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ENVIRONMENTAL PROFILE OF ANAEROBIC AND SEMI-AEROBIC LANDFILLS WITHIN SUSTAINABLE WASTE MANAGEMENT: AN OVERVIEW

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Abstract

The new perspective of circular economy accelerates the efforts to increase reuse and recycling of products and reduce the need of resources. Although the quantity of waste reaching the end-of-life has decreased, landfills can't be eliminated from the waste management systems (WMS) since the current treatment processes still produce unrecyclable materials. Anaerobic landfills have great environmental impacts due to the long-term emissions, therefore, to reach a more sustainable waste management less impacting alternatives are being implemented. Semi aerobic landfills can reduce the environmental burdens by enhancing waste stabilization with natural air flow inside the landfill body through the leachate collection pipes. The presence of aerobic areas implies biogas with less methane and leachate with lower pollutant concentrations. The research goal is to deepen the evidence that the semi-aerobic landfills are environmentally preferable to traditional anaerobic landfills, by considering the scientific information published in international peer-reviewed journals from 2000 to 2022. To obtain comprehensive answers to the research question, papers using the life cycle assessment (LCA) methodology are included in the review, with the aim of understanding what the environmental profiles of traditional and semi-aerobic landfill are when all life cycle phases are considered. The results clarify what the main contributions to environmental impacts of these two types of landfills are. The review only partially demonstrates the environmental convenience of semi-aerobic landfill. Instead, it reveals a lack of papers analyzing the comparison between different landfill technologies, suggesting new research perspectives to optimize the sustainability of final treatment solutions in WMS.

Key words: environmental impact, life cycle assessment, semi-aerobic landfill, waste management systems

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1. Introduction

In recent years the European Union (EU) is moving from a linear economy, in which the resources are considered available and plentiful, to a more sustainable and circular economy in which the generation of waste is minimized by keeping the materials and resources in the loop as long as possible (Barreiro-Gen and Lozano, 2020). The concept of circular economy derives from the will of reaching a sustainable development by reducing treatment and disposal and prioritizing the reduction, reuse, and recycling; this can be achieved through a sustainable and effective waste management system (WMS) (Cherubini et al., 2009). The increasing complexity and quantity of waste represent a challenge for a sustainable WMS (Christensen et al., 2020).

When choosing the most suitable solutions for a city or region's waste treatment system, it is not sufficient to consider only technical and economic aspects, but the environmental impacts should be included in the choice (De Feo and Malvano, 2008). The selection of a technology over another can't be generalized and it is strictly related to the case study

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and local conditions; recycling is one of the less impacting choices although the benefits depend on different factors like the type of material to recycle and the recycling efficiency (JRC, 2011). Moreover, different surface and population density, per capita gross domestic product and per capita municipal solid waste production determine different options in WMS (Calabrò et al., 2015). Given the high position of recycling in the waste hierarchy, it is often perceived as the solution for the waste management criticalities by politicians and public opinion (Cossu et al., 2020). For this reason, the focus has been on increasing the recycling rate and the separate waste collection, meanwhile reducing the quantity of waste going to landfills that, on the contrary, are seen as negative for the environment. The European Union and other developed countries have already set a limit to the quantity of waste that can be disposed in landfills; in these countries the conventional landfills are mostly controlled sanitary landfills to reach the sustainability (Interreg Europe, 2020). The policy change also includes the closing of old landfills and consider them as a source of alternative raw materials (Muica et al., 2021).

The WMS changes dramatically in less developed or developing countries where the sustainable management is one of the biggest challenges due to the rapid increase of waste produced given by the population growth and the rising standard of living (Ahmadifar et al., 2016). Generally, the integrated WMS of developing countries is less organized, incomplete, and insufficient due to the lack of infrastructures and weaker technical skills; complex waste treatment technologies have too high construction costs for those countries and frequently resources are not available for skilled personnel, appropriate equipment and infrastructure and their proper maintenance (Iqbal et al., 2020; Guerrero et al., 2013). It is also recognized that the WMS of developed countries are counterproductive for developing countries due to the lack of connection to the local social and economic conditions (Marshall and Farahbakhsh, 2013). Moreover, in developing countries separate waste collection is difficult to obtain, due to the lack of customer commitment (Calabrò and Satira, 2020). For these reasons, most of the waste produced in these countries ends up in open dumps and uncontrolled landfills (Ferronato and Torretta, 2019).

In case of such complex circumstances, landfills would have a lower effect on the environment: in every case even the landfills are always a better alternative than an uncontrolled waste disposal (Maalouf et al., 2020; Manfredi et al., 2011). The landfill cannot be avoided, due to unrecyclable residual flow, so the concept should be remodeled to reduce the negative impact on the environment and to act as a sink to close the material loop and fulfil its role in the circular economy strategy (Cossu et al., 2020). In the aim of doing this and given the still elevated quantity of landfills around the world, new technologies are being designed and analyzed. One of these is the semi-aerobic landfill, also called "Fukuoka method landfill", from the Japanese university in which it was originally designed (Hanashima et al., 1981).

The Life Cycle Assessment (LCA) methodology can help give a comprehensive estimation of the environmental impacts associated to each phase of product's life cycle, from cradle to grave (ISO, 2020a). LCA is frequently adopted to quantify the environmental impacts associated to products, services, and technologies (ISO, 2020a). This methodology is widely recognized as a decision support tool in the field of integrated WMS since it provides relevant information to evaluate, by weighting the benefits and drawbacks, the environmental preferability of one alternative over another (JRC, 2011; Manfredi et al., 2011).

A particular importance should be given to the LCA of landfills given their need and their great impact on the entire WMS. Due to the many factors influencing the performance of the landfill a comparative assessment between types of landfills should be performed to select the best option for each specific situation.

Semi-aerobic landfills are characterized by a different design which enables natural air intrusion into the waste body and the consequent contemporary presence of anaerobic and aerobic spots that enable very specific conditions for enhanced and accelerated waste stabilization processes. As a consequence, the quality of landfill leachate and biogas emissions is enhanced as well (Huang et al., 2008). Although it is a convenient technology, there is a lack of a systematic literature analysis on the environmental convenience of the semi-aerobic compared to the traditional anaerobic landfill technology.

Hence the purpose of this paper is to verify that semi-aerobic landfills are environmentally preferable for the final disposal of waste, to identify the best solutions for the last step of the waste hierarchy. To understand the environmental performances of different alternatives in the WMS, the scientific evidence published in peer-reviewed journals derived by LCA studies related to traditional and semi-aerobic landfills are analyzed and discussed.

2. Background

2.1. Waste management systems

The WMS includes all the treatments and technologies used from the waste collection to the final disposal; it can vary greatly depending on the waste composition, geographical characteristics, and cultural patterns (Christensen et al., 2020). The WMS should follow the waste hierarchy that puts prevention and recycling as a priority and indicates the landfilling as the least preferable option. The prevention has the highest priority since it avoids the impacts of the waste and its treatments on the environment (JRC, 2011).

The waste produced can undergo different treatment technologies; the most frequently considered in scientific studies are recycling for materials like plastic and glass, composting and anaerobic digestion for organic waste, thermal treatment for high calorific waste and landfilling for the unsorted, unrecyclable, and residual waste (Laurent et al., 2014). Although the recycling is widely agreed to be the most sustainable option, the actual environmental benefits depend on the type of waste; in addition, some recycled material cannot be compared to the virgin material since it can be used as a replacement only for a limited extend or for a reduced amount of time (Rigamonti et al., 2018). For this reason, it is important to quantify these benefits and compare them with the advantages of other technologies to choose the most sustainable option for each case study (Ripa et al., 2017).

The recyclability and the final treatment option depends on the state and composition of waste. Homogeneous waste facilitates the recovery of materials and increases the efficiency of treatments having higher quality outputs; unsorted waste instead ends up in the landfill (Bakas et al., 2018). Examples of treatment technologies for homogeneous waste are the composting and anaerobic digestion of the organic fraction. An alternative option to recycling is the thermal treatment; through combustion of waste with a high calorific content, it is possible to stabilize it, decrease its volume and produce electricity obtaining significant environmental benefits (JRC, 2011; Mendes et al., 2004). While from recycling the benefits are given by the avoided impacts for extraction of new virgin material, the waste incineration with energy recovery avoids the impact of energy production (Cherubini et al., 2009; Scipioni et al., 2009). As final option in waste hierarchy, the landfill can be realized with ad-hoc technical solutions to reduce the environmental impacts associated to its operability.

2.2. The role of landfill in the waste management systems

The recycling and thermal treatments are usually preferred over landfilling which has the worse environmental performance (Laurent et al., 2014). On the other hand, the performance depends on the type of waste; the landfills can even be the best environmental solution, with the lowest environmental impacts, in case of inert waste that might need further processing and long-distance treatment (JRC, 2011).

Landfills are also parts of the WMS and cannot be avoided but only minimized and, if possible, made more sustainable (Vaverková, 2019). The great quantity of emissions produced from the waste disposed in landfills makes them the least preferable options. Although the public opinion and politics are pushing for the minimization of landfills, they are still necessary and integrated in the WMS. This is very important for countries with a poor management in which due to the inadequate infrastructure most of the waste produced is either uncollected or badly disposed (Idowu et al., 2019). The collected waste mostly ends up in open dumps and poorly controlled landfills. This means that the waste is directly disposed on the ground without any emission control system to prevent and stop the pollution on the environment resulting in a damage of the groundwater, soil and air quality as well endangering the public health; the priority in this case is to upgrade the disposal method to more controlled and engineered landfill that is easily implemented and managed to reduce and control the pollution (Lavagnolo, 2019).

While in developing countries most of the waste is still disposed in landfills, in more developed countries the quantity of landfills is minimized (Laurent et al., 2014) but still present; active measures have been taken to remediate the open dumps and substitute with engineered sanitary landfills. The modern landfill can play a fundamental role in SWM strategies, serving as a geological repository to close the material cycle (Khan et al., 2022). In developed countries, like the EU, the most frequent landfill technology is the sanitary anaerobic, often called traditional or conventional landfill (Interreg Europe, 2020). In this type of landfill, the waste is anaerobically degraded, partially converted in biogas, with a high percentage of methane, and in leachate, with high pollutant concentration. As represented in Fig. 1, in the traditional landfills most of the measures are taken to control and collect the biogas and leachate, with the purpose of reducing the uncontrolled emissions, but little is done to actively increase the waste stabilization (Manfredi and Christensen, 2009). The multi-barrier principle was introduced to highlight the benefits of a combination of features, including waste pre-treatment and measures to enhance waste stabilization processes in the landfill body, to effectively control landfill long term emissions (Cossu, 2018). In this perspective, semi-aerobic conditions enable the acceleration of waste stabilization processes and the enhancement of leachate and biogas quality; for these reasons they provide an effective barrier to contaminant release into the environment.

2.3. Semi-aerobic landfill

Also known as the Fukuoka method, the semi-aerobic landfill combines the presence of aerobic and anaerobic areas to improve the waste degradation; this method allows to have aerobic areas without the needs of additional aeration (Ahmadifar et al., 2016). This combination allows to decrease the landfill life and therefore decrease the pollution on the environment; the shorter life is given by the faster waste stabilization due to the characteristics of this technology (Huang et al., 2008).

The method consists of inserting large, slotted pipes on the bottom of the landfill to collect the leachate by gravity (Fig. 1). The pipes in the landfill are designed to not be filled of leachate to also allow the natural air flow in the landfill body (Huang et al., 2008).

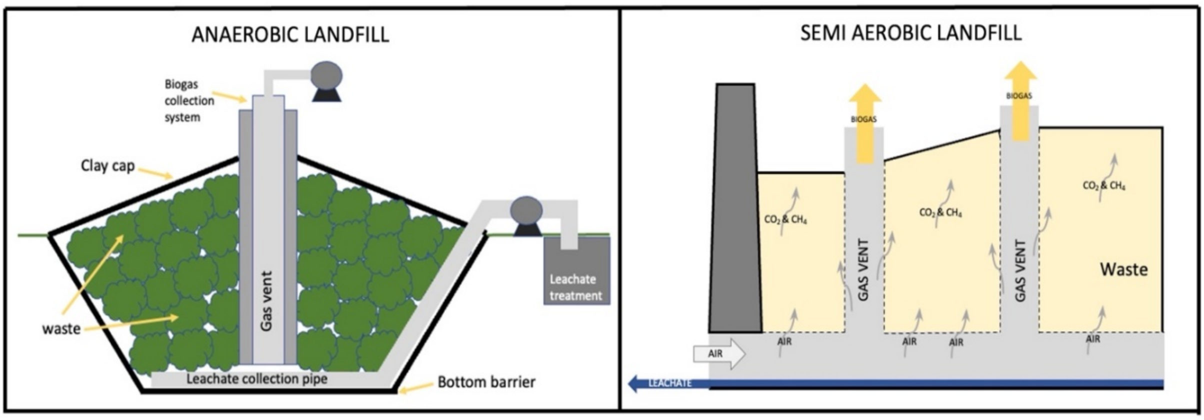

Fig. 1. Anaerobic and semi-aerobic landfill schemes comparison

They are also connected with the gas vents in the landfill body directly connected to the atmosphere, this allows the aeration of the waste in every part of the landfill body (Matsuto et al., 2015). The natural airflow is induced from a chimney effect resulting from a difference in temperature between the landfill body and the outside air (Ahmadifar et al., 2016). The aerobic degradation of the waste increases the temperature making the gas rise and creating a negative pressure inside the landfill body that draws the outside air in the waste from the leachate pipes (Matsuto, et al., 2015). The temperature in the landfill body was proven to remain high during the landfill life. Although the temperature difference is the main driver for the waste aeration, other factors such as the composition and compaction of the waste and the characteristics of the cover materials, have been proven to be influencing it; the efficiency of this technology also depends on the location of the landfill since a warmer climate will reduce the temperature difference (Matsuto et al., 2015).

Regarding the biogas produced, the quantity of methane is negligible respect to the percentages of it in the biogas of the traditional landfill. Instead, the biogas produced is high in CO_2 and N_2 (Manfredi and Christensen, 2009). Due to the low concentration of methane the biogas produced is usually not used for energy recovery; the biogas is often directly released in the environment. The use of biofilter and bio covers were also proven, by Bacchi et al. (2018), to be effective in reducing the CH_4 emissions, when energy recovery is not a feasible option, and to be a sustainable alternative to further decrease the environmental impacts given by the release of the biogas. Beside accelerating the waste stabilization, this methodology allows to quickly reduce the concentration of both organic substances and ammonia in the leachate if compared with the leachate of a traditional landfill; the quality of the leachate increased rapidly, therefore requiring fewer treatments (Huang et al., 2008). Leachate from traditional anaerobic landfills normally requires intensive and expensive biological and chemical treatments off site for a long time after landfill closure. On the contrary, semi-aerobic landfill leachate is expected to show lower concentration of solutes and it could be treated by means of less costly and purposely designed systems (Aziz et al., 2010). Furthermore, the collection of the leachate by force of gravity, that makes the construction of the landfill and its operation easier, allows to avoid the use of pumps and the consumption of electricity for their operation that are instead needed in the traditional landfill.

2.4. The LCA methodology in WMS

A helpful instrument to better understand the impacts associated to the waste treatment technologies and to take actions to implement more sustainable solutions in WMS is the life cycle assessment (LCA) methodology (De Feo and Malvano, 2008). The LCA methodology can be used to understand the consequences of human choices on the environment by modeling the cause-effect relationships in the environment (Mazzi, 2020).

To support the practitioners in the conduction of a thorough LCA study, two international standards are present: the ISO 14040 (ISO, 2020a) which contains the general principles and the ISO 14044 (ISO, 2020b) with more specific requirement. The methodology consists of 4 phases, namely goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and results interpretation. During the first phase of LCA, the goal of the study and its scope must be explicated; coherently the functional unit and the system boundaries have to be defined, in order to clearly decide which processes, inputs and outputs are included in the study. Secondly, in LCI, all relevant information about input and output flows associated to each process included in the boundaries are collected, in terms of material and energy consumption, product and byproduct flows and emissions to air, water and soil. The environmental impacts are calculated in the life cycle impact assessment (LCIA) phase, using ad-hoc environmental impact assessment methods and indicators, with the support of LCA software. The result obtained by the LCIA is the environmental profile of the product: environmental hotspots and critical points are identified aiming at the subsequent interpretation phase, in which additional deepening of LCIA results enable a better understanding of the contribution of each life cycle stage and of specific materials and substances to the total environmental profile (Mazzi, 2020; Silva, 2021).

Different features, like the life cycle perspective, the coverage of an extensive range of environmental issues and its quantitative and science-based nature, make the LCA a complete support tool for sustainable commitments of corporations and markets (Bjørn et al., 2018). According to Hellweg and Mila` i Canals (2014) to support companies internal decision-making for products eco-design, optimizations of processes and supply-chain management, many LCA analyses are being done. The LCA approach can be a valuable tool in all consumption sectors through the display of information on a variety of impact categories in product labeling (Toniolo et al., 2019).

The LCA methodology for WMS, often called "waste LCA", is widely used to evaluate and compare the end-of -life of products (Bakas et al., 2018). It can be used to calculate the environmental impacts and to help choosing the less impactful treatment technologies, to optimize the environmental performance of waste separation and recycling, or to design new WMS solutions at local level (Christensen et al., 2020; Ripa et al., 2017). Many papers on waste LCA analyze the benefits and advantages of the recycling technologies for different materials given the importance of it in the waste hierarchy (Mazzi, 2021). Given the great influence of site-specific data on the WMS, the LCA can help identifying the critical aspects and suggest improvement by reproducing local condition and taking them into account in the impact calculation (Laurent et al., 2014).

In the waste LCA the functional unit is usually expressed in terms of the system input like the quantity of waste to be treated or disposed (Cherubini et al., 2009). The waste LCA has mostly a comparative nature and consequently it has a different system boundary than a product LCA; indeed, the previous stages before the collection of the waste are not included (Bakas et al., 2018; Barreiro-Gen and Lozano, 2020).

Generally, when applying the LCA in waste management, the zero-burden assumption is considered; the waste it's not assumed to be already associated with any environmental impact when it enters the system (Laurent et al., 2014). Except for the entering waste, all the input and output of the system boundaries are transformed in environmental impacts through an impact assessment method. When comparing different alternatives for WMS, it is important to include in the system boundaries the materials needed for the construction and operation and the possible additional waste flows (Mazzi et al., 2022).

According to Cherubini et al. (2009) to have a consistent information on the impact assessment of the system considered, several assessment methods should be used. When analyzing possible scenarios, it is possible that the improvements are not proportional in all the impact categories therefore it is advised to carefully analyze the results and the benefits before decision making to avoid a burden shift situation (Ripa et al., 2017). According to Christensen et al. (2020) the waste LCA have different applications to support the management of solid waste which are the understanding of the impacts of the entire WMS and its improvement, the comparison of different technologies and the development of new ones. Other important functions are the reporting and the policy making development.

3. Material and methods

From the overview presented in the introduction section, some considerations emerged, and further insights must be verified, as research hypotheses that can be confirmed or denied through the literature review.

- In the international scientific debate, LCA studies can be conducted to evaluate the potential impacts on the environment caused by the final treatment solid waste through the use of different landfill technologies.
- It is plausible that the scientific discussion analyzes the convenience of semi-aerobic landfill compared to the traditional one.
- A comprehensive quantification of the environmental profile of semi-aerobic landfill can be obtained using the LCA methodology.
- The environmental convenience of semi-aerobic landfill in WMS has to be demonstrated in particular in developing countries, where the alternative final treatment could be the open dumps.

To verify the research hypotheses, qualitative research based on a systematic literature review is conducted, exploring the research topic in scientific papers published during the last 20 years. In line with the methodology suggested by Luederitz et al. (2016) and Mazzi et al. (2016) the research is structured in four steps, detailed in Table 1:

- Step 1 – Screening: preliminary survey with international databases, using specific research keywords and ad-hoc inclusion and exclusion criteria.
- Step 2 – Cleaning: selection of relevant papers, on the base of their consistency with the research topic and the research hypotheses.
- Step 3 – Classification: analysis of the selected papers in terms of type of publication, type of landfill, and other LCA characteristics.
- Step 4 – Discussion: deepened overview of the LCA results, to verify the research hypotheses and to obtain answers to the research question.

4. Results and discussion

4.1. LCA studies related to landfill

From the steps of screening and cleaning, 29 papers, published from 2000 and 2022 and related to the LCA of landfill, are identified: these papers, listed in Table 2, are further analyzed in the steps of the classification and discussion. To reach the goal, the review is limited to the LCA studies of landfill technology; other LCA studies on WMS published in the last 20 years are therefore not considered in this research.

Only studies comparing the landfill on its own, and not included in the solid waste management, are included in the study. If the landfill impacts are considered separately, also the papers comparing the landfill to other treatments are assumed to be relevant for the research.

Articles analyzing only parts of the landfill, like the leachate or the biogas treatment, are integrated in the literature review if considerate significant. The papers describing the waste characteristics are included in the study, due to great impact that they have on the resulting emissions of the landfill (Manfredi et al., 2010b).

Table 1. Objectives, contents, and criteria of the research steps

Research step	***Objectives***	***Source of inputs***	***Criteria***
Step 1 – Screening	Obtain a preliminary list of papers discussing the LCA of landfills in WMS	Firstly, Scopus and Google Scholar's and the editors' libraries (Emerald Insight, Science Direct, Springer Library, Wiley Library)	Search through the keywords "LCA" and "landfill" in title and abstract Only papers published in peer-reviewed journals Only papers in English Years of publication 2000 – 2022 (last access on August 31st 2022)
Step 2 – Cleaning	Select only the papers consistent with the research goal and scope	The preliminary list of papers obtained by the Step 1 Deepen analysis of abstract and text of papers	Selection of papers that report results of LCA studies related to landfill, both anaerobic and semi-aerobic
Step 3 – Classification	Classification of studies on the base of the main characteristics of landfill and LCA	All papers selected in the Step 2 Deepen analysis of papers' contents	Case studies analyzed in terms of: - Year of publication - Journal of publication - Landfill technology - Geographical location - Steps of life cycle included - Impact categories considered
Step 4 – Discussion	Comparison of the LCA results and verification of research hypotheses	All papers selected in the Step 2 Deepen analysis of papers' contents	Case studies discussed in terms of confirmation or deny of research hypotheses

Table 2. List of papers exploring the environmental profile of landfill technologies

Reference	***Title***	***DOI***
Xiao et al., 2022	Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate	https://doi.org/10.1016/j.jclepro.2022.130674
Ouedraogo et al., 2022	Life cycle assessment of gasification and landfilling for disposal of municipal solid wastes	https://doi.org/10.3390/en14217032
Mazzi et al., 2022	Environmental performance of semi-aerobic landfill by means of life cycle assessment modeling	https://doi.org/10.3390/en15176306
Ferrans et al., 2022	Life cycle assessment of management scenarios for dredged sediments: environmental impacts caused during landfilling and soil conditioning	https://doi.org/10.3390/su142013139
Wang et al., 2021	Life-cycle assessment of a regulatory compliant U.S. municipal solid waste landfill	https://doi.org/10.1021/acs.est.1c02526
Sauve and Van Acker, 2021	Integrating life cycle assessment (LCA) and quantitative risk assessment (QRA) to address model uncertainties: defining a landfill reference case under varying environmental and engineering conditions	https://doi.org/10.1007/s11367-020-01848-z
Sauve and Van Acker, 2020	The environmental impacts of municipal solid waste landfills in Europe: a life cycle assessment of proper reference cases to support decision making	https://doi.org/10.1016/j.jenvman.2020.110216

Henriksen et al., 2017	Linking data choices and context specificity in life cycle assessment of waste treatment technologies a landfill case study	10.1111/jiec.12709
Di Maria et al., 2016	Treatment of mechanically sorted organic waste by bioreactor landfill: experimental results and preliminary comparative impact assessment with bio stabilization and conventional landfill	https://dx.doi.org/10.1016/j.wasman.2016.03.033
Yang et al., 2014	Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study	https://dx.doi.org/10.1016/j.wasman.2014.02.017
Khoo et al., 2012	Projecting the environmental profile of Singapore's landfill activities: comparisons of present and future scenarios based on LCA	https://doi.org/10.1016/j.wasman.2011.12.010
Damgaard et al., 2011	LCA and economic evaluation of landfill leachate and gas technologies	https://doi.org/10.1016/j.wasman.2011.02.027
Manfredi et al., 2010a	Environmental assessment of low-organic waste landfill scenarios by means of life-cycle assessment modelling (easewaste)	https://doi.org/10.1177/0734242x09104127
Manfredi et al., 2010b	Contribution of individual waste fractions to the environmental impacts from landfilling of municipal solid waste	https://doi.org/10.1016/j.wasman.2009.09.017
Niskanen et al., 2009	Environmental assessment of Ämmässuo landfill (Finland) by means of LCA-modelling (easewaste)	https://doi.org/10.1177/0734242x08096976
Manfredi and Christensen, 2009	Environmental assessment of solid waste landfilling technologies by means of LCA-modeling	https://doi.org/10.1016/j.wasman.2008.02.021
Kirkeby et al., 2007	Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program easewaste	https://doi.org/10.1016/j.wasman.2006.06.017
Ménard et al., 2004	Comparative life cycle assessment of two landfill technologies for the treatment of municipal solid waste	https://dx.doi.org/10.1065/ica2004.09.180.6
Nikkhah et al., 2018	Hybrid landfill gas emissions modeling and life cycle assessment for determining the appropriate period to install biogas system	https://doi.org/10.1016/j.jclepro.2018.03.080
Beylot et al., 2013	Life cycle assessment of landfill biogas management: sensitivity to diffuse and combustion air emissions	https://dx.doi.org/10.1016/j.wasman.2012.08.017
Voronova et al., 2011	Environmental assessment and sustainable management options of leachate and landfill gas treatment in Estonian municipal waste landfills	https://doi.org/10.1108/14777831111170876
Ouedraogo et al., 2021	Comparative life cycle assessment of gasification and landfilling for disposal of municipal solid wastes	https://doi.org/10.3390/en14217032
Demetrious and Crossin, 2019	Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis	https://doi.org/10.1007/s10163-019-00842-4
Grzesik, 2017	Comparative environmental impact assessment of the landfilling and incineration of residual waste in Krakow	https://doi.org/10.5277/epe170411
Nabavi-Pelesaraei et al., 2017	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	https://dx.doi.org/10.1016/j.jclepro.2017.01.172
Al-Fadhli, 2016	Assessment of environmental burdens of the current disposal method of municipal solid waste in Kuwait vs. waste-to-energy using life cycle assessment (LCA)	https://doi.org/10.7763/ijesd.2016.v7.806
Assamoi and Lawryshyn, 2011	The environmental comparison of landfilling vs. Incineration of MSW accounting for waste diversion	https://doi.org/10.1016/j.wasman.2011.10.023
Abduli et al., 2010	Life cycle assessment (LCA) of solid waste management strategies in Tehran: landfill and composting plus landfill	https://doi.org/10.1007/s10661-010-1707-x
Mendes et al., 2004	Comparison of the environmental impact of incineration and landfilling in São Paulo city as determined by LCA	https://doi.org/10.1016/j.resconrec.2003.08.003

The selected studies are then analyzed and classified; several elements are examined for each paper and reported. The issuing year and the country and the journal in which they are published, are checked to get a summary view. The main characteristics of the LCA studies are summarized: the goal and functional units are initially evaluated to assess the pertinency of the paper. The characteristics of modelled landfill are reported, in terms of life cycle phases included, the landfill lifetime, and the system boundaries. Concerning the impact assessment phase, the selected papers are analyzed in terms of methods, impact categories and software used to calculate the environmental hotspots. A summary of the LCA results is considered to conclude the review, including possible sensitivity analyses.

4.2. Main characteristics of LCA studies related to landfills

The cases studies included in the review (as in Table 2) are distributed during the years as reported in Fig. 2. More than 50% of papers are published in the last 10 years; however, in recent years, the papers focusing on landfill don't follow the same increasing trend as the other WMS LCA studies, probably due to the decreased interest on this solution in the waste hierarchy and the reduction of its use, especially in developed countries. Out of the selected papers, 20 are comparative studies, while 3 studies analyze only some parts of landfill life cycle. Most of the studies although analyzed the traditional anaerobic landfill for municipal solid waste and either compared it with another typology or with different types of leachate and gas treatments. Most of the waste LCA studies compare different technologies to apply in the WMS; the comparison is usually made between the recycling or the thermal treatment with a traditional anaerobic landfill.

Although the developed countries are decreasing the landfill use, the geographical distribution in Fig. 3 shows that the majority of the LCA studies are from European countries. Only 5 studies were done in developing countries, of which most of them were done to compare the landfill with other treatment to prove their preferability over the landfill's. Over 40% of the analyzed papers specifies the ISO 14040 and ISO 14044 standards as methodological framework to conduct the LCA study. In two papers published before 2006 the references for LCA study are the standards published before the present version. However, almost 50% of the papers found did not specify the use of any standard to perform the study.

By virtue of the selection criteria used (first step – Screening), all papers are published on peer review international journals, but there is a particular concentration of papers in few journals.

In LCA studies about landfills, the functional unit (FU) is usually the landfilling of a certain amount of waste. Most of the studies use as FU a reference value of waste, like 1 ton or 1 kg, to be landfilled; this also sometimes includes characteristics of the type of waste and of the type of landfill and the lifetime. Some papers instead use as FU the total quantity of waste to be disposed or the quantity of electricity and heat produced form the landfill biogas. Although the waste fraction and characteristics assumed are different for each study, they are all considered to be from the municipal solid waste collection with average characteristics form the country or city where the landfill case study is located; only one study includes contaminated soil and construction and demolition waste to be disposed in the landfill.

As shown in Fig. 4 the attention of authors in LCA studies is not always referred to the entire life cycle of the landfill. Out of the selected papers, few cases only report the impacts related to all the landfill life cycle stages, from cradle to grave; frequently operation phase is included in the analysis, rather than the construction, closure or aftercare phases, that are considered by only few LCA studies.

In comparison with other treatment plants, which have immediate direct emission, the landfills release small concentrations of pollutants for a very long period of time. Because of the difficulties in considering the long-term emissions from the landfill, a hundred-year period is usually assumed in the landfill LCA studies. About 10% of the studies in literature assume 30 years to assess only the phase with the highest emissions while another 10% considered 140 years to evaluate the impact of the landfill for longer time.

During a LCA study, different choices that can affect the results have to be made; to assess the influence of those assumptions a sensitivity analysis can be performed. In the LCA of landfills many factors can be analyzed; according to Kirkeby et al. (2007) one of the most affecting elements is the waste type assumed. Only 8 studies among the selected papers included the sensitivity analysis. The analysis was done on input parameters like the energy consumed, the biogas collection and the gas production.

Due to the many assumptions that have to be made when analyzing the landfill, the results of the studies could have many uncertainties. To test those uncertainties the Monte Carlo uncertainty analysis can be done; only 2 papers performed this analysis.

When assessing the landfill impact on the environment through a life cycle methodology, all the steps of the landfill life should be considered, which includes all the materials needed for the construction and the energy used even after the landfill's closure. About 60% of the studies include the construction of the infrastructure or at least the fuel for the disposal of the soil and waste. Only about 40% of the studies include the waste transportation to the site due to the low influence on the results and due to the defined system boundaries. The leachate and biogas treatment are not always included as well. The leachate treatment is assessed in only 11 papers, while 5 of them only partially include it by assuming a removal efficiency but without the energy and materials to do the treatment itself. The biogas management instead is present in almost all the analyzed cases. Regarding the software used in waste LCA studies, the EASYWASTE is the preferred since it is used in 9 papers; probably because this software includes a landfill model that allows to use defaults datasets for conventional landfills. In few papers information about the software used for the impact assessment is reported: SimaPro is used in 4 papers, GaBi software in 3 studies, and EASETECH in 1 study.

The impact assessment method adopted in the LCIA step is declared in 20 studies only: the EDIP method is the most frequently named, followed by TRACI and CML. Otherwise, in all the studies a multicriteria impact assessment model is used to quantify the environmental impacts, through several impact categories, as represented in Fig. 5. The global warming potential is always included in the LCA studies. Moreover, acidification, ecotoxicity, eutrophication, human toxicity and ozone depletion are generally adopted to quantify environmental impacts of landfills. Some impact categories are not frequently used, and several categories are very rarely considered to quantify the environmental profile of landfills.

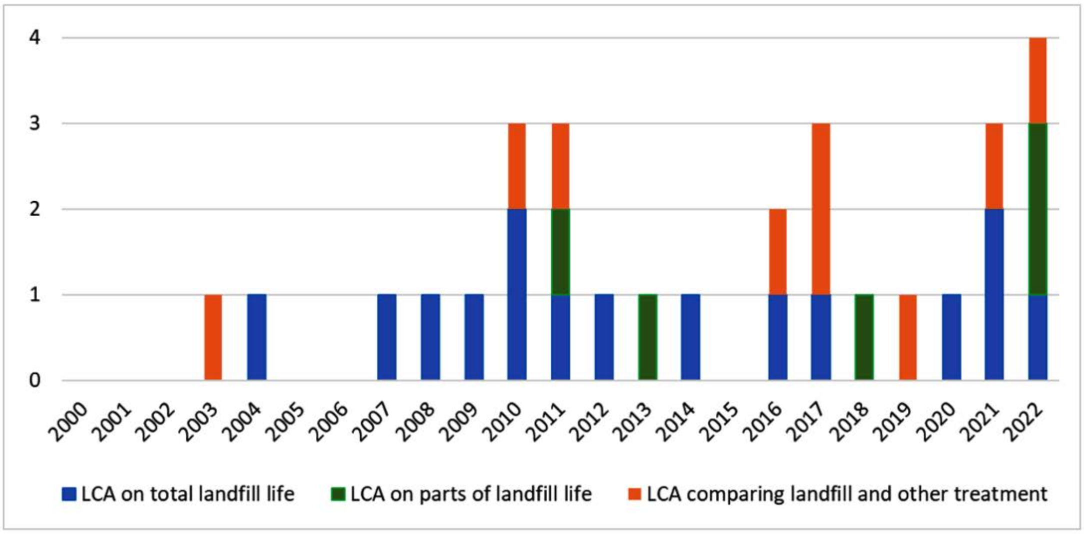

Fig. 2. Studies distribution in time divided by type of study

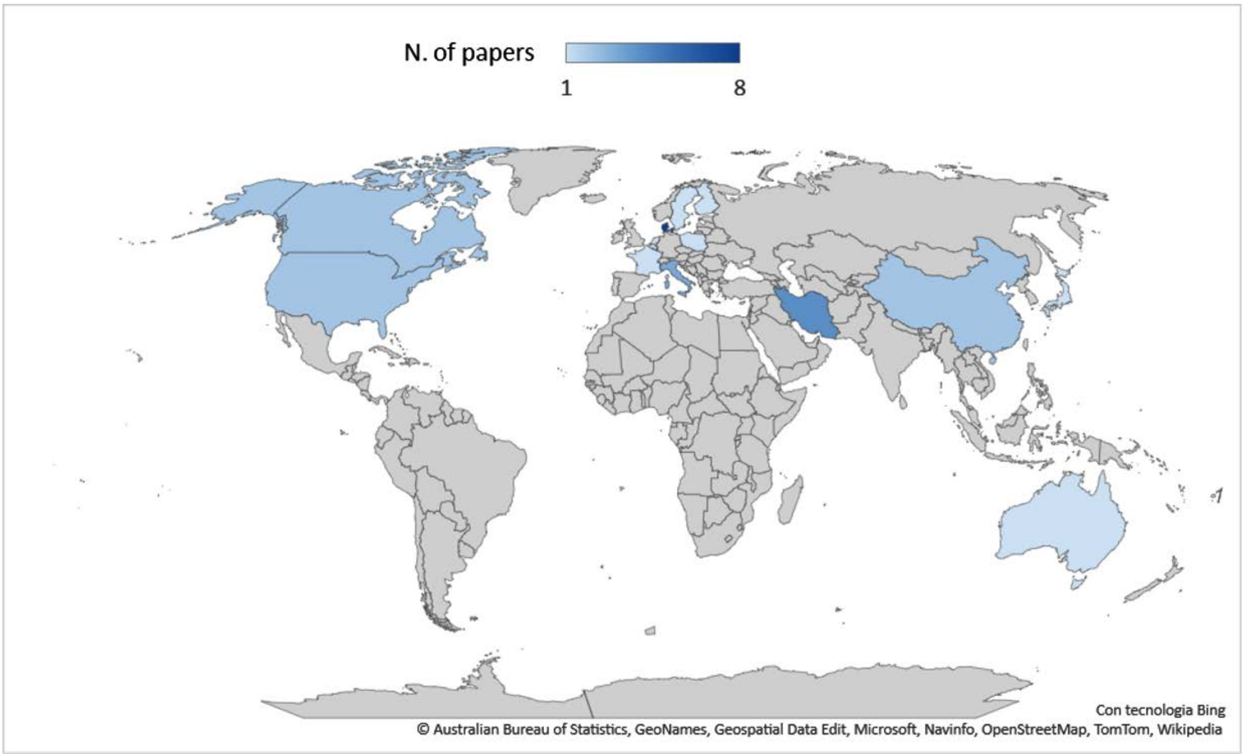

Fig. 3. Geographical distribution of landfill LCA studies

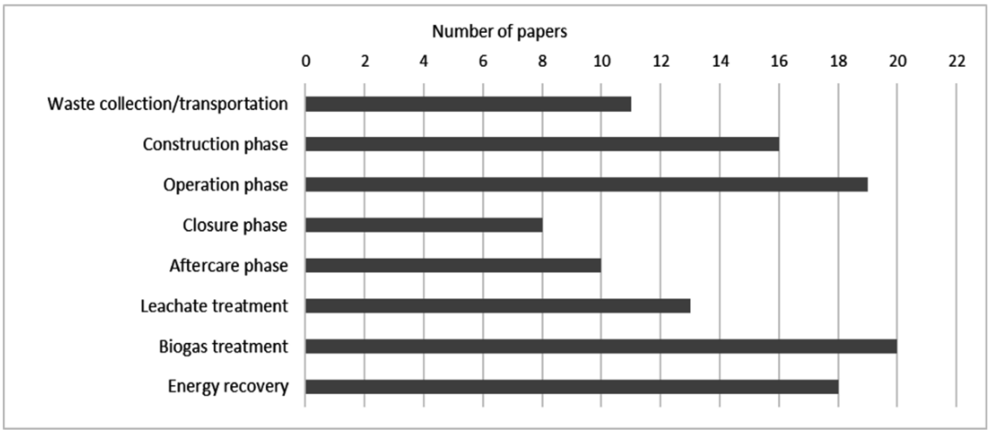

Fig. 4. Distribution of papers per life cycle phases included in the system boundaries

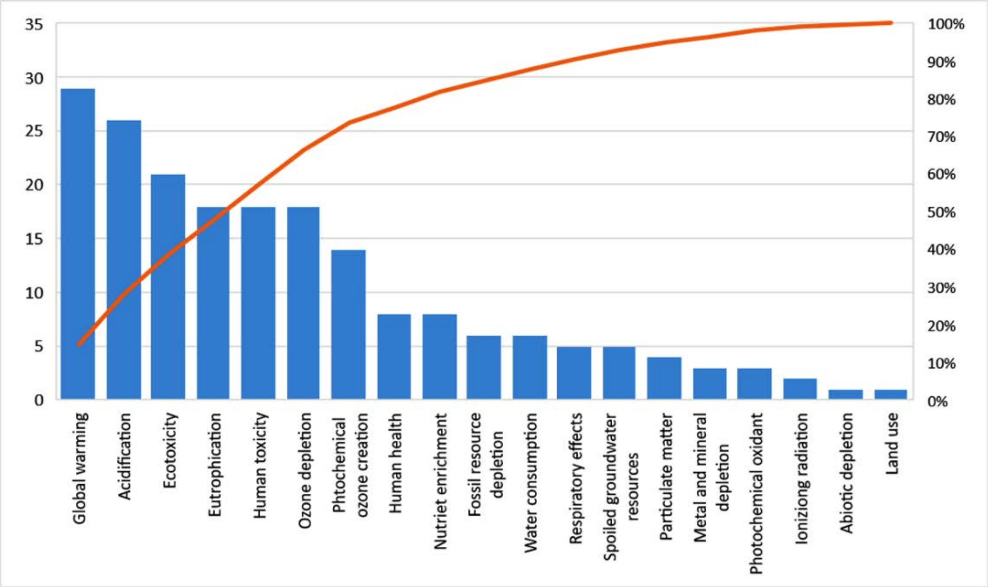

Fig. 5. Impact categories used in landfill LCA studies

4.3. Environmental performances of landfill

Different types of landfills are analyzed through the LCA methodology in scientific literature. The open dump, the conventional, the hybrid, the bioreactor landfill and, in only two studies, the semi-aerobic landfill were included.

The open dump is the worst alternative since it is defined as an uncontrolled disposal and there are no measures to stop the emissions of the waste on the environment. The studies addressing the problem of open dumps from a LCA point of view appears to have similar results; the dump shows to have a much higher impacts on global warming, human toxicity and ozone depletion potential compared to traditional landfill with leachate and biogas collection and treatment. These results prove the importance of the control of the emissions and the collection of biogas and leachate to significantly reduce the landfill impacts and improve its environmental performance (Damgaard et al., 2011). According to Beylot et al. (2013) the open dump has the worse impacts than the traditional landfill on the climate change, ozone depletion, human toxicity and ecotoxicity impact categories.

The most analyzed landfill type is the anaerobic landfill due to its wide use around the world. When compared with other WMS technologies it results to be the worse alternative due leachate and biogas emissions and the lack of material recovery. The production of biogas and leachate lasts for a long time with high concentrations of pollutants. According to Wang et al. (2021), the normalized results show that the traditional landfills mostly impact on the global warming potential due to the gas emission. From the results of the study of Kirkeby et al. (2007) emerges that the landfill biogas also has a relevant impact on human toxicity and photo chemical ozone. While the biogas can be collected and utilized for energy production, the leachate must go through numerous treatments to reach the legislative limits concentration. Both the direct long-term emissions from the leachate pollutants and the emissions of the treatment plant have relevant impact. As can be seen from the paper of Sauve and Van Acker (2021) wastewater treatment has a great impact on the ecotoxicity and human toxicity potentials.

Although it is not always considered, the construction of the landfill site can be one of the major contributors of the total impacts like in the case of Yang et al. (2014); the diesel used for daily operations appears to have a great influence on all the impact categories.

An advantage of this type of landfill is the possibility, when a high percentage of methane is produced, to use the biogas as an energy source. The energy recovery is highly influenced by the landfill design and composition of waste: the gas extraction can be done for a limited amount of time after which other possibilities have to be employed (Kirkeby et al., 2007). This benefit is limited, other than the period of high methane production and extraction, to the energy production already used in the area and that the landfill biogas would substitute. According to Manfredi and Christensen (2009) the energy recovery from the landfill gas allows to have avoided impacts greater than the landfill direct emissions on the global warming potential impact category when the electricity is produced in a coal fired power plant. This is because the green house generated in the power plant are higher than the ones emitted by the landfill to produce the same electricity. In this case, the energy recovery is also beneficial on impact categories like human toxicity (via soil and water), acidification, nutrient enrichment, and photochemical ozone formation; the negative contribution to the total impact of each category is although not enough to outbalance the impact from the direct emissions as seen in Fig. 6 (Manfredi and Christensen, 2009).

The waste composition also greatly influences this benefit; an example is given by Manfredi et al. (2010a) who analyzed the landfilling of low organic waste which resulted in poorer production of methane and lower avoided impact from energy recovery. Benefits of the energy recovery given by the high presence of organic waste are also proven by the paper of Manfredi et al. (2010b).

Different studies address the impacts of hybrid landfills respect to the traditional one; the results from those studies all agree to the better environmental performance of the hybrid landfill due to the active measures to stabilize the waste.

4.4. Environmental performances of the semi-aerobic landfill

From the literature review, two studies report the application of the LCA methodology to semi-aerobic landfills. Despite the limits related to these case studies, it is notable to analyze the main results because of the relevant information available, concerning the environmental profile associated to the semi-aerobic landfills. Moreover, they report important recommendations to support consistent evaluations about the environmental impacts related to the life cycle of a landfill.

The first study, published in 2009 by Manfredi and Christensen, compares the environmental performances of semi-aerobic and other type of landfills. The second one, recently published (Mazzi et al., 2022) quantifies the impacts associated to the entire life cycle of a semi-aerobic landfill, including construction, filling, aftercare, closure, and conversion.

Manfredi and Christensen (2009) compared 6 different types of landfills, from the worse option which is the open dump to newer technologies like the bioreactor and the semi-aerobic landfill. According to this study the semi-aerobic landfill total impact is lower than open dumps and are also slightly better than the traditional and bioreactor landfill (Fig. 7).

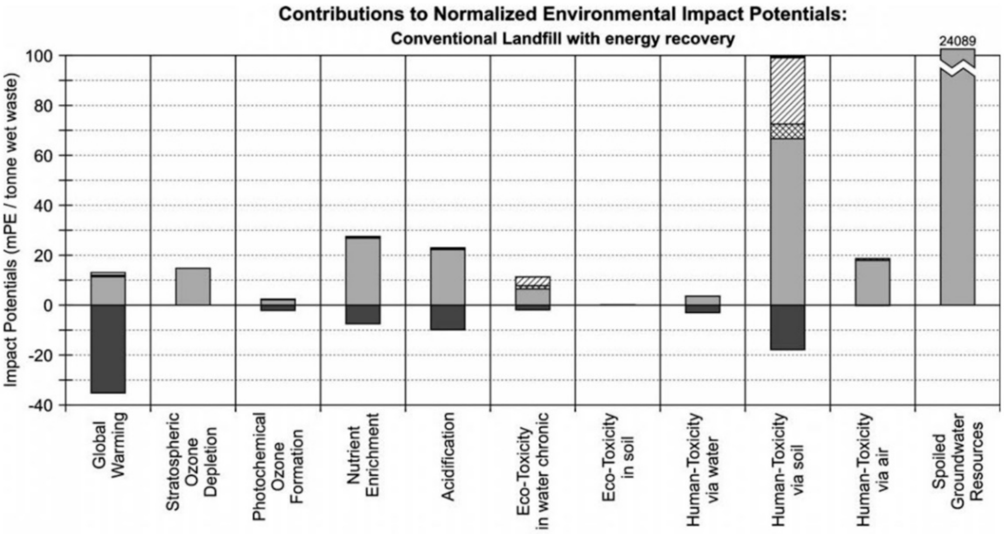

Fig. 6. Environmental impacts of conventional landfill (Manfredi and Christensen, 2009)

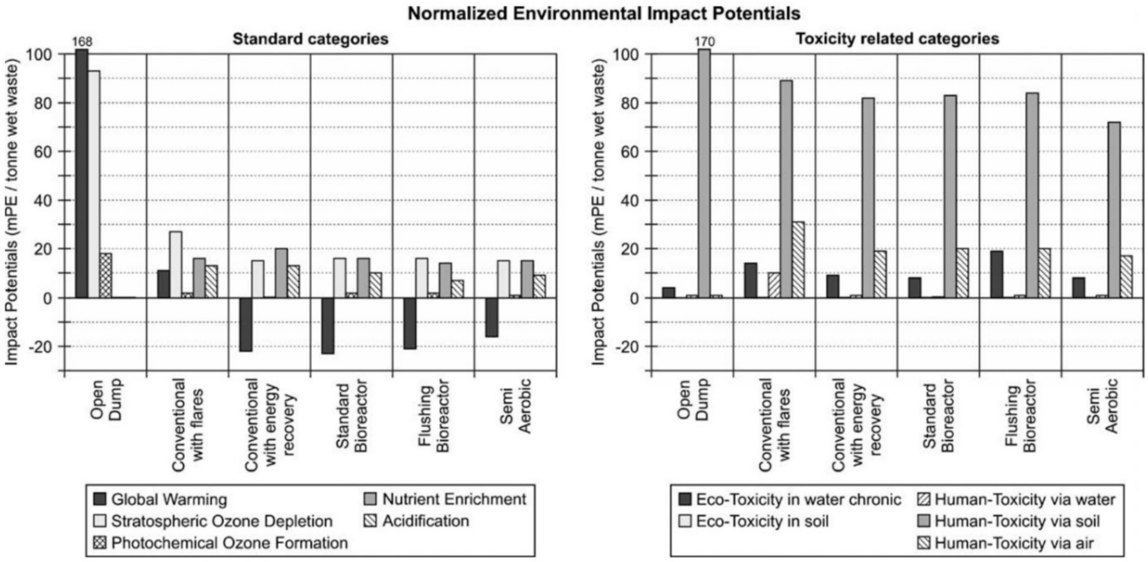

Fig. 7. Comparison of 6 landfill type's normalized impacts potential (Manfredi and Christensen, 2009)

According to the model used, Manfredi and Christensen (2009) took into account both anaerobic and aerobic conditions expected in the semi-aerobic landfill and they assumed that gas management and utilization for energy recovery was carried out for the first 8 years; in the same period leachate recirculation was carried out as well. Afterwards, an artificial air flow was activated to start waste aerobic degradation processes; as a consequence, methane concentration in the gas was assumed to drop to 5%.

From the results of the study by Manfredi and Christensen (2009) (Fig. 7) it was found that the semi-aerobic landfill had lower impacts in all the toxicity related impact categories in comparison to the other technologies analyzed while in the standard categories the benefits are less evident but still present.

Manfredi and Christensen (2009) demonstrate the main benefits of the semi-aerobic landfill compared to the traditional landfill. The direct emissions are lower than a traditional landfill due to the aerobic areas. The faster waste stabilization allows to decrease the impact of the biogas since the quantity of methane in it is low. The higher presence of CO_2 in the biogas decreases the global warming potential. A further benefit of this technology is the avoided impacts due to the leachate collection by gravity as the use of pumps can be avoided. The fast stabilization of the waste, that reduces the need for costly leachate treatment, makes this technology a great opportunity for both developed and developing countries. A disadvantage is the very limited possibility for energy production from the landfill biogas due to the low concentration of methane. The disadvantage is although limited to the country energy source for electricity production. Mazzi et al. (2022) assessed the potential impacts and the environmental performance of the semi-aerobic landfill technology through the LCA, using project data of an Italian pilot plant. All the life cycle phases were included into the system boundaries, from landfill construction to filling, aftercare, closure and conversion for future use. The results show that the overall environmental impacts associated to semi-aerobic landfill are primarily due to filling and aftercare phases, and secondly to construction and closure phases (Fig. 8).

The results of case study in Mazzi et al. (2022) show that the biggest share in the total impact is given by the leachate: even if its pollutants concentrations are below the concentration limit, the volumes released are significant and, consequently, the impact on the marine and freshwater ecotoxicity are relevant. Methane emissions reduction through enhanced methane oxidation would have a lower impact reduction than improving the efficiency of leachate treatment. 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. From the normalization of impact assessment results, 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.

The Italian case study analyzed in Mazzi et al. (2022) demonstrates the relevance of comprehensive analysis, including all the life cycle stages of landfill plant, from cradle to grave: as underlined by these results, materials used in landfill construction, filling and closure significantly contribute to the environmental profile of semi-aerobic landfill. From these results, it is notable that 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.

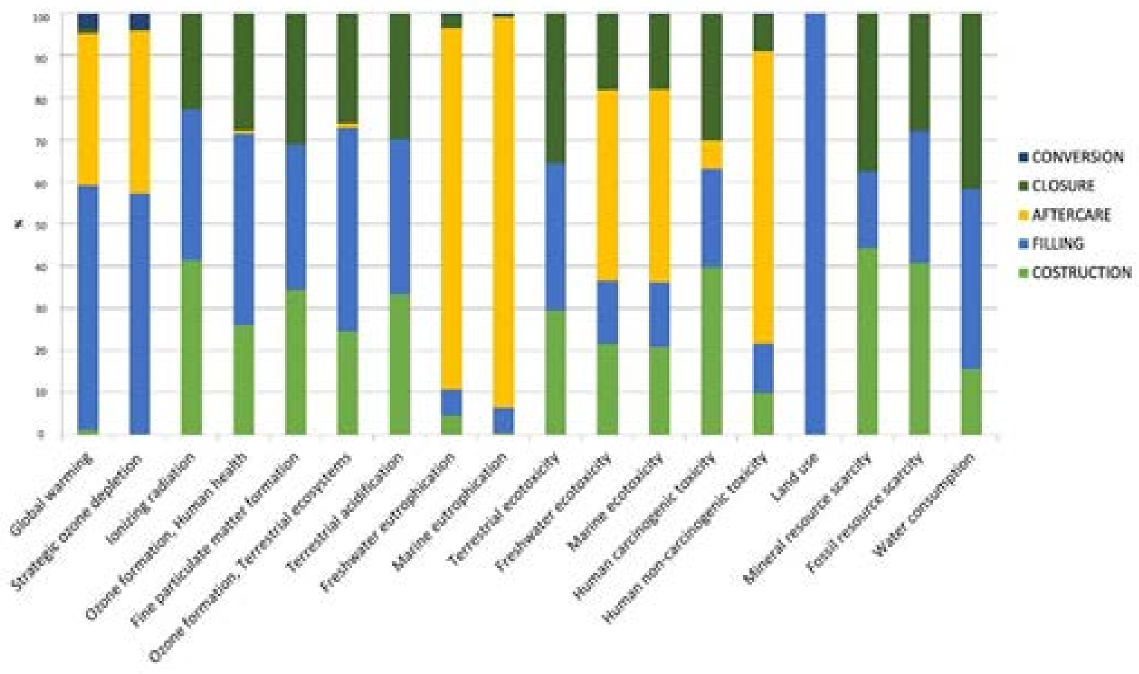

Fig. 8: Impact assessment results of life cycle phases of semi-aerobic landfill (Mazzi et al., 2022)

5. Conclusions

A literature review on different waste LCA studies, based on English paper from peer review international journals available online, has been performed to analyze the environmental profile related to landfill construction, filling, closure and aftercare. Different types of landfills have been taken into consideration. Strong focus has been placed on the impact assessment of municipal solid waste disposed in traditional landfill; different options for leachate and biogas treatment were compared in the reviewed studies. From the comparison of open dumps with other technologies emerged the importance of the control of the emissions to diminish the impacts. Active measures to increase the waste degradation, like in the bioreactor or hybrid landfill, was observed to improve of the landfill’s burden on the environment in various impact categories.

The benefits of the semi-aerobic landfill were described and its preferability was partially proven by the scientists. The semi-aerobic landfill was found to be effective in reducing the direct and indirect impact of the traditional landfill; indeed, it allows to reduce the biogas and leachate emissions, reaching waste stability in shorter times and leaving out the need of pumps and specific treatments. The waste stabilization is shortened by the aerobic areas that, at the same, reduce the methane concentration in the biogas limiting the energy recovery and its avoided impacts. Due to faster waste stabilization, the management of the landfill is shorter and easier making this technology viable also by developing countries. From the results published in these papers it is possible to state that the semi-aerobic landfill, decreasing the time its emissions have a concerning environmental impact, helps to move forward a more sustainable solid waste management.

Although the environmental benefits related to the semi-aerobic landfill are clear, evidences are limited by the lack of studies on this topic; only two papers in last 20 years focus the attention on the semi-aerobic landfill, and quantify the environmental profile associated to the entire life cycle of this technology. Further studies should be conducted to better analyze the total impacts of the semi aerobic landfill throughout its life. Newer research comparing different landfills, also inserted in the total solid waste management system performances should additionally be done including the sensitivity analysis varying the waste composition and landfill location.

These additional comparisons are helpful to further prove the preferability of this technology, in both developed and developing countries. Moreover, possible conversion into semi-aerobic conditions might be considered for closed traditional landfills.

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