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Environmental Performance of Semi-Aerobic Landfill by Means of Life Cycle Assessment Modeling

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Abstract: The potential impacts and the environmental performance of the semi-aerobic landfill technology were assessed through the Life Cycle Assessment (LCA) methodology. Project data that referred to a hypothetical Italian plant design were used and ISO 14040/14044 standards were applied. All the life cycle phases were considered, from landfill construction to filling, aftercare, closure and conversion for future use. All the landfill processes and the inflow of materials, energy and rainwater, and the outflow of biogas and leachate, were included in the system boundaries. The results show that the overall environmental impacts associated to semi-aerobic landfill are primarily due to the filling and aftercare phases, but the impacts related to construction and closure phases are not negligible. The contribution analysis underlines the processes with major responsibility within the environmental profile, while the normalization of results demonstrates what are the environmental categories on which the landfill impacts fall most. Important lessons emerging from this research can support practitioners and scientists in optimizing semi-aerobic landfill design and management.

Keywords: semi-aerobic landfill; life cycle assessment; impact assessment results; ISO 14040-14044

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1. Introduction

The continuous increase of waste production causes concerns about the sustainability of Solid Waste Management (SWM) systems, that need to be upgraded to comply with circular economy EU directives [1]. In developing countries waste is mostly disposed of in open dumps [2]. In the European Union, waste recycling has reached 30% and landfilling has dropped to 25% of the produced waste; most of landfills in operation are sanitary landfills, but issues related to closed landfills have to be addressed [3]. Controlled landfills are currently the most common destination for waste from remediation of contaminated sites [4]. The modern landfill can play a fundamental role in SWM strategies, serving as a geological repository to close the material cycle. Actually, waste stabilization in the landfill body should be enhanced in order to reach a site-specific Final Storage Quality, that should prevent significant interactions with the surrounding environment. Further long lasting and very slow processes should produce the so-called Rock Quality in the long term, making the landfill a potential geological sink [5]. However, current technology keeps landfills far from reaching this goal: climate-relevant emissions from the waste sector mainly consist of methane (CH_4) and carbon dioxide (CO_2) emissions from landfills [6,7]; aftercare measures are expected to be necessary for a very long time after landfill closure and the risk of uncontrolled leachate and gas emissions and the related environmental impacts have to be considered [8–10]. The improvement of landfill technology has been recognized as among the main recommended actions towards the sustainability of the waste management sector [6,11]. Innovative options for landfill design and management, with the addition of passive and active features to better control landfill processes and emissions and to accelerate waste stabilization have been proposed [12,13]. Among those, the semi-aerobic landfill technology is the most promising technology applicable in several countries in different conditions [14]. Although some studies related the performance of semi-aerobic landfill are available, comprehensive assessment of the environmental impacts associated with this type of landfill is missing.

Life Cycle Assessment (LCA) is the scientific methodology to assess the environmental impacts of products and systems throughout their entire life cycle. Using the LCA methodology, a comprehensive quantification of environmental impacts associated to a product or technology is obtained with a holistic approach, including raw materials extraction, materials processing and transportation, manufacture or construction, use and dismission [15]. LCA of waste management systems has been performed by numerous authors worldwide and it proved suitable for the assessment of different options [16,17]. The LCA methodology is a helpful tool to support environmentally sound decision-making and it is often used in waste management to weigh the benefits and drawbacks of management options for particular situations [18,19]. Local conditions have a dual effect: a high influence on the impacts and a loss of generalization of the preferable solution [20–22]. LCA can be used to calculate the total impacts of the landfill, including all the impacts from the construction, through the filling phase, to its conversion for a future use [23]. In very few cases, landfills designed with non-conventional technologies are considered in scientific articles dealing with LCA. Among these, the impacts of semi-aerobic landfills have been calculated and compared with the impacts of other landfill technologies in one article only [10]; where total impacts only were considered, with no reference to different phases of landfill life.

From this helicopter overview, several gaps in the literature experience can be underlined:

- Even if emerging technologies are studied to reduce the environmental impacts of leachate and methane emission due to the landfill, few studies quantify the environmental performance associated to semi-aerobic landfill.
- Even if the life cycle approach is commonly recommended to obtain comprehensive evaluation of environmental impacts associated to waste treatment, several LCA applied to the landfill technology consider the filling and closure phase only, while instead LCA studies including landfill construction, closure and conversion are missing.
- Even if the LCA is applicable to every type of technology and recommended to support the eco-design, LCA studies focused on the semi-aerobic landfill are missing.

To fill the lack of evidence in the literature about the overall environmental performances of semi-aerobic landfill, the research intends to quantify the impacts associated to this technology through the “cradle-to-grave” perspective, from construction to final conversion, with the aim of understanding what are the impact contributions associated with each phase of the landfill life cycle. To do this, an LCA study was conducted to quantify the impacts of a hypothetical Italian semi-aerobic landfill designed to treat residual unsorted waste. Every phase of the landfill life cycle has been included in the analysis: construction, filling, aftercare, closure and conversion. Project data and information were used, which include calculations of input and output flows on energy, materials and emissions related to each life cycle phase.

The paper is structured as follows: Section 2 summarizes information on the semi-aerobic landfill and reviews the literature inherent to the application of LCA to landfills; Section 3 presents the methodological choices for the LCA case study, including goal and scope, landfill life model, inventory data assumptions and impact assessment methods and tools used; Section 4 reports the life cycle impact assessment results, in which the contribution of each life cycle phase of landfill construction and management is underlined; Section 5 discusses the results; Section 6 concludes with comments and limits on the LCA study and the value for practitioners and scientists.

2. Background

2.1. Semi-Aerobic Landfill

The concept of a semi-aerobic landfill was introduced in Japan in the 1970s. The co-existence of aerobic and anaerobic zones in the landfill body enables a faster waste stabilization, lower methane production and improved leachate quality [18]. The natural air flow is driven inside the landfill by the difference of temperature, through a network of large pipes at the bottom of the landfill that at the same time collect the leachate by gravity; this design avoids the use of pumps for the leachate collection. The ducts are designed to promote air circulation and to only be partially occupied by the leachate to have enough air flow from the outside. The pipes are attached to the gas vents inside the landfill body to better aerate the waste inside by allowing the air to reach every part of the landfill body.

In the semi-aerobic landfill, aerobic and anaerobic processes are present so both CO_2 and methane are produced although the percentage of methane is lower than in an anaerobic landfill [14,24]. To evaluate the proportion of anaerobic and aerobic areas in the landfill, the methane correction factor (MCF) is used to represent the percentages of anaerobic degradation occurring in the landfill [25]. The MCF is important when calculating the environmental impacts since, depending on its value, different percentages of methane are produced. When calculating the global warming potential impact, the impacts of methane are over 28 times higher compared to CO_2 in a 100-year horizon [26]; hence, if the same volume of biogas released has a lower percentage of methane, and, therefore, a higher one of CO_2, the impact would have a lower global warming potential. According to the IPCC [27], the MCF for the semi-aerobic landfill is equal to 0.5; hence, half of the waste is degraded in aerobic condition and half in anaerobic condition [28]. Therefore, methane production under semi-aerobic conditions is assumed to be half the amount expected under anaerobic conditions.

Leachate quality also is affected by semi-aerobic conditions. Based on lab- and full-scale experiments, both organic substances and ammonia concentrations decrease faster than in traditional landfill [29,30]. Lower pollutant concentrations allow the treatment of the leachate to be less intensive and reach the legal limits faster.

2.2. Landfills in LCA

The LCA of SWM systems, also called Waste LCA, has gained more importance in recent years [31]. The LCA methodology can be a valuable tool to understand the impacts related to the waste treatment technologies in order to apply more sustainable solutions in SWM [18]. In this type of assessment, the system boundaries are strictly defined to only consider the end-of-life stage of a product excluding the rest of its life. From 2000 and 2021, only 25 scientific papers were found assessing landfill life through the LCA methodology; most of the papers were published in the last 10 years and in developed countries. The LCA of landfills is more challenging than other waste treatment technologies due to the long-term emissions [32]; in the literature, the problem is often tackled by assuming that the emissions stop after 100 years [31]. The parameters that have the greatest influences when calculating the landfill emissions are the waste composition, landfill management and climatic conditions [33–35]. These parameters should be considered when calculating biogas and leachate production; their influence is highlighted by sensitivity analyses [35]. Despite this, waste composition influences the emissions, applying the zero-burden assumption that the waste entering the system has no environmental impact already associated with it [20]. The waste collection and transportation are rarely present in the literature, but the diesel consumption due to the waste transportation can have a great effect if long distances are the assumed form of the locations of waste production and its treatment [23,36]. The types of landfills analyzed in the literature are the open dump, the anaerobic, hybrid and semi-aerobic landfill; the most analyzed is the traditional landfill. As expected, the evidence proves that the open dumps have the worst environmental performance when compared with other technologies, due to the uncontrolled emissions [10].

According to several authors, biogas produced from traditional landfills has a relevant impact on multiple categories including global warming, human toxicity and photo chemical ozone [33,37]. However, in landfills with significant residual biogas production potential, extraction and energy recovery are almost always included in LCA studies. Leachate treatment is frequently neglected; emissions were estimated assuming that leachate was treated, although the emissions of the treatment itself were not included. The construction phase of the landfill is not considered in many LCA studies, but further research should be carried out, as its contribution to total landfill impacts can be significant [23].

Different papers analyzing the hybrid landfill have proven that additional active and passive measures to increase the waste stabilization reduce the overall impact of the landfill. The semi-aerobic landfill, as analyzed by Manfredi and Christensen [10], has a lower impact compared to the traditional landfill. While this technology appears to have benefits over the other types, only one paper was found that analyzes its impacts and compares them to the impacts of other landfill technologies; no LCA studies analyzing the semi-aerobic landfill on its own seem to be available.

3. Materials and Methods

The working conditions and emissions of semi-aerobic landfills depend on different parameters, such as weather conditions, waste compositions and local legislation, among others. To analyze the environmental impacts of this technology, a hypothetical semi-aerobic landfill located in northern Italy was designed according to the Fukuoka method [14]; Italian legislation and guidelines for environmental protection were also considered [38]. The annual average climatic, geological and morphological characteristics of the chosen site were taken into consideration for the design of the new landfill; the site characteristics were chosen to be representative of the entire northern Italy. The decision to consider a specific case study was taken in order to conduct an LCA study with primary data and obtain more specific and reliable result.

3.1. Goal and Scope of LCA Study

This study was conducted according to the LCA standards: ISO14040 and ISO14044 [39,40] and was performed on the SimaPro software. The goal of the study is the evaluation of the potential impacts of a semi-aerobic landfill on the environment; the results include the principal contribution of the activities, materials and substances to the environmental impacts. The novelty of this study lies in making the assessment considering all life cycle phases (construction, filling, closure, aftercare and conversion); the expected results are expressed as the contribution of each phase on the total impact. This approach has been recently used for the assessment of a landfill in China [23]; however, no case studies are reported for the comprehensive assessment of the semi-aerobic landfill technology. The functional unit is the quantified performance of a product system [39]; for this study, it was defined as "landfilling of 1 ton of wet unsorted waste in a semi-aerobic landfill with a mean depth of 10 m for 100 years".

The lifetime of the landfill was considered to be 100 years to study the long-term emissions as performed in the literature [31]. The landfill life was subdivided into construction, operation lasting 20 years, aftercare lasting 40 years, closure lasting 1 year and conversion lasting 39 years. The system boundaries (Figure 1) include all the landfill processes involved and take into consideration the inflow of materials, energy and rainwater and the outflow of biogas and leachate. According to the zero-burden assumption, the waste is not associated with any environmental impact entering the landfill. In the design, biogas was considered to be directly released in the atmosphere, while leachate was assumed to be treated to reach concentrations below or equal to Italian legislation limits. As suggested by Ouedraogo et al. [13], in which the removal efficiencies of the leachate treatment were assumed to calculate the leachate emissions impact but disregard the impact of the treatment itself, the impact related to leachate treatment processes was neglected.

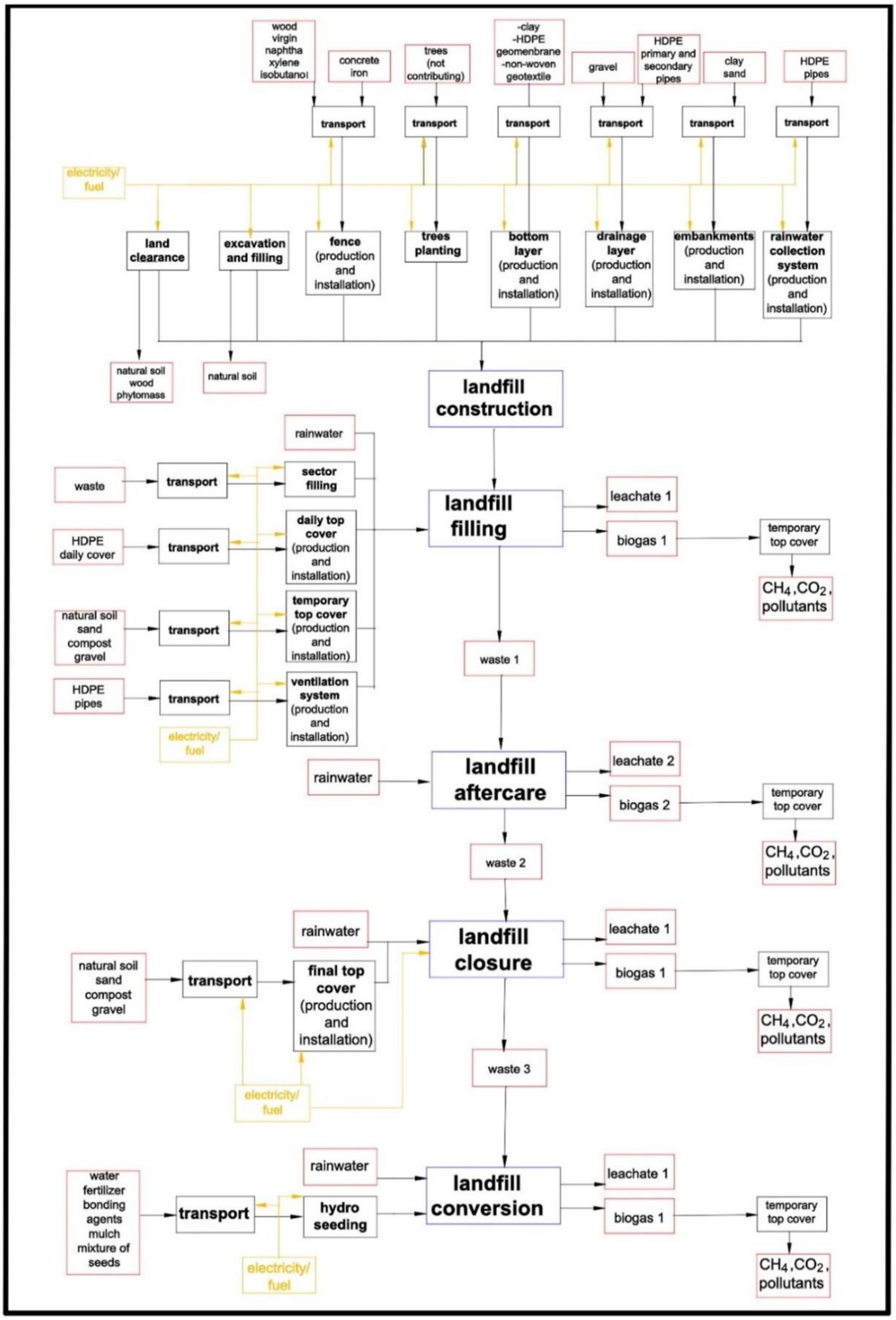

Figure 1. Landfill life model representation related to the boundaries of the life cycle study.

3.2. Inventory Analysis

The life cycle inventory phase is an iterative procedure that involves the collection of data and the calculations to quantify the system's input/output [39]. Primary data used for the study are derived from the landfill design and dimensioning process. Secondary data were selected from the Ecoinvent 3 database; due to the absence of information about the production's location, it was decided to select market processes considering an average global impact. For this project, only residual waste is considered to be disposed in the landfill, without being treated, while separately collected fractions are sent to a treatment or recovery facility; the composition of the waste disposed (Table 1) was assumed for the estimation of the landfill emissions.

Table 1. Waste composition.

Fraction	%
Food waste	10
Green waste	5.2
Paper	15.3
Cardboard	12
Wood	5.6
Textiles	5.6
Plastic	26.1
Glass and inert	5.6
Metals	2.7
Napkin	10.5
Undersieve 20 mm	1.4

The landfill was designed to receive about 11,000 tons per year of waste, with a density of 0.8 t/m^3, for 20 years, until it reaches a mean height of 10 m and a total volume of 275,000 m^3. The biogas begins to be produced and released during the filling phase. Based on the assumed biodegradability of each fraction, waste is divided into three groups: highly, moderately and slowly biodegradable. The maximum yield is calculated for each group through a first order kinetic model [25]. The waste is assumed to be progressively disposed at a regular pace over the 20 years; the volume of the waste increase linearly during the filling phase and then constantly in the remaining years. The annual biogas production is estimated, and the cumulative amount is calculated for each phase; the biogas is calculated for the individual quantity of waste disposed each year along the remaining landfill life and then added together. Each ton of waste was estimated to produce about 173 Nm^3 over the 100-year life of the landfill. The MCF is assumed equal to 0.5; therefore, the methane produced corresponds to 30% of the total volume, leaving the remaining 70% of CO_2 [27]; meanwhile the concentrations of trace gases, regarding the biogas composition, were taken from Manfredi and Christensen [10]. The biogas cannot be used for energy recovery due to the low percentage of methane, which is further decreased by its oxidation through the bio-cover installed; a value of 0.1 for the oxidation factor can be assumed for a covered, well-managed landfill [27]. Apart from the filling phase which has no cover and where all the biogas is released into the atmosphere, 10% of the methane produced in the remaining phases is considered to be oxidized and transformed into CO_2. The total quantities are reported in Table 2.

The leachate production was calculated considering the location's annual climate conditions and rainfall, the presence of surface cover and the size of the area progressively occupied as the waste was disposed [41] and is reported in Table 3. For the filling phase, leachate production was calculated assuming that no cover was installed. To estimate the leachate production, the monthly evaporation that takes place in the absence of the top cover and of vegetation, was calculated and subtracted from the average rainfall quantity. In the following phases, due to the installed cover, less rainwater leachates in the landfill body; the monthly runoff and the evapotranspiration were estimated to calculate the infiltrated rainwater. For the conversion phase, it was considered that only 5% of the rainwater of the previous phases would infiltrate after the final impermeable top cover was installed.

Table 2. Biogas quantity, pollutants concentrations and quantity.

Phase	Filling		Aftercare		Closure		Conversion	
Years	20		40		1		39	
Production [m^3]	21,661,105		14,800,681		84,589		1,466,680	
CH_4 [%]	30		30		30		30	
CO_2 [%]	70		70		70		70	
CH_4 [m^3]	6,498,332		4,440,204		25,377		465,381	
CO_2 [m^3]	15,162,774		10,360,477		59,212		1,085,888	
Oxidized CH_4 [%]	0		10		10		10	
Non oxidized CH_4 [%]	100		90		90		90	
Non oxidized CH_4 [m^3]	6,498,332		3,996,184		22,839		396,004	
Produced CO_2 [m^3]	0		444,020		2538		44,000	
Tot CH_4 [kg]	3,600,076		2,213,886		12,653		219,386	
Tot CO_2 [kg]	23,199,044		16,530,880		94,477		1,638,135	
	mg/m^3	kg	mg/m^3	kg	mg/m^3	kg	mg/m^3	kg
Benzene	7	152	7	104	7	0.59	7	10
CFC 11	10	217	10	148	10	0.85	10	15
CFC12	50	1083	50	740	50	4.23	50	73
Dichloromethane	50	1083	50	740	50	4.23	50	73
HCFC 21	12	260	12	178	12	1.02	12	18
HCFC 22	13	282	13	192	13	1.1	13	19
Hydrogen chloride	6	130	6	89	6	0.51	6	9
Hydrogen fluoride	2	43	2	30	2	0.17	2	3
Hydrogen sulphide	0.07	2	0.1	1	0.1	0.01	0.1	0.147
Propyl benzene	50	1083	50	740	50	4.23	50	73
Tetrachloroethene	27	585	27	400	27	2.28	27	40
Toluene	160	3466	160	2368	160	13.53	160	235
Trichloroethylene	16	347	16	237	16	1.35	16	23
Vinyl chloride	21	455	5	74	0	0	0	0
VOCs	230	4982	230	3404	230	19.46	230	337
Xylenes	60	1300	60	888	60	5.08	60	88

Table 3. Leachate concentrations and quantity.

Phase	Filling		Aftercare		Closure		Conversion	
Years	20		40		1		39	
Leachate production [m^3]	181,586.7		435,113.9		10,877.8		21,211.8	
	mg/L	kg	mg/L	kg	mg/L	kg	mg/L	kg
BOD	40	7263.47	40	17,404.56	40	435.11	40	848.47
BOD	160	29,053.88	160	69,618.23	160	1740.46	160	3393.89
Ammonia	15	2723.80	15	6526.71	15	163.17	15	318.18
Chloride	1200	217,904.09	1200	522,136.70	1200	13,053.42	980	20,787.57
Sodium	0.7	127.11	0.7	304.58	0.7	7.61	0.7	14.85
Phosphate	10	1815.87	10	4351.14	10	108.78	10	212.12
Toluene	0.16	29.05	0.16	69.62	0.02	0.22	0.02	0.42
Bromine	0.5	90.79	0.3	130.53	0.2	2.18	0.16	3.39
Cadmium	0.012	2.18	0.01	4.35	0.008	0.09	0.006	0.13
Arsenic	0.03	5.45	0.025	10.88	0.02	0.22	0.02	0.42
Zinc	0.5	90.79	0.5	217.56	0.5	5.44	0.5	10.61

The monthly leachate quantities were then added to obtain the yearly leachate production for each phase; they were then multiplied for the phase duration to obtain the total quantity. Leachate quality was estimated assuming mean concentrations reported in Manfredi and Christensen [10] for each phase of landfill life. Since the leachate is treated before being released, the concentrations used in the LCA are set equal to the Italian legislation limit unless the mean values calculated from Manfredi and Christensen [8] were lower (Table 3). The input data and the calculation are reported in the following paragraphs.

3.2.1. Construction

The first phase of the landfill life is the construction; it is an assembly of eight different processes needed to clear and prepare the area and to build the structures needed in the following phases.

The subassemblies included in this phase are land clearance, excavation and filling, fence production and installation, tree planting, bottom layer production and installation, drainage layer production and installation, embankment production and installation, and rainwater collection system production and installation. The landfill occupies an area of 27,500 m^2 but an area of 32,000 m^2 was assumed to be cleared from the vegetation and of the first 30 cm of topsoil; the bottom area was then prepared and levelled by a skid-steer loader. The soil volume removed from the excavation is estimated by multiplying the area for the height of the topsoil, and it is assumed to stay in the location and to be used for the filling of other areas. A 2 m high fence, made of an iron grid with treated wooden poles every 2.5 m, was constructed, and 120 maple trees were planted around the perimeter of the landfill to delimit the landfill perimeter and prevent unauthorized access [38]; the impact of the tree production was neglected [42] and only the work of the hydraulic digger to dig 3 m^3 holes in the ground to plant the trees was considered.

The landfill bottom liner of the landfill, with the purpose of containing the leachate, was designed according to the Italian regulations, including the natural geological barrier and an additional clay barrier with the permeability lower than 10^{-9} m/s: the HDPE geomembrane and the non-woven textile layer [38]. The clay layer is assumed to be placed by a skid steer loader and compacted by a padfoot drum compactor while the geomembrane and geotextiles are laid manually with the help of a welding machine.

The drainage layer, which plays a fundamental role in making semi-aerobic conditions possible, was designed according to Matsufuji et al. [14]. It is composed of slotted HPDE primary and secondary pipes laid on the bottom of the landfill and covered by a layer of gravel with a permeability higher than 10^{-2} m/s. The pipes and the gravel layer are laid by a skid-steer loader.

According to the Italian regulations, the project must include the management of the rainwater; this is performed by a net of HDPE pipes designed with a return period of 10 years [38]. The pipes are to be placed with a hydraulic digger.

The soil used for the embankment construction is assumed to be composed of sand and clay, about 67% and 33% in mass, respectively; the soil needed is spread and compacted by the skid-steer loader.

For each subassembly, the entries values for the materials, the energy used for the machinery and the activities are summarized in Table 4; the transportation of all the material was included and a distance value of 100 km was assumed for each material.

Table 4. Materials and energy/fuel used in the landfill life.

Phase	Subassembly	Process	Material/Energy	Quantity	Unit
Construction	Land clearance	Topsoil removal	Skid-steer loader	9600	m^3
			Hydraulic digger	26.1	m^3
			Chainsaw	6400	min
	Excavation and filling	Soil leveling	Skid-steer loader	12,291	m^3
	Fence realization	Pole material	Fir wood	1.4	ton
		Iron grid	Iron	8.2	kg
		Excavation	Hydraulic digger	9.2	m^3
		Installation of poles	Concrete	9.2	m^3
		Transport	Lorry euro5	2208.8	tkm

Table 4. *Cont.*

Phase	Subassembly	Process	Material/Energy	Quantity	Unit
	Tree planting	Excavation	Hydraulic digger	360	m^3
		Transport	Lorry	264	tkm
	Bottom layer	Clay layer	Clay	66,806	ton
		Geotextile	Non-woven polyester	34.8	ton
		Geomembrane	HDPE	72.5	ton
		Clay placing	Skid-steer loader	31,812	m^3
			Diesel	6487.5	kWh
			Diesel	70	kWh
		Transport	Lorry euro5	6,680,600	tkm
		Transport	Light commercial vehicle	11,090	tkm
	Drainage layer		Gravel	22,688	ton
		Pipes	HDPE	122	ton
			Skid-steer loader	15,125	m^3
			Skid-steer loader	490	m^3
		Transport	Lorry euro5	2,268,800	tkm
		Transport	Light commercial vehicle	12,200	tkm
	Embankment		Clay	2527	ton
			Sand	5055	ton
			Skid-steer loader	4460	m^3
		Transport	Lorry euro5	758,200	tkm
	Rainfall water collection	Pipes	HDPE	76	ton
		Pipes placing	Hydraulic digger	354	m^3
		Transport	Light commercial vehicle	7600	tkm
Filling	Waste 1	Transport	Lorry euro5	4,488,000	tkm
		Waste placing	Skid-steer loader	275,000	m^3
	Daily cover		PE-HD	3.3	ton
			PE-LD	3.3	ton
	Temporary cover		Gravel	22,688	ton
			Sand	6050	ton
			Compost	9075	ton
			Natural soil	52,938	ton
			Skid-steer loader	60,500	m^3
		Transport	Lorry euro5	9,075,100	tkm
	Vertical ventilation system	Pipes	HDPE	13.57664	ton
			Gravel	242.5	ton
			Skid-steer loader	161.6	m^3
		Transport	Lorry euro5	242,500	tkm
		Transport	Light commercial vehicle		tkm
Closure	Final top cover		Gravel	45,376	ton
			Clay	31,763	ton
			Natural soil	52,938	ton
			Skid-steer loader	75,625	m^3
		Transport	Lorry euro5	13,007,700	tkm
Conversion	Lawn		Water	55	m^3
			N fertilizer	120	kg
			Polybutadiene	550	kg
			Mulch	6000	kg
			Field sprayer	2.75	ha
		Transport	Light commercial vehicle	749.5	tkm

3.2.2. Filling Phase

The landfill filling phase was modelled according to the collection and transportation of waste and its allocation into the landfill. During the filling, vertical gas HDPE venting pipes, surrounded by a layer of gravel, are installed to increase the natural air flow in the landfill body [14]. Also included in this phase are the materials and the fuels for the machines to install the temporary cover (Table 4). The daily cover installed is made of removable synthetic sheets: it was assumed that the daily cover was manually laid on the waste. The chosen temporary top cover allows the rain infiltration and gas flow; it is composed of a layer of coarse gravel, fine sand and compost, and natural soil [14,38]. The SimaPro databases do not include a natural soil entry due to the great heterogeneity of the natural soil composition, so the soil composition for this project is considered to be: 32% sand; 33% silt, 35% clay. The compost used in the temporary top cover was chosen from the Ecoinvent 3 database; the compost quality of this entry is much higher than the one usually used in the landfills cover due to the absence of other entries in the database. Due to the better quality, the contribution of the compost is much higher than the one in reality, but it was still included as the worst-case scenario. The spreading and the compaction of the materials of the temporary cover is performed by a skid-steer loader. The rain infiltration and waste degradation cause the production of leachate and biogas, which, for the filling phase, were calculated assuming that no cover was installed.

3.2.3. Aftercare

The aftercare phase starts when the landfill is completely filled, and the temporary cover is installed. In the design phase, it was decided to make this phase last 40 years in order to let the waste stabilize before installing the final top cover, which is impermeable. No other materials are used, so the only input is the rainwater infiltrating in the top cover; the output, as in the previous phase, are only the leachate and the biogas produced. The leachate and biogas produced were calculated assuming that the temporary top cover was installed on the landfill (Tables 2 and 3) and, therefore, less rain was able to permeate, and more methane was oxidized. Given the presence of the top cover, the runoff and evapotranspiration processes were assumed to reduce the leachate produced.

3.2.4. Closure

Following the end of the aftercare phase and the achievement of the mechanical stability of the waste, the landfill is closed with the impermeable final top cover. The final top cover is composed of a regularization layer, 0.5 m coarse gravel layer with a hydraulic conductivity higher than 10^{-3} m/s, 0.5 m clay layer with a hydraulic conductivity lower than 10^{-8} m/s, 0.5 m coarse gravel layer and 0.5 m of natural soil (Table 4) [38]; a skid-steer loader was used to place the cover. During this phase, the biogas is still considered to be oxidized and the leachate produced as in the previous phase with the pollutant's concentrations reported (Tables 2 and 3).

3.2.5. Conversion

The landfill is covered with grass seed to convert it to its final destination. To plant the grass, a hydroseeding technique is used; the materials needed are water, mulch, a bonding agent, fertilizer and seeds (Table 4). During this last phase the top cover reduces the rainwater entering the landfill, so the leachate produced is significantly lower than before (Table 3); since the final impermeable top cover is installed, it was considered that only 5% of the annual leachate produced in the previous phases would be formed in this phase. Waste degradation proceeds slowly, and the residual biogas emissions are partly oxidized by the final top cover (Table 2).

4. Results

The results from the life cycle impact assessment phase are calculated through the SimaPro software. The characterization was conducted using the ReCiPe 2016 multi-impact method at midpoint level, which transform emissions and resources into 18 different impact categories [43]. To better understand the hotspots of life cycle impact assessment results, the contribution analysis and normalization of results were carried out coherently with the literature guidelines [39,40,44,45].

4.1. Characterization Results

The life cycle impact assessment results obtained using the ReCiPe 2016 characterization method are reported in Figure 2.

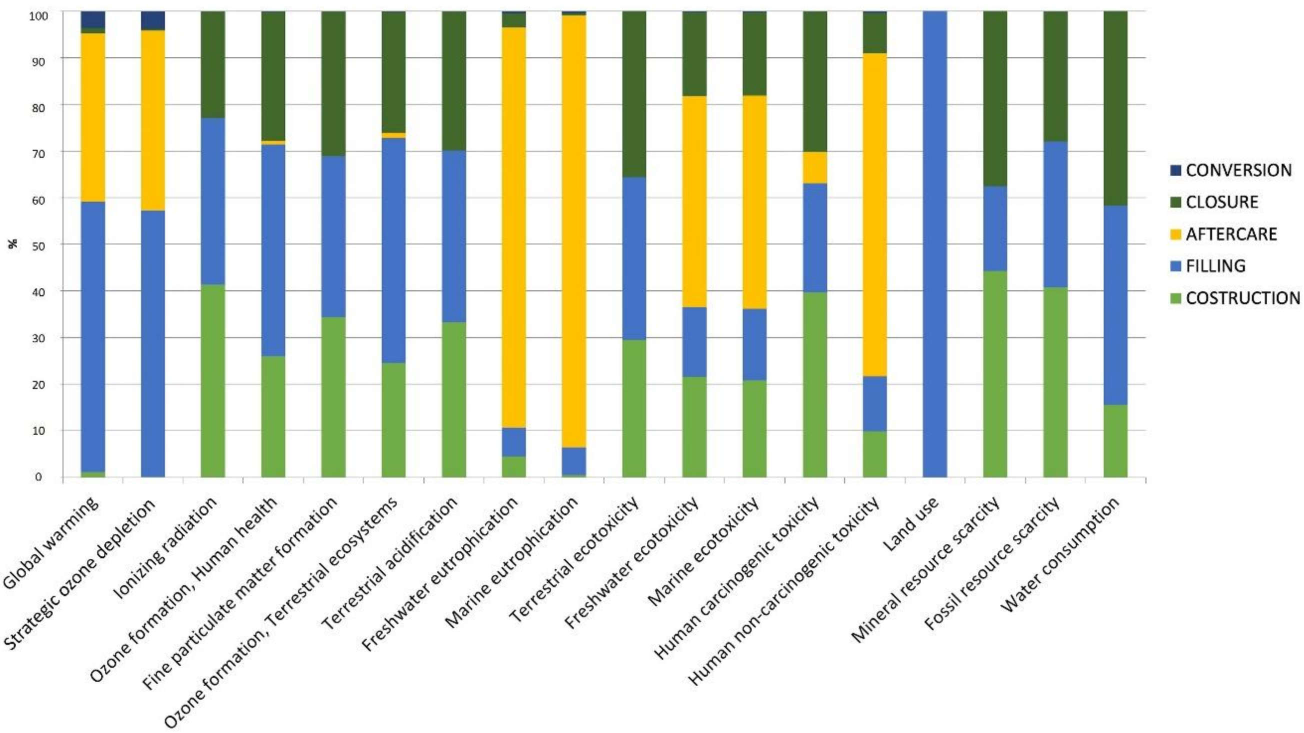

Figure 2. Graphical representation of characterization results, through ReCiPe 2016 method, for the entire landfill life.

Each life cycle phase of semi-aerobic landfill contributes to the overall environmental profile, with different relevance in different impact categories. In general, it emerges that there is not a single phase in the landfill life that is the most impacting in every impact category; indeed, almost every phase has a relevant impact on more than one category. The phases with higher impact are the filling and aftercare; however, construction and closure contribute significantly to several impact categories. Only the conversion phase can be considered negligible with minimum contribution on the environmental impact profile. This is due to the low quantity of biogas and leachate produced, since the waste is stabilized and the final top cover stops the rainwater's infiltration; after 60 years the quality of the leachate is also significantly improved.

4.2. Contribution Analysis

Figure 3 details the results of life cycle impact assessment focusing on the contribution of each process within the life cycle phases.

In the construction phase (Figure 3A), the most significant process is the bottom layer realization; it is the most impacting in each category and its impact is mostly given by the clay materials and their transportations. The second most contributing process is the drainage layer construction. Embankment and rainfall water collection cause minimal impact, while the other processes can be considered negligible.

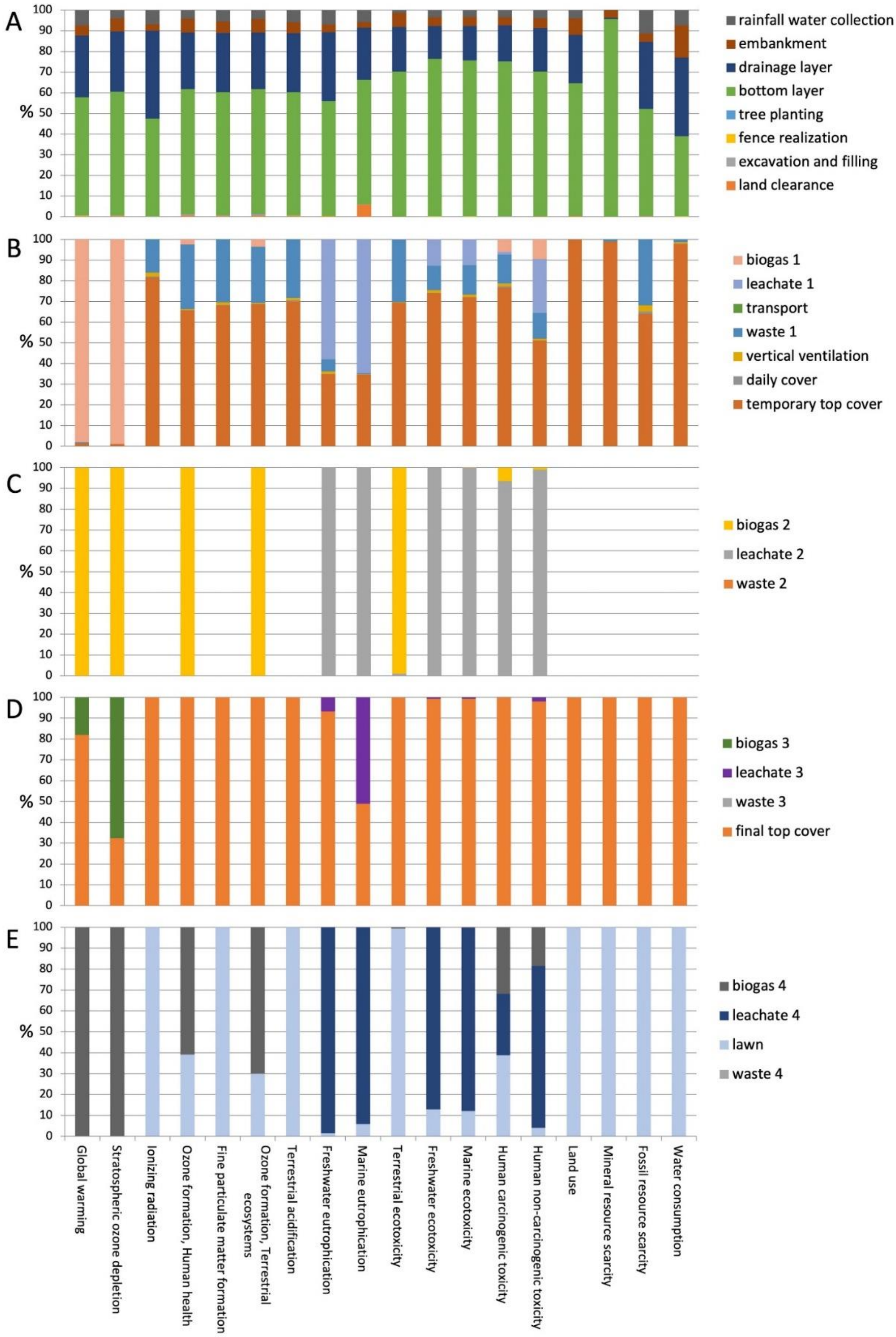

Figure 3. Characterization results for each phase: (**A**) construction, (**B**) filling, (**C**) aftercare, (**D**) closure, (**E**) conversion.

In the filling phase (Figure 3B), the impact is shared by the materials for the covers and the emissions from the biogas and leachate production. In the majority of the impact categories, the temporary top cover materials, especially the high-quality compost, and the waste transportation are the major contributors of the impact. The biogas emissions mostly impact the first two impact categories, while the leachate impact is on mostly the freshwater and marine eutrophication. Daily cover, vertical ventilation and transport are the only negligible processes.

In the aftercare phase (Figure 3C), the impact is due to the large amount of biogas and leachate, released in the environment during a period of 40 years. Although the biogas released was further oxidized to reduce the methane concentration and the leachate has gone through the treatment plant, the pollutants concentrations were still relatively high, and since large quantities are produced in the phase, they create a relevant impact. The release of biogas impacts mostly on four impact categories (global warming, stratospheric ozone depletion, ozone formation human health, ozone formation terrestrial ecosystem and terrestrial ecotoxicity) but is negligible in other impact categories. Meanwhile, the leachate mostly impacts the freshwater and marine eutrophication, freshwater and marine ecotoxicity, and human carcinogenic and non-carcinogenic toxicity categories. This means that in this phase, no process can be considered negligible.

In the closure phase (Figure 3D), the impact is mainly given by the final top cover due to the large amounts of materials used; the greatest contribution is given by the natural soil and clay, and their transportation. Biogas and leachate contribute with relevant impact in terms of stratospheric ozone depletion and marine eutrophication, respectively.

The environmental impacts in the conversion phase (Figure 3E) are substantially due to lawn preparation. However, biogas and leachate have important contribution in some impact categories.

4.3. Normalization

Figure 4 reports the results of life cycle impact assessment applying normalization: relative contributions of each life cycle stage on the environmental profile are underlined to better understand their relevance, check plausibility of results and guide to the conclusions.

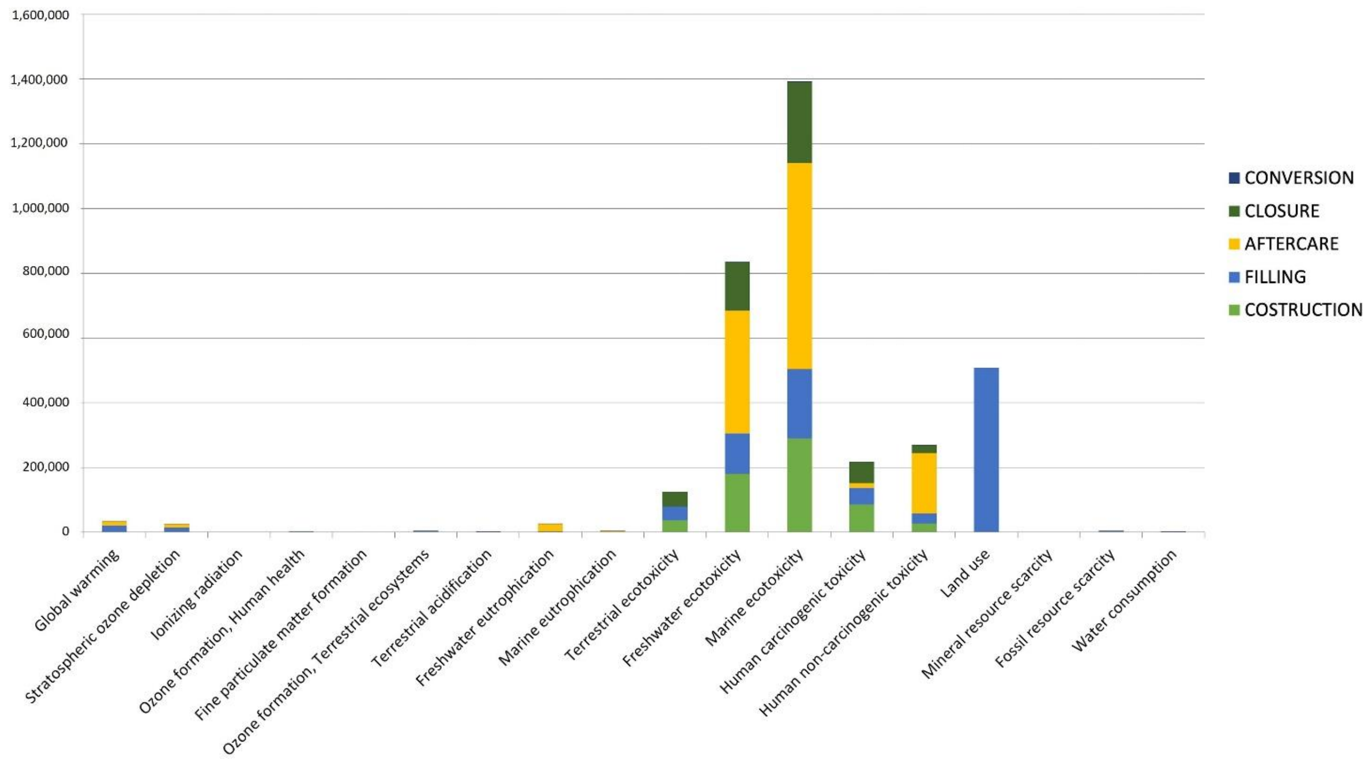

Figure 4. Normalization results of the landfill life through ReCiPe 2016 method.

Normalized environmental profile proves that the biggest contribution of the entire semi-aerobic landfill life is given by the aftercare phase. Since the aftercare impact is given by the emissions, the leachate released in the environment is the major contributor on the total impact of the landfill life; the impacts of the biogas are very low if compared with the leachate impacts. Another significant contribution is given by the material used in the construction, filling and closure phases. Conversion phase remains with negligible contribution, confirming the result already emerged of the characterization (Figure 2).

From the normalization, it is possible also to recognize what are the environmental categories on which the impacts of the landfill fall most: primarily marine and freshwater ecotoxicity, followed by land use, human carcinogenic and non-carcinogenic toxicity, and terrestrial ecotoxicity. Other impact categories can be considered negligible in the overall environmental landfill profile.

5. Discussion

Reviewing the results, some considerations should be underlined.

The time duration of the phase is not always proportional to the impact of the phase. An example of this is given by the impacts related to the closure and the conversion phases: the closure only lasts one year, but since a lot of material are used for the final top cover, the impact of the entire phase is much higher than the impacts of the conversion phase that lasts 40 years. On the contrary, the filling and the aftercare have a high impact due to their long duration; the quantity of biogas and leachate produced each year is still high, and so if they are multiplied by the phase duration, the total quantity is very significant. Another relevant aspect is that if the closure was included in another phase, due to the small duration, the significant contribution of that single year would have been confused with the rest of the impacts of the other phase.

The results show that the biggest share in the total impact is given by the leachate, because, even if its pollutants concentrations are below the concentration limit, the volumes released are enormous and, consequently, the impact on the marine and freshwater ecotoxicity are significant. It should be highlighted that a reduction of methane emissions through enhanced methane oxidation would have a lower impact reduction than improving the efficiency of leachate treatment: reaching lower concentration values for relevant parameters in leachate treatment plants, even lower than current legislation limits, would produce significant environmental benefits.

In addition, the impact of landfill construction, filling and closure, in terms of material use and transportation, cannot be neglected as it can be comparable to impacts caused by emissions. This finding should not be disregarded by landfill designers, who should be encouraged to look for more efficient solutions to limit the environmental cost of material use and transportation.

Regarding the impact assessment method, considering several impact categories allow to see impacts that would not be noticed if another method that only considers the global warming was used, the greater impact on the marine ecotoxicity given by the leachate would not have been noticed in this study if another method was chosen.

6. Conclusions

The aim and novelty of the study was the assessment of the impacts of the semi-aerobic landfill technology through the LCA methodology considering all phases, from the construction through to the filling and landfill conversion for a future use. A hypothetical landfill was designed including all the material and emissions from its construction to its conversion. The results show that the most impacting phases are the filling and aftercare phase due to the greater quantity of leachate produced; the impact of the materials used for the landfill construction was also significant. The transportation should also not be neglected, since the impact given by the transportation are relevant. The final results only partially reflect the expected outcomes; the great impact of the leachate was predictable since its production can continue for decades while biogas production decreases with time.

The low impact of biogas emissions was not expected since a great quantity of methane and CO_2 are produced and directly released into the atmosphere.

From the research results important lessons for practitioners and scientists emerge:

- The overall environmental impact associated to semi-aerobic landfill is primarily due to the filling and aftercare phases, but the construction and closure phases determine non negligible contributions: in the LCA study, all phases of landfill life cycle should be included to obtain consistent results.
- Materials used in landfill construction, filling and closure significantly contribute to the environmental profile of semi-aerobic landfill: when assessing the impacts of a landfill, the analysis should not only focus on the biogas and leachate, but should also include all the materials used during the landfill life cycle.
- Using a multi-criteria impact assessment method, the contributions of each process were highlighted: when studying the impacts of landfills through the LCA methodology, methods with only one impact category (for example global warming) should not be used because they could neglect relevant contributions.
- The LCA study performed from project data has produced useful information to optimize landfill design in terms of material use and transportation: when designing a waste treatment plant such as a landfill, the LCA study should be used to support the decision-making process.

The limits of this study are mostly related to the assumptions made, the data chosen and the intrinsic limits of LCA methodology. The study was performed on a purposely designed landfill; for this reason, the characteristics of biogas and leachate were estimated, thus limiting the significance of the results. The narrow selection of data from the SimaPro database had a limiting effect on the results since the worst-case scenario had to be chosen.

From the results of this study, it is possible to notice that, due to the great contribution of the leachate to the total impacts, lower concentration limits for discharge into surface waters would produce a significant effect on the reduction of environmental impacts of landfills. As previously discussed, and in accordance with other studies, the decision of not considering the impacts caused by leachate treatment processes was taken; further research should be conducted to analyze the contribution of leachate treatment processes to the overall impacts and the benefits produced by reaching lower concentrations of relevant parameters through enhanced leachate treatment before discharge to surface waters.

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References

1. Di Foggia, G.; Beccarello, M. Designing waste management systems to meet circular economy goals: The Italian case. *Sustain. Prod. Consum.* **2021**, *26*, 1074–1083. [CrossRef]
2. Ferronato, N.; Torretta, V. Waste Mismanagement in Developing Countries: A Review of Global Issues. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1060. [CrossRef]
3. Interreg Europe. Sustainable Waste Management in a Circular Economy: A Policy Brief from the Policy Learning Platform on Environment and Resource Efficiency. 2020. Available online: https://www.interregeurope.eu/sites/default/files/inline/Policy_brief_on_waste_management.pdf (accessed on 22 August 2022).
4. Khan, S.; Naushad, M.; Lima, E.C.; Zhang, S.; Shaheen, S.M.; Rinklebe, J. Global soil pollution by toxic elements: Current status and future perspectives on the risk assessment and remediation strategies—A review. *J. Hazard. Mater.* **2021**, *417*, 126039. [CrossRef]
5. Cossu, R. The environmentally sustainable geological repository: The modern role of landfilling. *Waste Manag.* **2012**, *32*, 243–244. [CrossRef]
6. Powell, J.T.; Chertow, M.R.; Esty, D.C. Where is global waste management heading? An analysis of solid waste sector commitments from nationally-determined contributions. *Waste Manag.* **2018**, *80*, 137–143. [CrossRef]

7. Górka, M.; Bezyk, Y.; Sówka, I. Assessment of GHG interactions in the vicinity of the municipal waste landfill site—Case study. *Energies* **2021**, *14*, 8259. [CrossRef]
8. Laner, D.; Crest, M.; Scharff, H.; Morris, J.W.F.; Barlaz, M.A. A review of approaches for the long-term management of municipal solid waste landfills. *Waste Manag.* **2012**, *32*, 498–512. [CrossRef]
9. Turner, D.A.; Beaven, R.P.; Woodman, N.D. Evaluating landfill aftercare strategies: A life cycle assessment approach. *Waste Manag.* **2017**, *63*, 417–431. [CrossRef]
10. Manfredi, S.; Christensen, T.H. Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. *Waste Manag.* **2009**, *229*, 32–43. [CrossRef]
11. Khan, S.; Anjum, R.; Raza, S.T.; Bazai, N.A.; Ihtisham, M. Technologies for municipal solid waste management: Current status, challenges, and future perspectives. *Chemosphere* **2022**, *288*, 132403. [CrossRef]
12. Cossu, R.; Stegmann, R. *Solid Waste Landfilling, Concepts, Processes, Technology*; Elsevier: Amsterdam, The Netherlands, 2019; ISBN 9780128183366.
13. Ouedraogo, A.S.; Frazier, R.S.; Kumar, A. Comparative life cycle assessment of gasification and landfilling for disposal of municipal solid wastes. *Energies* **2021**, *14*, 7032. [CrossRef]
14. Matsufuji, Y.; Tanaka, A.; Cossu, R. Chapter 14.2: Semiaerobic landfilling. In *Solid Waste Landfilling, Concepts, Processes, Technologies*; Cossu, R., Stegmann, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 807–830.
15. Mazzi, A. Introduction: Life cycle thinking. In *Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies*; Ren, J., Toniolo, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–19.
16. Toniolo, S.; Mazzi, A.; Garato, V.G.; Aguiari, F.; Scipioni, A. Assessing the "design paradox" with life cycle assessment: A case study of a municipal solid waste incineration plant. *Resour. Conserv. Recycl.* **2014**, *91*, 109–116. [CrossRef]
17. Zhang, J.; Qin, Q.; Li, G.; Tseng, C.-H. Sustainable municipal waste management strategies through life cycle assessment method: A review. *J. Environ. Manag.* **2021**, *287*, 112238. [CrossRef] [PubMed]
18. De Feo, G.; Malvano, C. The use of LCA in selecting the best MSW management system. *Waste Manag.* **2009**, *29*, 1901–1915. [CrossRef]
19. Scipioni, A.; Mazzi, A.; Niero, M.; Boatto, T. LCA to choose among alternative design solutions: The case study of a new Italian incineration line. *Waste Manag.* **2009**, *29*, 2462–2474. [CrossRef]
20. Laurent, A.; Bakas, I.; Clavreul, J.; Bernstad, A.; Niero, M.; Gentil, E.; Hauschild, M.Z.; Christensen, T.H. Review of LCA studies of solid waste management systems—Part I: Lessons learned and perspectives. *Waste Manag.* **2014**, *34*, 573–588. [CrossRef]
21. Mazzi, A.; Spagnolo, M.; Toniolo, S. External communication on legal compliance by Italian waste treatment companies. *J. Clean. Prod.* **2020**, *255*, 120325. [CrossRef]
22. Ramos, A.; Teixeira, C.A.; Rouboa, A. Environmental analysis of waste-to-energy—A Portuguese case study. *Energies* **2018**, *11*, 548. [CrossRef]
23. Yang, N.; Damgaard, A.; Lü, F.; Shao, L.-M.; Brogaard, L.K.-S.; He, P.J. Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study. *Waste Manag.* **2014**, *34*, 929–937. [CrossRef]
24. Matsuto, T.; Zhang, X.; Matsuo, T.; Yamada, S. Onsite survey on the mechanism of passive aeration and air flow path in a semi-aerobic landfill. *Waste Manag.* **2014**, *36*, 204–212. [CrossRef]
25. Andreottola, G.; Cossu, R.; Ritzkowski, M. Chapter 9.1: Landfill Gas Generation Modeling. In *Solid Waste Landfilling, Concepts, Processes, Technologies*; Cossu, R., Stegmann, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 419–438.
26. Rosenbaum, R.K.; Hauschild, M.Z.; Boulay, A.-M.; Fantke, P.; Laurent, A.; Núñez, M.; Vieira, M. Chapter 10: Life Cycle Impact Assessment. In *Life Cycle Assessment, Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer: Cham, Switzerland, 2018; pp. 167–270.
27. IPCC. Chapter 3: Solid Waste Disposal. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019.
28. Jeong, S.; Nam, A.; Yi, S.-M.; Kim, J.Y. Field assessment of semi-aerobic condition and the methane correction factor for the semi-aerobic landfills provided by IPCC guidelines. *Waste Manag.* **2015**, *36*, 197–203. [CrossRef]
29. Ahmadifar, M.; Sartaj, M.; Abdallah, M. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. *J. Mater. Cycles Waste Manag.* **2016**, *18*, 703–771. [CrossRef]
30. Qifei, H.; Yufei, Y.; Xiangrui, P.; Qi, W. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. *J. Environ. Sci.* **2008**, *20*, 499–504. [CrossRef]
31. Bakas, I.; Laurent, A.; Clavreul, J.; Saraiva, A.B.; Niero, M.; Gentil, E.; Hauschild, M.Z. Chapter 35: LCA of Solid Waste Management Systems. In *Life Cycle Assessment, Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer: Cham, Switzerland, 2018; pp. 887–926.
32. Obersteiner, G.; Binner, E.; Mostbauer, P.; Salhofer, S. Landfill modelling in LCA—A contribution based on empirical data. *Waste Manag.* **2007**, *27*, S58–S74. [CrossRef]
33. Kirkeby, J.T.; Birgisdottir, H.; Bhander, G.S.; Hauschild, M.; Christensen, T.H. Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program EASEWASTE. *Waste Manag.* **2007**, *27*, 961–970. [CrossRef]
34. Manfredi, S.; Tonini, D.; Christensen, T.H. Contribution of individual waste fractions to the environmental impacts from landfilling of municipal solid waste. *Waste Manag.* **2010**, *30*, 433–440. [CrossRef]

35. Sauve, G.; Karel, V.A. The environmental impact of municipal solid waste landfills in Europe: A life cycle assessment of proper reference cases to support decision making. *J. Environ. Manag.* **2020**, *261*, 110216. [CrossRef]
36. Nabavi-Pelesaraei, A.; Bayat, R.; Hosseinzadeh-Bandbafha, H.; Afrasyabi, H.; Chau, K.-W. Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management—A case study in Tehran Metropolis of Iran. *J. Clean. Prod.* **2017**, *148*, 427–440. [CrossRef]
37. Wang, Y.; Levis, J.W.; Barlaz, M.A. Life-Cycle Assessment of a Regulatory Compliant U.S. Municipal Solid Waste Landfill. *Environ. Sci. Technol.* **2021**, *55*, 13583–13592. [CrossRef]
38. Regione Lombardia, 2014, October 10. D.g.r. 7 Ottobre 2014—n. X/2461 Linee Guida per la Progettazione e Gestione Sostenibile delle Discariche. Available online: https://gse.it/normativa_site/GSE%20Documenti%20normativa/LOMBARDIA_DGR_nx-2461__07_10_2014.pdf (accessed on 22 August 2022).
39. *ISO 14040:2020 (ISO 14040:2006+A1:2020)*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization (ISO): Geneva, Switzerland, 2020.
40. *ISO 14044:2020 (ISO 14044:2006+A2:2020)*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization (ISO): Geneva, Switzerland, 2020.
41. Alibardi, L.; Cossu, R. Chapter 6.1: Leachate generation modeling. In *Solid Waste Landfilling, Concepts, Processes, Technologies*; Cossu, R., Stegmann, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 229–246.
42. Ingram, D.L. Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. *Int. J. Life Cycle Assess.* **2012**, *17*, 453–462. [CrossRef]
43. Pré Sustainability. ReCiPe. 2016. Available online: https://pre-sustainability.com/articles/recipe/ (accessed on 22 August 2022).
44. Benini, L.; Sala, S. Uncertainty and sensitivity analysis of normalization factors to methodological assumptions. *Int. J. Life Cycle Assess.* **2016**, *21*, 224–236. [CrossRef]
45. Kim, J.; Yang, Y.; Bae, J.; Suh, S. The importance of normalization references in interpreting life cycle assessment results. *J. Ind. Ecol.* **2013**, *17*, 385–395. [CrossRef]