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BIBLIOMETRIC ANALYSIS OF LANDFILL MINING: WORLDWIDE RESEARCH EVOLUTION

Anaxsandra da Costa Lima Duarte [1,2,*], Taise Bonfim Jesus [2] and Alessandra Cristina Silva Valentim [1]

[1] UFRB, Center of Exact and Technological Sciences, Rua Rui Barbosa, Cruz das Almas, Bahia 44380-000, Brazil
[2] UEFS, Department of Exact Sciences, Avenida Transnordestina, Feira de Santana 44036-900, Brazil

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ABSTRACT
Landfill Mining (LFM) aims to recover resources by partially or completely excavating waste stored in landfills. Research on Enhanced Landfill Mining (ELFM) has been advanced to include the combined valuation of waste as both materials and energy carriers. In this article we present an overview of the literature on the global development of landfill mining based on domestic waste. Here we analyze the existing information on the chronological and geographic distribution in countries that publish in the area, and to describe the dynamics of the conceptual and scientific knowledge. The analyzed articles were retrieved from Scopus, using the "Landfill* Mining" search term. The LFM research on co-occurrence network (1990-2022) found 29 terms in the first decade, increasing to 52 terms in the second decade and, finally, 234 terms in the third decade, indicating the importance of the LFM research field in present days. Four prominent aspects of LFM research can be observed: a. LFM provides an efficient contribution to waste management strategy, b. the objectives of LFM are similar to those of Circular Economy, c. LFM uses advanced techniques for identifying metals and chemical elements; and d. there is a need for ecological and ecotoxicological assessment, and determination of microorganisms and microplastics in the mined material.

1. INTRODUCTION

Landfill Mining (LFM) is a more sustainable waste management practice which aims to mitigate impacts related to landfills while recovering inactive resources (Laner et al., 2019). In the case of dumps, which cause greater concern due to environmental pollution, LFM practice is also relevant for revitalizing degraded areas (Sabour et al., 2020).

This practice was first carried out in Israel in 1953 as a way to obtain fertilizers for orchards (Krook et al., 2012). However, it was only revisited in the 1990s, with the aim of extracting methane and eliminating contaminants from the soil and water, without excavating the stored waste; only later landfill mining was developed to recover resources by partial or total excavation of waste (Jones et al., 2013).

LFM involves the excavation, processing, treatment and/or recycling of deposited materials, providing material and energy recovery, as well as land reclamation (Frändegård et al., 2013; Marella and Raga, 2014). However, mining can unearth fractions of hazardous waste and cause slope instability, due to excavation, and also generate large volumes of materials with low commercial value (partially and completely decomposed organic matter, corroded metals, contaminated soils) (Chandana et al., 2021).

In order to include operating landfills and emphasize the recovery of waste, a more advanced concept was proposed: the Enhanced Landfill Mining (ELFM), characterized by the combined valuation of different flows of waste, both as materials (waste-to material, WtM) and as carriers of energy (waste-to-energy, WtE), in addition to land reclamation (for residential and industrial uses) and extending landfill life (Einhäupl et al., 2019; Esguerra et al., 2021). The practice is carried out aiming at the maximum recovery, for example, the non-recyclable fraction needs to be stored again in such a way that future mining is possible (Bosmans et al., 2013).

ELFM has operational steps similar to LFM; enhancement consists of the use of innovative technologies (such as gasification, pyrolysis and plasma incineration) for energy recovery, aiming to reduce the final volume of waste to almost zero and including the recovery of historical and future waste, considering the ecological, social and economic criteria. It also involves actions regarding the mitigation of CO_2 emissions, health and safety of workers and

* Corresponding author:
Anaxsandra da Costa Lima Duarte
email: anaxsandra@ufrb.edu.br

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neighbors, quality of separation fractions, location, cost of labor, equipment and market value (Burlakovs et al., 2017; Chandana et al., 2021; Danthurebandara et al., 2015; Van Passel et al., 2013).

The improvement proposed by ELFM is a consequence of the increasing environmental problems, and is not depending on the use of any specific technique or equipment. Thus in this paper both terms will be used interchangeable, and the acronym LFM will be used for both.

Calderón Márquez et al. (2019) cataloged, based on the relation between the proposed objectives and compliance with the Sustainable Development Goals, about one hundred projects carried out in North America, Europe, Asia and the Middle East; the authors concluded that LFM fits into the current transition that countries all over the globe are making towards the Circular Economy.

Despite being relatively recent, some literature review has already been published on the field of Landfill Mining. Krook et al. (2012) performed a meta-analysis with 39 papers published between 1988–2008, with the aim of identifying the main challenges for LFM implementation. The authors concluded that there are three main challenges in this field of research: a. technological innovation, b. addressing the underlying conditions for its achievement, and c. developing standardized frameworks for evaluating the performance of material recovery.

Additionally, Krook & Baas (2013) reviewed papers published in a special volume of the Journal of Cleaner Production, on urban mining and landfill mining, in order to explore the feasibility of such waste management approaches and also identify which social changes and which search fields are essential for its dissemination. The authors compared the environmental impact of two mining techniques, namely, biogas recovery (in-situ mining) and landfill waste recycling (ex-situ mining). They concluded that ex-situ mining are significantly more positive, as the recycling of mined materials avoids the extraction of raw materials and decreases primary emissions during the manufacture of products.

In a more recent review article, Vollprecht et al. (2021) analyzed the entire research output of NEW-MINE (European Union Training Network for Resource Recovery Through Enhanced Landfill Mining) with regard to its practical applicability in waste management systems. These authors found that the amount of resources recovered from landfills can be significant, if the use of the inert fraction and fuels become viable technological routes. They also point out that the quality and credibility of anthropogenic resources obtained from waste in landfills represent significant challenges for future ELFM projects.

Jain et al. (2023) published a review focused on the difficulties related to the extraction, analysis and use of excavated materials from 34 landfills (reported in 27 articles) and observed issues related to: a. convergence regarding the parameters that must be determined, which are defined according to the intended use of the material; and b. the application of the ore can be obstructed due to the high concentration of contaminants (fine solids, heavy metals and chlorine).Despite the relevance of the cited reviews, the LFM research field has advanced since the years 2012/2013 and is already present in several countries, in addition to those belonging to the European Union, which are in the article by Vollprecht et al. (2021). Thus, the aim of this work is to present an overview of the literature on the global development of domestic waste landfill mining. Here, we present information about the chronological and geographic distribution in countries that publish in the area and describe the conceptual structure underlying it. We also investigate the chronological development of publications and the main research institutions that take the lead in the research about LFM.

1.1 List of acronyms

DLM: Dynamic landfill management
DST: Decision Support Tool
ELFM: Enhanced Landfill Mining
FDEM: Frequency-domain electromagnetic
FTIR: Fourier Transform Infrared Spectroscopy
GCMS: Gas Chromatography Mass Spectrometry
IWWG: International Waste Working Group
KEG: Kalman Ensemble Generator
LBR: Aerobic Leach Bed Reactors
LCA : Life Cycle Analysis
LFM: Landfill Mining
MCA: Multi-criteria Analysis
NPV: Net Present Value
RDF: Refuse Derived Fuel
REE: Eletronic waste
SRF: Solid Recovered Fuel
WtE: waste-to-energy
WtL: waste-to-land
WtM: waste-to material
WtP: Waste-to-Product

2. METHODS

The analyzed articles here were retrieved on January 5, 2023 from the Scopus database, with the search equation “Landfill* Mining”; this term was required to appear in the abstract, title and/or keywords of the paper. An initial refinement was carried out, in which only article-type documents, published in Journal-type sources, published until 2022, remained in the database. In subsequent refinement, we removed articles which were: a. review or opinion articles; b. documents which do not present all the elements of a scientific article (authors, abstract, keywords); c. articles with content outside the specific theme; d. articles that deal with waste outside the scope of this research. With the resulting articles, using the function “Export”, the following information was collected: Citation information, Bibliographic information, Abstract and keywords, Financing details, Other information.

3. RESULTS AND DISCUSSION

The initial search on the Scopus database found 334 documents; after the first and second refinements, this number was reduced to 237 and 190 articles, respectively. A list of these articles can be found in the Supplementary material.

3.1 General status

The selected articles were published between 1990 and 2022, with an annual publication growth rate equal to 9.64% and an average of 5.97 articles per year. Figure 1 presents the world's annual scientific production in the Landfill Mining research field. It can be observed that in the first two decades (between 1990-1999 and 2000-2009) publication was incipient, with less than one article published per year. From 2013 on, a sharp growth line can be observed, with an annual growth rate of 27.8%, and an average of 13.8 articles published each year.

Dhar (2015) stated that the promulgation, in the USA, of stricter environmental legislation propelled the interest in LFM; in the early 1990s, landfills were closed and then post-closure costs increased. The author also reports that in Europe and Asia, legislation aimed at the remediation of old landfills and the removal of those that hinder urban development.

The year of 2013 marks a change in the curve slope in Figure 1 and coincides with the start of the operation of the first comprehensive Enhanced Landfill Mining (ELFM) project by the Machiels Group, Belgium (Danthurebandara et al., 2013).

The 190 articles in the field of LFM have been published in 63 different journals. By Bradfort's law, the essential sources (source core) for understanding the state-of-the-art of LFM are the first two journals with the highest publication, namely, Waste Management (total = 38 articles) and Detritus (total = 22 articles). The first journal, launched in 1989, renovated and managed by IWWG (International Waste Working Group) since 2002, is dedicated to the presentation and discussion of information on solid waste, in term of reserch, management, education, and economic and environmental assessment.

The second journal publishes work from scientific sources not limited to research laboratories but includes results from full-scale plants, best practices, operational activities, discussions in working groups and associations, unsuccessful experiences, case studies from developing countries, administration, etc. Probably for that reason, it has published on LFM a greater number of articles in the last five years than the journal Waste Management, which published only 12 articles in the same time frame.

The lack of a more flexible type of journal for LFM publication has been identified as an obstacle since 2012. Krook et al. (2012) suggested that, due to the immaturity of the research field, a significant amount of valuable practical knowledge would be available in the gray literature and in organizations that practice landfill mining, and that the creation of the journal Detritus would possibly allow the publication of this type of material.

Detritus and Waste Management are both official journals of IWWG and intend to promote integrated and sustainable waste management, practical scientific development in the field and effective communication within of the professional community (Cossu, 2018). Figure 2 presents the 20 institutions that most publish in the Landfill Mining area. It is important to note that from the 14 countries mentioned in Figure 2, only 6 of them (Brazil, China, India, Russia, Singapore and United Kingdom) are not part of the European Union, however, the United Kingdom was part of it until the beginning of 2020.

Among developing countries, the most expressive ones in the field of LFM are China and India. China began to publish in this field in 2006, but remained stagnant until 2013, when the "Thought of Ecological Civilization" (Xiang-Chao, 2018) gained force.

The Twelfth Chinese National Five-Year Plan for Municipal Solid Waste Treatment and Management suggested a budget of 21.1 billion Chinese Yuan ($ 3.5 billion) for the ecological remediation of 1,882 old landfills in China from 2011 to 2015 (Zhou et al., 2015). In turn, India only started publishing in 2018, but with a remarkable performance and

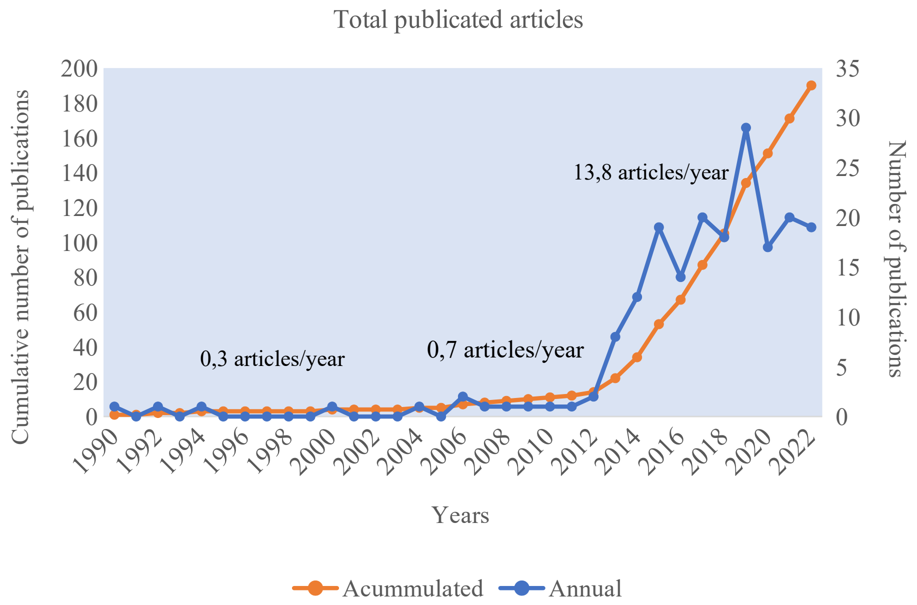

FIGURE 1: Worldwide Annual Scientific Production.

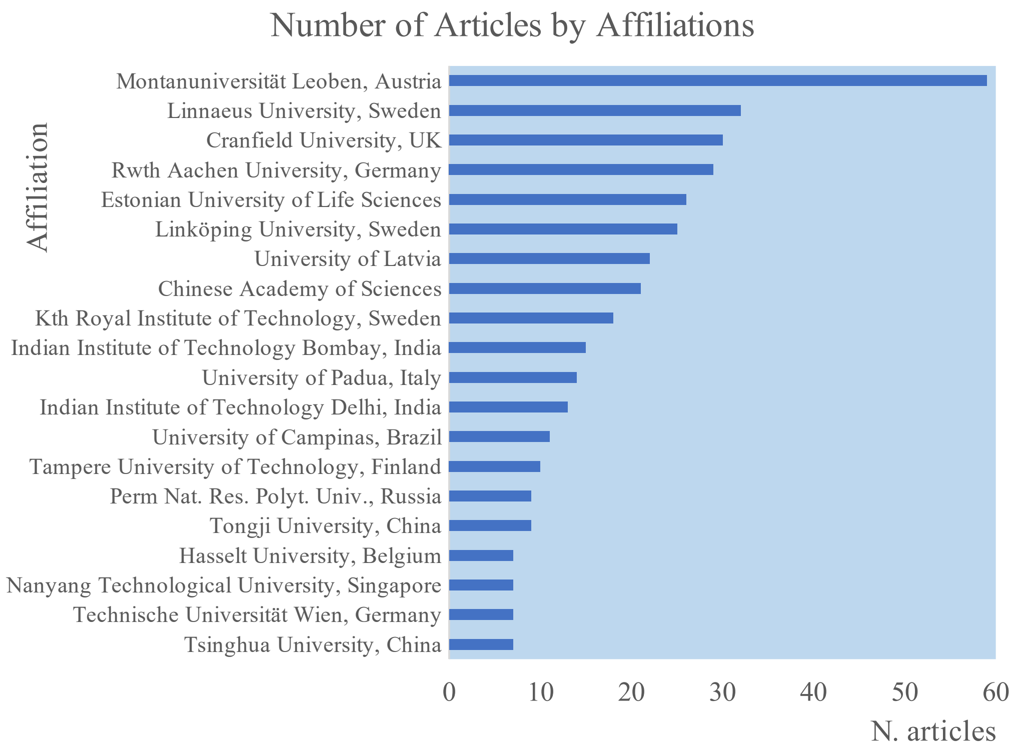

FIGURE 2: Number of articles published by the main research institutions.

is already on the top compared to other countries in number of articles.

3.2 Conceptual Framework

Figure 3 shows the distribution of co-occurrence terms over three decades of LFM research,between 1990 and 202. The terms were selected from theabstracts and titles of the papers. For each decades the terms were grouped according to clusters, reflecting the technical and scientific interests in the given period.

In the first decade (1990-1999)29 terms were grouped into three clusters. LFM Products, both beneficial ones (such as soil, aggregates, fine fraction) and others more linked to emissions and potencial contaminantions (such as leachate, gas production, methane, heavy metals, environmental analysis).

LFM space optimization, as a strategy for landfill operation, which includes varied terms (feasibility, landfill space, organic material, recycling, economic assessment, mining operation) reflectings the benefit deriving from LFM in terms of material and space recovery. Landfill mass conditioning, which includes terms related to improving and speeding waste stabilisation (aerobic landfill, airflow technology, composting, degradation, moisture).

In decade 2000-2009 the six following clusters (out of 52 terms) were determined: Mined waste components (black soil, fine fraction, glass, nitrogen and phosphorus). LFM management and strategies (reduction and recycling strategies, market, business studies and government regulation) suggesting the use of waste as material or energy. Characterization of mined waste, including dumps, probably with a focus on the application in fuel, humus and recovery of soil and metals. It is also noteworthy the high occurrence of the term Urban waste to reinforce the relevance of LFM for this type of waste. The other clusters are composed of terms with low occurrence, because they were, at the time, emerging techniques: Energy use of mined waste; Landfill geophysical characterization and Plastics recovery.

The extended decade 2010-2022 includes 234 terms grouped in eight clusters. It is noteworthy that the number of terms quadrupled in relation to the previous decade indicating the increased relevance of the LFM field.

Hull, Krogmann and Strom (2005) identified the reasons for the high prevalence of research on recovery of landfills through LFM in Central Europe, which coincides with the terms mentioned above: a. availability of special cleanup funds for contaminated sites; b. being a cheaper or more publicly accepted remediation option; c. clearing sites for housing establishment, especially in densely populated and gentrified areas; d. fuel supply for the cement industry; e. reusing available landfill infrastructure which simplifies the licensing process.Some terms that have recently emerged show the maturation of the technique, as several issues related to the technical feasibility are analyzed: e.g. ELFM, LCA, Landfill taxes, Stakeholders.

Cluster 1 (45 terms) refers to the Physicochemical characterization of mined residues (Arsenic, Cadmium, Carbon, Cobalt, Copper, Nitrogen, Organic material, Phosphorus) and the treatment given to these residues (Aerobic landfill, Aerobic leach bed reactors -LBR, Anaerobic Treatment, Biodegradation, Dry Mechanical process) in order to use this resource (Composting, Offsite application, Reuse, Soil).

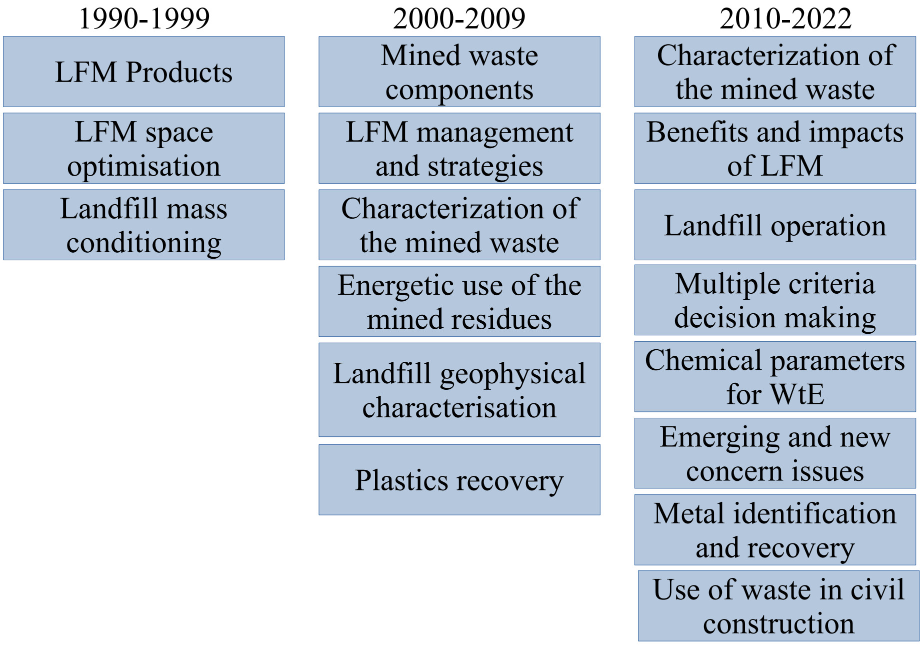

FIGURE 3: Clusters of significant terms which appeared in titles and abstracts of LFM papers published in course of three decades.

In this cluster appear the terms WtE (from waste to energy), WtL (waste-to-land, from waste to land space), and WtM (from waste to material) which consolidate the purpose of the LFM: to take advantage of the waste already landfilled in the energy, to production, to increase the useful time of the landfill or to make the area available for other purposes and material recovery to reinsert it directly into the production chain. There are also terms that deal with economic viability, such as the use of fine fractions from landfills, which would contribute to increased revenues and reduced expenses, given the ower need for backfilling (Parrodi et al., 2018).

Cluster 2 (44 terms) deals with the Benefits and impacts of LFM. There are terms that portray the various aspects that must be observed, such as a. economic (Economic Assessment, Market operational, Upcycling, Profitability, NPV - Net `Present Value); b. Environmental (Environmental analysis, Impact assessment, LCA, Global Warming, CH_4); c. social (Public acceptance); d. landfill costs (Aftercare control, Airspace use, Land reclamation, Land space, Material flow, Re-landfilling); e. possible uses (Aggregate, Cement industry, Coal, Fossil, Energy, Gas production, Plasma).

Gaitanarou, Tentes and Katselis (2014) argue that the market is not suitable for effective LFM for three reasons: a. there is no economically sustainable demand for recycled materials; b. there is a lack of technical advances for full exploration; c. There is evidence that landfilling waste can contribute to CO_2 sequestration. Therefore, Bhatnagar et al. (2017) state that LFM projects will become more profitable and necessary when the global demand for metals and the costs of their extraction grow, considering that primary sources of high-quality ores decrease.

NPV of a LFM project is inversely proportional to the waste treatment and disposal costs, re-landfilling taxes and gate fees for external WtE treatment; on other hand is directly proportional to the avoided costs for landfill management and aftercare (Laner et al., 2019).

Cluster 3 (36 items) refers to Landfill operation, its composition, management, location, collection rate and closure (Public park, Recreational area, Remediation) and how LFM can promote environmental benefits (Resource recovery, Renewable energy, Revenue) when considered a public policy (Government regulation) and a sustainable secondary source of raw material asmetals (Secondary copper, Zinc), trough techniques for extracting and processing excavated material (Stationary Separation Plant).. In this cluster, the term WtP summarizes the new perspective of LFM: excavated waste as raw material for industrialization in the form of new products. According to the WtP concept, waste treatment by-products are used to manufacture valuable co-products, that is, scalable (Bosmans et al., 2013).

It is important to note that, although the focus of this article is urban waste landfills, when it comes to metal recovery, the analyzed articles include in their studies two relevant terms: industrial landfill and REE (electronic waste) Despite the great theoretical benefit of LFM Burlakovs et al. (2018) found in the case of 2 REE landfills located in Sweden and Estonia that only a small fraction of elements can be exploited using existing technologies, therefore the potential can be referred to as a reserve for the future.

Cluster 4 (35 terms)deals with Decision-making with multiple criteria (Decision Maker,MCA - Multi-criteria analysis, DST - Decision support tool). These criteria are: a. environmental (Environmental footprint, Upcycling, Soil pollution), b. social (Stakeholders, Post consumer), c. operational (DLM- Dynamic landfill management, Mechanical sorting, Waste management) and d. economic (Circular economy, Secondary fuel). In this cluster, the term ELFM appears for the first time, and already has a high occurrence. ELFM is an evolution of the term LFM whose objective is to fully determine the value of the various waste cases (Danthurebandara et al., 2015). Research with nanomaterials (Solgel) also becomes popular. The geophysical characterization, also present in the previous decade, continues to be relevant in this decade.

Cluster 5 (29 items) deals with and analyzes more deeply the Chemical characteristics (Chemical Composition, FTIR - Fourier Transform Infrared Spectroscopy, Thermogravimetry) aiming at the Energetic use of the mined residues (WtE) either in the form of thermal energy (Ash, Biochar, Lignina content), electricality (H_2, Syngas) or fuel (Biomass, Fuel RDF - Refuse Derived Fuel, Oil) through biological, thermal and thermochemical processes (airflow technology, gasification, thermal treatment, thermochemical process, torrefaction).

The most common challenges when using the fuel fraction as RDF are the high ash content, the presence of chlorine and low energy value. However, we can use this fraction by implementing pre-cleaning techniques like sorting, cleaning and drying (Jain, Kumar and Kumar, 2023).

The term Plastic is the one with the highest occurrence and the highest number of connections with other clusters; it is linked to the terms Fine Fraction, SRF-Solid Recovered Fuel, Gasification, Calorific Power, Power Generation, and Pyrolysis, which points out to the various technological routes for applying the material. Another point to be researched is the amount of lignin in landfills that function as bioreactors.

Cappucci et al. (2020) highlighted that the scenario of recovering mined plastic is environmentally preferable because it prevents the extraction of a non-renewable resource (crude oil) and emissions from its refining process.

Cluster 6 (19 terms), presents very recent issues (mainly published between 2021 and 2022), namely: determination of microorganisms and microplastics present in mined material, ecological and ecotoxicological evaluation, application of enzymes to stabilize the material and use of Gas Chromatography Mass Spectrometry (GCMS) for chemical characterization. These terms point to possible paths for Emerging and new concern issues.

Orupold et al. (2022) found a low toxicity of the fine fraction of the mined to bacteria, marine rotifer and microcrustaceans, and also a slight inhibitory effect on seed germination. On the other hand, Singh and Chandel (2022) concluded that the fine fraction cannot be used directly in agriculture, and that the most promising alternatives are soil enrichment for the growth of biomass or renewable energy crops.

Microplastics are a chemical contaminant that can be present in the fine fraction, and they can prevent, in the long term, water infiltration into the soil; therefore, further research is needed to develop adequate and economical treatments for the fine fraction (Singh and Chandel, 2021).

Cluster 7 (15 items) refers to an increasingly relevant theme: Metal identification and recovery. This is a very recent area of research, with studies published in 2022, which employ advanced techniques for identification (FDEM - Frequency-domain electromagnetic and KEG - Kalman Ensemble Generator) and separation of metallic materials (Magnetic sorting, Physical sorting).

Cluster 8 (11 terms) presents a new technological route for the Use of waste: in civil construction (Building material, Burnt clay brick, Green construction), which uses both more advanced techniques for the separation of fractions of the mined material (Ballistic separation, used to recover calorific and fuel fractions) and the most common ones (Manual screening, possibly targeting the coarsest fractions of demolition waste).

In relation to fine fractions, another factor must be considered in terms of economics: the costs of additional cleaning or treatment processes to recover critical metals and fuels; research on these techniques is in broad development (Esguerra et al., 2021). For the best use of this fraction, it is suggested to determine: chemical and mineralogical composition, location, size and volume of the landfill, type of landfilled waste, operational procedures, degree of degradation of landfilled waste, markets for recovered materials and environmental and health risks (Parrodi et al., 2018).

Figure 4 summarizes all the 238 key terms in LFM research. Thirteen terms were mostly cited in the three decades of LFM research,3 of which are very relevant. The production of stabilised organic matter ("Compost") was the first case of LFM product that still today remains relevant, particulary in developing countries, where generally selective collection is not common and, consequently, a large amount of organic matter is sent to landfills.

The second important term is Environmental Analysis, since there is still no validated method for environmental assessment, although there is recent research employing the LCA. Additionally, there is a trend towards the increase of related terms, such as Biological Assessment, Ecological Assessment and Ecotoxicological Assessment. The third term is Fine Fraction, which corresponds to 40 to 80% by weight of the total waste excavated (Parrodi et al., 2018) and therefore can be decisive in determining the viability of Mining.

Some recent terms in the field of LFM, published around the 2020s, were: Torrefaction, Physical-chemical characteristics, Landfill age and Thermochemical processes. These terms may indicate the direction to which the research points: to know the mined material in greater detail, in order to identify its potential use and investigate the applicability of Technologies for energy production with the material.

In order to choose the best technological route, the age of the landfill, and consequently the degree of inertization of the excavated material, must be considered. Thus, the characterization of the deposited material (composition and/or physical-chemical characteristics) continues to be an important topic within landfill mining research (Krook et al., 2012).

Economic evaluation is also a very recurrent term. The literature points out that, in most cases, resource extraction through landfill mining cannot yet be carried out solely for commercial reasons, but it is only an economic option if there are subsidies or other types of support (Van Passel et al., 2013). On the other hand, standardization of eco-

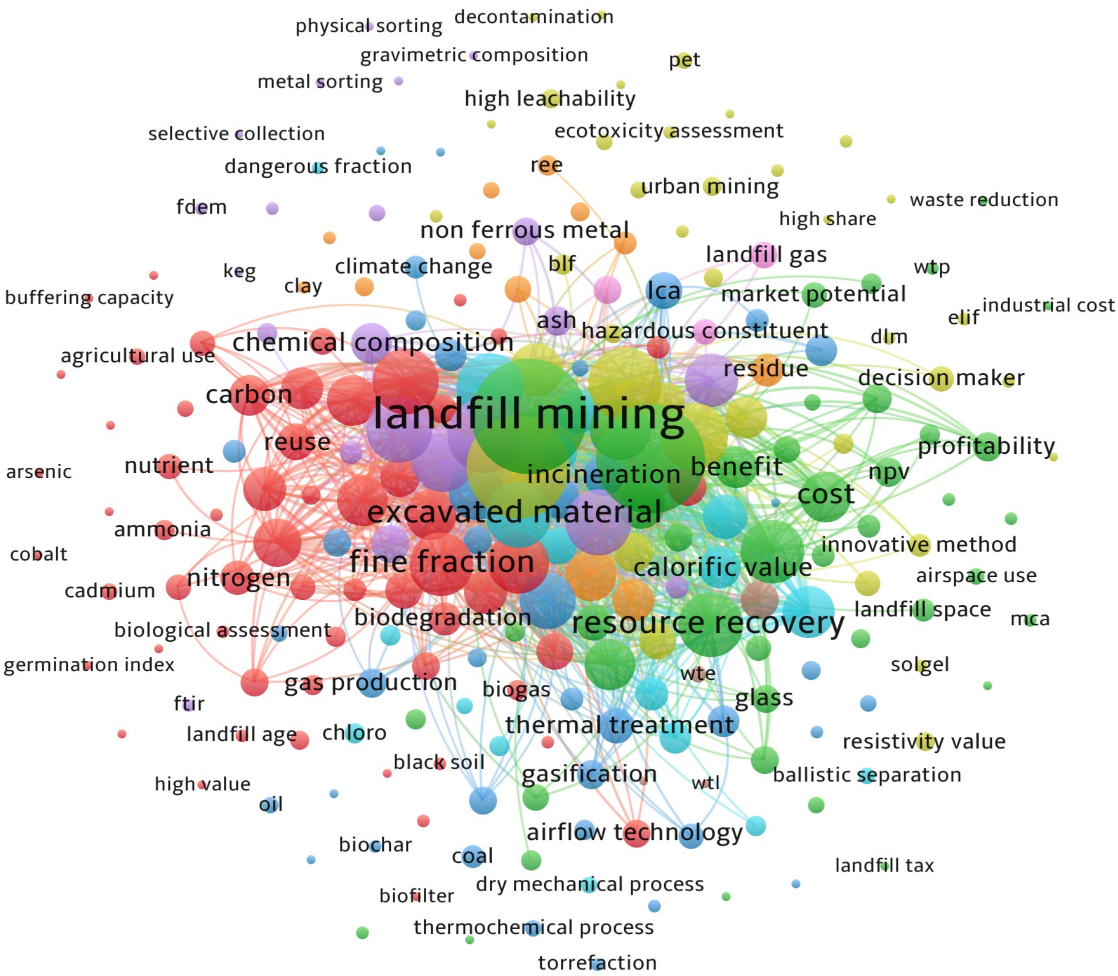

FIGURE 4: Complete network of co-occurrence of terms in the years 1990-2022.

nomic assessment is difficult, because the economic performance of landfill mining is restricted to highly specific projects carried out in different regions and under varying conditions and objectives (Laner et al., 2019).

The most recent terms, published in the years 2021 and 2022,that are noteworthy are: Standard limits and Regulatory body. Both keywords suggest the need for the public power to play a leading role in implementing the LFM. Esguerra et al. (2021) suggest two ways to improve the economic performance when using RDF and Fine Fraction: a. replacing taxes with tax incentives for the production of renewable energy and b. imposition of a quality standard dependent on the leachability of the pollutant and not the total concentration.

4. CONCLUSIONS

Based on information extracted from the Scopus database, we can observe the evolution of the research in Sanitary Landfill Mining. In the first decade of publication (1990-1999), the terms were centered on in-situ mining, whith the following technological aspects: a. with aerobic treatment aiming at obtaining compost; b. biogas capture (with or without reuse) and leachate treatment; and c. increased airspace. In the second decade (2000-2009) there was still a predominance of in-situ mining, as the most used terms in the articles related with energy use, compost production and remediation of dumps.

Over the years, four new aspects of research have been introduced and gained prominence in the last decade (2010-2022). The first aspect is the understanding that Mining is an efficient strategy for the complete management of waste, and that its implementation will positively influence the goals of reducing and recycling waste. In the second decade, LFM also started beeing seen as a business opportunity, subject to public regulation. In the third decade, LFM viability has been understood in the context of public policy.

The second aspect is the recognition that similarity between LFM's objectives with to those of the Circular Economysuch that, there is a prominence of terms related to ex-situ mining, in which the resource is mined in order to be used as energy, land, material or product. Thus LFM evolved into ELFM. In this context, the most promising techniques for operating a landfill (which will be mined in the future) and for treating the mined resources are BLF (Bioreactor Landfill) and Pyrolysis, respectively. Research on the application and cleaning/treatment techniques of the fine fraction is in full development.

The research of the Fine Fractions of the mined waste took place throughout the publication period and is still a field to be explored, since it is related to different routes of exploitation (plastic, fuel, RDF, energy). Therefore, its characterization is relevant even in cases of mining in landfills. Furthermore, the determination of heavy metals, mainly in fine fractions and in landfills, is also a relevant point of research, due to the risk of contamination and possible environmental restrictions.

The evolution of the LFM pratice can also be observed in relation to characterization techniques. In the first decade, characterization consisted of quantifying the common by-products of landfills; in the following decade there was a technological development, with the chemical and geophysical characterization. In the last decade, in order to recover metals or combustible materials, FPXRF analysis has also been used. This suggests a trend in this research field: the validation and standardization ofsampling and tests.

The third aspect is the use of advanced techniques for identifying metals (FDEM, KEG) and chemical elements (FTIR, GCMS, Thermogravimetry). The fourth aspect is in the field of ecological and ecotoxicological evaluation, with determination of microorganisms and microplastics present in the mined waste.

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