Semi-Aerobic Landfill by Life Cycle Assessment Modeling

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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.

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

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][9][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][21][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.

2. 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.

3. 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][34][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.

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