill conversion phase (Figure 79), the leachate treatment plant affects almost all categories, with particular evidence on ionising radiation, fine PM formation, terrestrial acidification and fossil resource scarcity.

The leachate plays a role in eutrophication, ecotoxicity, human carcinogenic and non-carcinogenic toxicity categories.

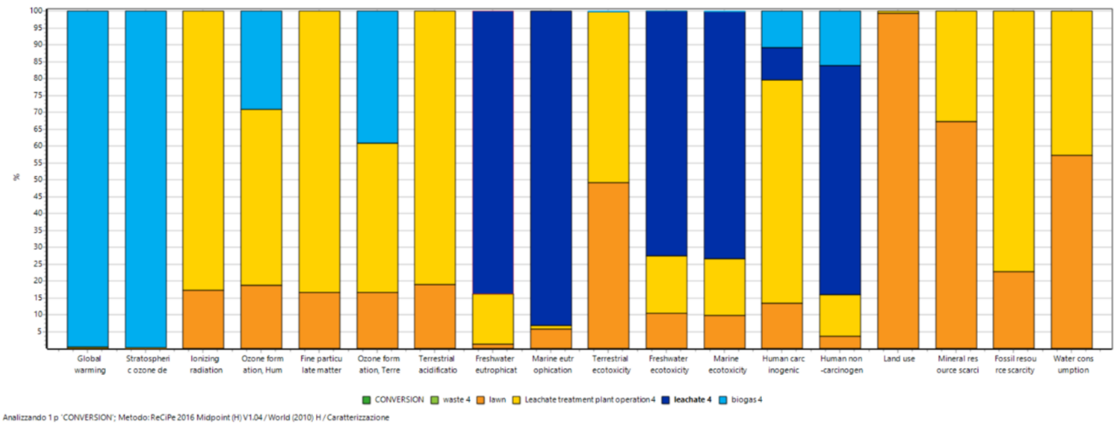


Figure 79. Graphical representation of characterization results through ReCiPe 2016 method for landfill conversion (personal elaboration from SimaPro software).

From the normalisation results reported in Figure 80, as with the closure phase, no noteworthy changes are observed with the introduction of leachate treatment. The greater contribution of leachate emissions among all the other landfill processes is evident.
As for the previous phases, the leachate and its treatment impact mostly on freshwater and marine ecotoxicity, as well as human carcinogenic and non-carcinogenic toxicity.

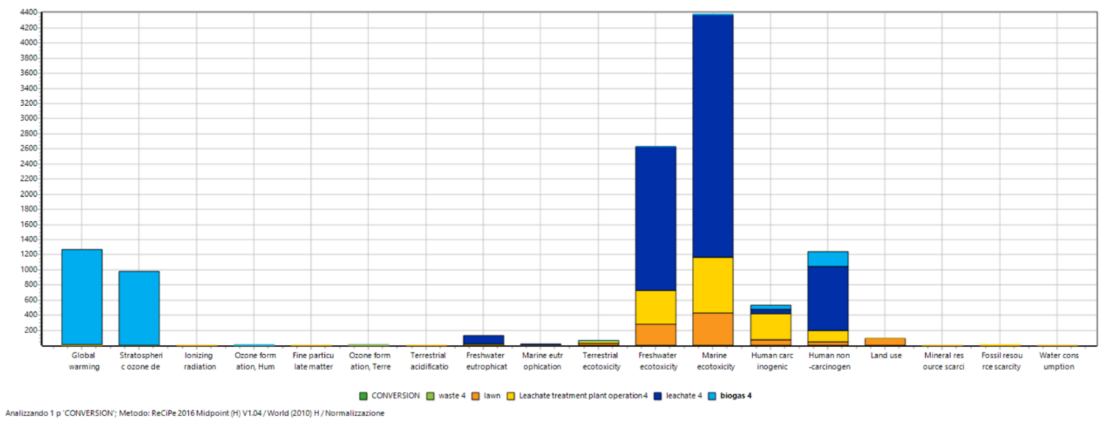


Figure 80. Graphical representation of normalization results through ReCiPe 2016 method for the landfill conversion (personal elaboration from SimaPro software).

5.2.13. Endpoint characterization and normalisation results

To complete the life cycle impact assessment, the characterization has been performed also at endpoint level. The results calculated by the SimaPro are grouped in 3 different categories: human health, ecosystem and resources (Figure 81).

Plant construction and plant operation during landfill filling and aftercare are the three most impacting phases for the endpoint impact categories.
The plant construction phase covers alone over 50% of the impact in all the cases; the intensive use of electricity for reverse osmosis operation appears of high concern.
The rest of the contribution is given by plant construction and plant operation in the aftercare; the great quantities of materials and waste by-products are responsible for that.

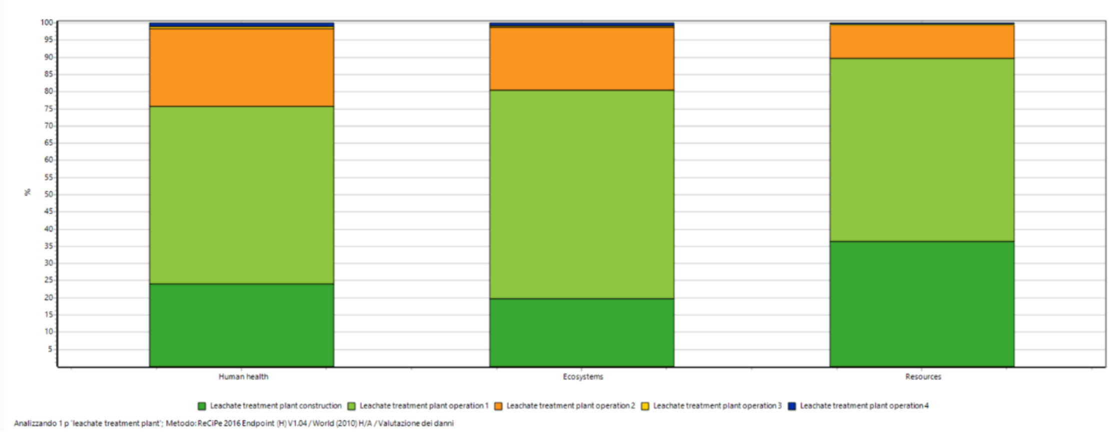


Figure 81. Endpoint results graphical representation (personal elaboration from SimaPro software).

From the normalisation of the results it can be seen that the most significant impact category is human health; ecosystems and resources categories have really a marginal role in determining the impacts of leachate treatment.

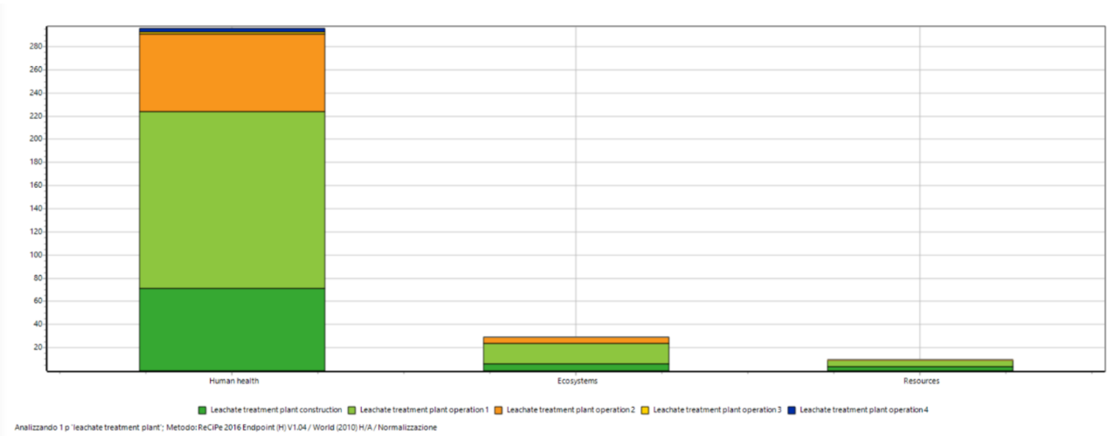


Figure 82. Endpoint normalization results graphical representation (personal elaboration from SimaPro software).

6. Discussion of results

The last phase of the LCA study is the interpretation of the results from the inventory analysis and the impact assessment; the results interpretation has to be done according to the goal and scope definition (ISO, 2020b).
In the next paragraphs few observations about the environmental impact of the studied leachate treatment plant are reported; moreover the ability of leachate treatment in improving the overall environmental performance of a landfill is discussed.
The hotspots of the system are identified and commented; some solutions to improve the environmental performance of the leachate treatment plant are also taken into consideration, as well as suggestions on how to run future studies starting from this project as a baseline scenario.

6.1. Interpretation of impact assessment results

Characterization and normalisation results demonstrate that three life phases of the leachate treatment plant contribute mostly in determining the total environmental impact, they are: plant construction, plant operation during landfill filling and plant operation during landfill aftercare.
While leachate treatment in the closure and conversion phases appears to have a negligible weight. Indeed, during the last phases of the landfill life, the volume of leachate produced is lower and of better quality thanks to the high degree of waste stabilization, and consequently the treatment units operation does not require an intensive exploitation of energy and materials.
The impact categories most affected by a leachate treatment plant are those relating to marine ecotoxicity and freshwater ecotoxicity, human carcinogenic and non carcinogenic toxicity, terrestrial ecotoxicity.
The greatest contribution associated to the plant operation during landfill filling can be explained by the reverse osmosis unit, which is used only in this phase and involves an intensive use of electricity from non-renewable resources.
The ideal would be to try to obtain an even better quality of leachate produced in landfills since the first decades of the operating phase, so as to be able to avoid reverse osmosis and rely only on phytoremediation and adsorption. This is made possible, for example, by a mechanical biological pre-treatment of the incoming waste, as is commonly carried

out in most cases according to the national regulations; while in this project, for sake of simplicity, it was assumed that incoming waste did not undergo any pre-treatment.

Phytoremediation impacts negligibly in all phases, except in the construction phase where, together with the solar evaporation pond, it is the source of the greatest impacts due to the large amount of gravel used as substrate to fill the basins and the relative transport.

Once again, the considerable impact deriving from the use of natural materials such as clay and gravel in the construction phases of the plants is highlighted; this suggests that it is possible to improve the performance of the system, at least as regards the leachate treatment plant, by replacing natural materials with recycled materials with the same properties.

As for adsorption, its impact is entirely related to the production of the granular activated carbon used as adsorbent. In fact, in this project the activated carbon considered was derived from fossil source; but this does not exclude the possibility of obtaining a better environmental performance by using a more ecofriendly carbon source such as nutshells, coconut shells, bamboo or even food waste.

Furthermore, it should be noted that the selection of data on ecoinvent followed a precautionary approach, in order to obtain conservative results that illustrate the worst possible case. But in the presence of more detailed information and calculations this analysis can be adjusted to model specific systems that adopt more advanced solutions.

Another modification that could be made is the expansion of the system to include more detailed disposal processes for the waste produced by the leachate treatment units (for example exhausted membranes, residual evaporation salts, spent carbon and residual phytomass) which consider the possibility of materials recycling.

At endpoint level, the leachate treatment plant impact contributes mostly to human health damage and it can be considered negligible for ecosystems and resources categories; but the uncertainty of this typology of results has to be taken into account.

Future studies can test the validity of the results obtained for the leachate treatment plant by varying the design parameters, technologies adopted and materials used.

Furthermore the model developed allowed to evaluate the contribution of leachate treatment on the entire life of the landfill and to understand to what extent a better purified leachate quality was able to improve the overall environmental performance of a semi aerobic landfill.

Despite the system modelled by Sciarrone (2020/2021) excluded the leachate treatment plant from the boundaries, and therefore the results obtained cannot be properly compared with those calculated in this project, we still want to observe some aspects that are a consequence of the changes made on the original model.

If we consider the normalisation relating to the entire life cycle of the landfill (Figure 83), it can be noted that, with the introduction of the leachate treatment plant, there is a clear reduction in the normalisation values assumed by the freshwater and marine ecotoxicity and human non-carcinogenic toxicity impact categories (they are practically halved compared to the original model where a worse leachate quality for discharge was considered). This effect is due to the drastic reduction of the contribution of the aftercare phase on the aforementioned impact categories, which are strictly linked to the quality of the leachate discharged into surface waters.

In the aftercare, the volume of leachate produced is considerable, therefore the quantity of pollutants abated by the treatment system is particularly high in this phase and this allows to greatly reduce the emissions into the water.

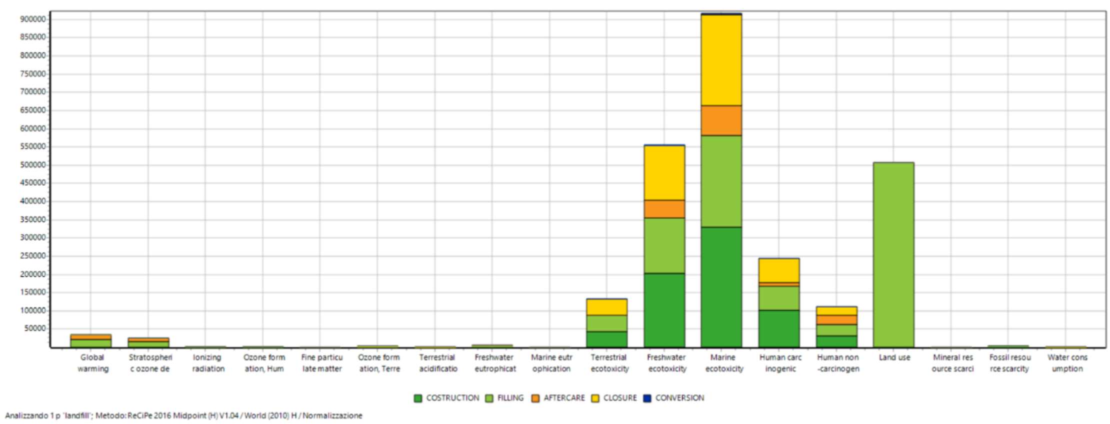


Figure 83. Graphical representation of normalisation results through ReCiPe 2016 method for the entire landfill life (personal elaboration from SimaPro software).

Specifically in this project, the improvement in the quality of the leachate in all phases is reflected in a reduction respectively of 83% and 94% of the BOD and COD parameters compared to the original model, in which the regulatory threshold limits were assumed (Legislative Decree 152/2006). Table 74 shows the quantities of pollutants released into surface waters obtained with the application of an advanced leachate treatment (and below the threshold limits), and those equal to the threshold limits considered by Sciarrone (Sciarrone, 2020/2021).

Table 74. Quantities of pollutants released into surface waters obtained with the application of an advanced leachate treatment (related to this project), and pollutant quantities in compliance with the threshold limits considered by Sciarrone (Sciarrone, 2020/2021) (Personal elaboration).

	FILLING (kg)		AFTERCARE (kg)		CLOSURE (kg)		CONVERSION (kg)	
	Sciarrone, 2020/2021	Advanced Treatment applied	Sciarrone, 2020/2021	Advanced Treatment applied	Sciarrone, 2020/2021	Advanced Treatment applied	Sciarrone, 2020/2021	Advanced Treatment applied
bod	7263	1271	17405	3046	435	76	848	148
cod	29054	1816	69618	4351	1740	109	3394	212
ammonia	2724	2724	6527	6527	163	163	318	318
chloride	217904	9079	522137	522137	13053	13053	20788	20788
sodium	127	127	305	305	8	8	15	15
phospate	1816	51	4351	4351	109	109	212	212
toluene	29	0.5	70	70	0.2	0.2	0.4	0.4
bromine	91	1.8	131	131	2.2	2.2	3.4	3.4
cadmium	2.2	0.04	4.4	4.4	0.1	0.1	0.1	0.1
arsenic	5.5	0.2	11	11	0.2	0.2	0.4	0.4
zinc	91	18	218	218	5.4	5.4	11	11

As regards the other phases, the effect of the better quality of the leachate is not so evident. In the case of the operating phase, in which a large production of leachate also occurs, the reduction in emissions is counterbalanced by the impact deriving from the operation of the treatment plant, in particular by the reverse osmosis unit (which is used only in this phase).

In the closure and conversion phases, although reverse osmosis is not envisaged as in the aftercare, the limited quantity of leachate produced does not make any reduction in impacts visible.

In any case, from normalisation it is clear that the most significant impact categories in a landfill context are those affected by the quality of the leachate (i.e. freshwater and marine ecotoxicity), and by improving the quality of the leachate at the outlet it is possible to reduce the impact of a landfill. It is therefore useful to install a passive in-situ leachate treatment because its construction, installation and operation contributes little compared to other processes strictly related to the construction and management of the landfill, and at the same time it guarantees a better environmental performance of the entire landfill life.

6.2. Results comparison with literature

It is not possible to make a direct comparison with the LCA studies in the literature due to the different goals and assumptions.

The LCA methodology is typically applied to analyse leachate treatment plants as single systems, i.e. separately from the life cycle of a landfill.

Often in this context, LCAs have the objective of evaluating which is the most advantageous technology between in-situ and ex-situ leachate treatment plants, and of identifying the hotspots of the technologies considered.

Furthermore, sometimes the production and transport of the materials/infrastructures necessary for the functioning of the plants are not included in the system boundaries, limiting to the operation of the same and making the assessment incomplete.

In the article of Di Maria et al. (2017), where on-site advanced processes based on reverse osmosis and evaporation were compared to conventional off-site co-treatment with civil sewage in wastewater treatment plant, the impact assessment showed that the impact categories most affected by the different options were human toxicity, both non-cancer and cancer, together with freshwater ecotoxicity. This shows that it is reasonable to consider leachate treatment as responsible for the impact of these categories.

Turner et al. (2016) evaluates the potential impacts of leachate emissions over a 10000 year time horizon by considering the loss of active environmental control measures during the aftercare period of landfill management. In this case the processes such as infrastructure, energy, and material use, waste transportation, landfill gas generation, collection, and utilisation were excluded from the boundaries. But also this study, in accordance with the present thesis, highlights that the quality of discharged treatment effluents can account for a substantial proportion of the potential impacts of landfilling.

7. Conclusions

Semi aerobic landfill is a technology introduced with the aim of accelerating the stabilisation of waste disposed of in landfills through a simple and cost-effective site configuration.

In this study, the LCA methodology was applied to evaluate the environmental performance of a leachate treatment plant used to purify the leachate produced by semi aerobic landfill in northern Italy.

A gap emerged from the literature regarding LCAs applied to landfill and leachate treatment sectors; this study aims to provide useful knowledge to the scientific community.

The landfill under study was properly designed and analysed through LCA in the previous studies of Lazzarin (Lazzarin, 2015/2016) and Sciarrone (Sciarrone 2020/2021).

Lazzarin and Sciarrone examined the entire life cycle of the landfill, considering a time span of 100 years divided into five phases; the goal was to evaluate the contribution of each temporal phase to the total impact generated by the landfill.

Many aspects, which are typically neglected in literature while they could have a significant impact, in the aforementioned studies instead became part of the modelled system: landfill construction materials and their transportation as well as infrastructures realisation processes were included within the boundaries.

In Sciarrone (2020/2021) the biogas was considered partially oxidised by the top cover and released into the air, while the leachate was considered treated in such a way as to release into the water pollutants concentrations below the limits established by the legislative decree 152/2006; however the impact of the treatment was not considered.

This project introduces leachate treatment as a useful tool to improve the environmental performance of a semi aerobic landfill. The treatment plant is active during the entire life of the landfill to treat the leachate produced during the different phases. The plant has been dimensioned in detail and consist of a combination of reverse osmosis, solar evaporation, phytoremediation and adsorption with activated carbon.

The LCA took into account the materials production and their transport, construction and installation of the treatment systems, as well as their operation and maintenance during all stages of the landfill life.

The LCA was performed according to the ISO 14040 and 14044 standards; the software SimaPro was used and the impacts were assessed using the ReCiPe 2016 method at midpoint level.

The goal of the study was to evaluate the impacts due to the entire life cycle of the leachate treatment plant, with a focus on the contribution of each operational phase. Moreover, from the model implemented it was possible to analyse the role of the leachate treatment units with respect to the total impact of the landfill and understand to what extent a better quality of the purified leachate was capable to improve the overall environmental performance of the landfill.

The goal was achieved and the results show that plant construction, plant operation during landfill filling and aftercare are the most impactful phases due to the large amount of materials used to build and operate the leachate treatment units.

The better quality and lower amount of the produced leachate during landfill closure and conversion makes leachate treatment in these two phases not really demanding in natural resources and energy, providing for a negligible contribution on the total impact.

The most threatened impact categories are marine and freshwater ecotoxicity, human carcinogenic and non carcinogenic toxicity and terrestrial ecotoxicity.

From the point of view of plant construction, the phytoremediation basins and the evaporation pond require the greatest amount of materials. While, when it comes to the treatment plant operation, reverse osmosis is more impacting than phytoremediation and adsorption because it requires the use of electricity.

The contribution of phytoremediation operation is almost completely associated to the residual phytomass produced by mowing, which is considered as biowaste to be treated.

Instead, the impact due to the adsorption operation derives mainly from the production of the activated carbon used as adsorbent.

Moreover, the model developed allowed to evaluate the contribution of leachate treatment on the entire life of the landfill.

From the analysis it can be confirmed that with the introduction of the leachate treatment plant it is possible to reduce the impacts of a landfill thanks to the excellent quality of the leachate released into surface waters, especially as regards the impact categories related to freshwater and marine ecotoxicity and human non carcinogenic toxicity.

Specifically, leachate treatment brings a net reduction of the contribution of the aftercare phase on the total landfill impact. If generally the better quality of the treated leachate is counterbalanced by the impact of the operation of the treatment plants, this does not occur in the aftercare phase. In fact, in the aftercare the volume of leachate produced is enormous and the reduction of a consistent quantity of pollutants is more evident; moreover, the absence of the reverse osmosis unit reduces the impacts related to the operation of the treatment plant.

As Sciarrone already observed (Sciarrone, 2020/2021), this study shows that the legal concentration limits for water discharge are not low enough to prevent damage to the environment. Improving the quality of the leachate, well below these thresholds, guarantees a better environmental performance of the landfill.

The limits of this study are mostly related to the assumptions made, the data chosen and the LCA methodology limits.

The performance of the leachate treatment units has been assumed from literature, but in reality it could be different.

Another limitation is the selection of data on the ecoinvent database; due to the lack of some specific materials it was necessary to select other ones with similar quality, but always trying to consider the worst case.

Future studies could focus on the use of more ecofriendly materials to be included in the model instead of the classic gravel used as a substrate for phytoremediation or fossil-based activated carbon used as adsorbent.

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