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The Impact of Biodegradable and Compostable Plastic Products on the Occurrence and Contamination of Microplastics in Compost Leachate

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The composting of organic and bio-waste is widely practised, and in some regions, it is even a mandatory waste management practice. A valuable by-product of this process is the nutrient-rich liquid known as compost leachate, which holds great potential for use in agriculture and horticulture. This investigation delves into the content, production methods, and impact of compost leachate on different crops while also emphasising its susceptibility to external factors. Compost leachate forms during composting and serves as an effective soil amendment material containing essential nutrients, microorganisms, and humic acids beneficial for plant growth. The quality of this by-product can be compromised by contamination from organic waste materials. Today, there has been widespread adoption of biodegradable or compostable plastic products in household composting systems due to misconceptions or public attitudes towards their usage. In-home composting, the process of decomposition might be slower, and there could be issues with the conventional waste management systems that are still commonly used. Additionally, not all degradable products are exclusively made from natural materials. Sometimes, synthetic polymer chains are utilised to accelerate degradation. This study aims to explore, through a simulated experiment, the possibility of microplastic contamination in composting environments, primarily due to the presence of biodegradable and compostable plastic items in these settings. The research findings indicate that the potential risks of microplastics to compost and compost leachate have been insufficiently explored, only recently becoming a focal point. The key conclusions suggest that the development of strategies to address these ecotoxicological factors is becoming increasingly pressing.

1. Introduction

Composting is a method of waste management that converts organic compounds into compost through a microbial process. This promotes crop growth, absorbs pesticides, enhances the crop's defences against certain factors, and reduces the polluting effect of heavy metals (Yao et al., 2023). In the 1990s, there was a lot of interest in water-based compost preparations, leading to the development of various processes and methods (Scheuerell and Mahaffee, 2002). As a result, compost products are known by several names: compost tea, organic tea, aerated compost tea, aqueous fermented compost extract, compost extract, amended extracts, steepings, and sludges (Litterick et al., 2004). Compost tea is a liquid organic preparation produced by soaking compost in a liquid, usually water, for a period of a few hours to two weeks, then extracting and oxygenating it, with or without the addition of additives and without the use of solvents. (Pergola et al., 2023). High-quality compost leachate can only be made from a fine-textured, pathogen-free compost containing soluble minerals, beneficial microorganisms, humic substances and phytohormones, with minimal phytotoxic compounds (Pant et al., 2012). The final characteristics are heavily influenced by the compost's feedstock, maturity, and processing (Saba et al., 2023). There is growing concern today about the physical contamination of compost used in various agricultural and horticultural sectors (Okori et al., 2024). The presence of non-biodegradable contaminants in composting materials is linked to the presence of contaminants such as plastic, glass, and

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metal in mature compost, which degrade the quality parameters of the compost (Cattle et al., 2020). In terms of composting and compost leachate, there has been a recent focus on biodegradable and compostable plastic products as alternatives to traditional plastics (Afshar et al., 2024). A compostable plastic is a polymer that, during the decomposition process, converts at least 90 % of its carbon content into carbon dioxide, as specified by ASTM International Standard (D5338) (Lucas et al., 2008). Bioplastics are materials derived from biopolymers, generally produced by combining components such as starch and plasticisers, polymers with processing and colouring additives, or polymers reinforced with natural fibres (Lackner et al., 2023). The importance of addressing plastic pollution has become a global priority, extending beyond the European Union (European Commission, 2018) to include organisations such as the World Economic Forum (WEF) (World Economic Forum, 2019) and the United Nations (United Nations Industrial Development Organization, 2019).

In December 2015, the European Commission adopted the Circular Economy Action Plan titled "Closing the Loop - An EU Action Plan for the Circular Economy" (European Commission, 2015). The strategy aims to develop a new consumption paradigm for European citizens that contributes to achieving a climate-neutral circular economy with minimal environmental impact. In connection with the concept of closing the loop, the circular economy transcends any single sector (Guerra-Rodríguez et al., 2020) and is essential for achieving the United Nations Sustainable Development Goals (SDGs) (Schroeder et al., 2019). In recent decades, the European Union has introduced numerous sustainable waste management regulations and policy concepts, central to which is the five-tier waste hierarchy established by Directive 2008/98/EC (European Commission, 2008). This framework was amended by Directive 2018/851, which mandates households to separately collect or recycle bio-waste by December 31, 2023 (Directive (EU) 2018/851, 2018). The plastics industry primarily operates within traditional linear processes, while bio-based plastics, biodegradable or compostable plastics (World Economic Forum, 2019), which represent the concept of a "circular" plastics economy, account for only 1 % of the total plastic production in 2022 (European Commission, 2022). The joint report by the WEF and the Ellen MacArthur Foundation found that, if no action is taken on plastic waste, not to mention the microplastic contamination affecting ecosystems, the ratio of plastic to fish in the ocean is projected to reach one to three by 2025, and plastic may outweigh fish in the ocean by weight by 2050 (Ellen MacArthur Foundation, 2016). The policy framework supports a “sustainable” plastics economy (Rosenboom et al., 2022) by enhancing our understanding of bioplastics and encouraging the recovery and recycling of plastics instead of focusing on energy production or landfill disposal (Visco et al., 2022). This approach also involves the promotion of bio-based, biodegradable or compostable plastics (European Commission, 2022). The EU Taxonomy, the Single Use Plastics Directive, the Plastic Carrier Bags Directive, the Packaging and Packaging Waste Directive, as well as the Waste Framework Directive address biobased, biodegradable, and compostable plastics. However, there is currently no specific EU legislation dedicated solely to bioplastics (European Bioplastics, 2024).

The EU policy framework on biobased, biodegradable and compostable plastics, adopted in 2022, serves solely as a guideline within existing EU legislation (European Commission, 2022). While it is non-legislative, it has the potential to inform future EU policymaking, including initiatives on eco-design for sustainable products and microplastics (European Bioplastics, 2024). According to the European Bioplastics and Nova-Institute (2020), bioplastics are plastics that are either bio-based and biodegradable, bio-based but not biodegradable, or fossil-based but biodegradable. Compostable plastics form a subset of biodegradable plastics, which can only be broken down through industrial processes in specialised facilities for composting or anaerobic digestion. Packaging that is compostable under the EN 13432:2000 European standard is industrially compostable; however, conditions for home composting can significantly differ, making home composting infeasible. Currently, there is no mandated minimum threshold for bio-based content in plastic goods, and there is also a lack of a standardised certification or labelling protocol to determine what constitutes a bio-based plastic product (European Commission, 2022). The Circular Economy Action Plan emphasises that to avoid misleading consumers, expanding the meaning of ‘biodegradable’ or ‘compostable’ labels is essential to prevent improper handling and disposal of these plastics (European Commission, 2022). According to European Bioplastics (2022), the global bioplastics market is dominated by lactic acid (PLA) and starch blends (20.7 % and 17.9 %, respectively), two biodegradable plastics. The use of biodegradable products is predominantly proposed in cases where there is a high risk of release into the environment to avoid their accumulation in natural and man-made environments (European Commission, 2020). However, several studies question the effectiveness of biodegradable plastics in terms of degradation, and biodegradable products with high degradation potential have been found to have a higher risk of fragmentation than conventional plastics (Wei et al., 2021), creating major problems related to the subject of microplastics (Cheung and Not, 2024). In addition to the problems of microplastics, additives used in biodegradable plastics may also pose a risk to the health of the environment (Flury and Narayan, 2021). Overall, it is evident that there is a significant need for well-founded testing and certification standards regarding the degradation of plastics in the open environment, ensuring the safe breakdown of additives used in the production of biodegradable plastics, avoiding consumer deception, and ensuring proper labelling of plastic products, as claims such as 'Compostable!' should not be made without

comprehensive evidence (European Commission, 2022). This research offers novel insights by analysing the key components and their interplay within relevant literature.

2. Methodology

The aim of the paper is a bibliographic, model-based approach to the risk factors of microplastic emissions from biodegradable and compostable plastic polymer products for compost and leachate. This research aims to examine the occurrence and risks of microplastics released from biodegradable and compostable biopolymer products in compost and compost leachate based on the literature. It also investigates how software-based network analysis can improve the understanding of these relationships while addressing existing gaps in their integration in current research. Ultimately, the results aim to contribute to the development of more effective strategies for incorporating circular economy principles into policy frameworks. By applying software-based network analysis, the study quantitatively evaluates the connections between these aspects and highlights areas requiring further research. It also aims to provide feasible recommendations for the effective integration of these principles into policy and practice, particularly in relation to managing the risks associated with microplastics in compost and compost leachate.

To test the fundamental hypotheses and propositions of the research, a bibliometric analysis was conducted using the Elsevier bibliographic data tool combined with VOSviewer version 1.6.20 (Van Eck and Waltman, 2020). This software tool was utilised to construct and visualise bibliometric networks of primary keywords in the fields of compost leachate, biodegradable compostable plastic polymers, and the resulting microplastics. The text mining feature of VOSviewer was employed for the analysis of co-occurrence networks. Based on VOSviewer, five types of bibliometric network analyses were performed: citation, bibliographic coupling, co-occurrence, co-citation and co-authorship relations. This paper adopts a bibliometric and content-review approach based on the total link strength of the most recent and relevant articles and studies on the subject. The analysis concludes with three complementary visual maps: cluster-based network visualisation, time-dependent overlay visualisation and concentration-based density visualisation.

3. Results

It is a startling fact that in the Elsevier database, there are only 54 articles on the topic of leachate and microplastics using combined keywords. This low number of publications suggests that the research area of understanding the release of microplastics and assessing the associated risk chain during the use and composting of biodegradable and compostable plastic polymer products is still an emerging and under-explored field. The distribution of these 54 articles is as follows: 3 articles in 2020, 3 articles in 2021, 16 articles in 2022, 22 articles in 2023, and 10 publications until June 2024. This indicates a growing interest and focus on this topic over the past few years, with a significant increase in the number of publications in the most recent years. Further analysis reveals that of these 54 articles, 26 are review articles, 16 are research articles, 9 are book chapters, and 3 fall into other categories. This suggests that the research community is actively synthesising the existing knowledge and exploring new research directions in this field. Figure 1 illustrates the distribution of the examined articles' topic-relevant network according to the year of publication, providing a visual representation of the temporal trends in this research area.

Based on the results obtained in the initial phase of topic-relevant research, it can be concluded that the most pertinent subjects in this field included food waste and its associated compost, biodegradable plastics, compost leachate, and the emergence of microplastics. These areas were identified as highly relevant due to their direct impact on environmental sustainability and waste management practices. In the middle of the available period, the focus of research expanded to include broader aspects of waste management, food waste treatment, and biodiversity. This shift in focus reflects an increasing awareness of the complex interactions between waste management practices and ecological health. Studies during this time began to explore the implications of waste management on ecosystem services, the role of biodiversity in waste decomposition processes, and innovative methods for enhancing the efficiency of food waste treatment. However, the most recent findings indicate a notable shift in research priorities. There has been a growing focus on climate change, addressing the current challenges in waste management systems, bioplastics, and the treatment and implications of sewage sludge. This shift underscores the urgency of adapting waste management practices to mitigate climate change impacts and address the evolving challenges posed by increased plastic use and the need for sustainable waste treatment solutions.

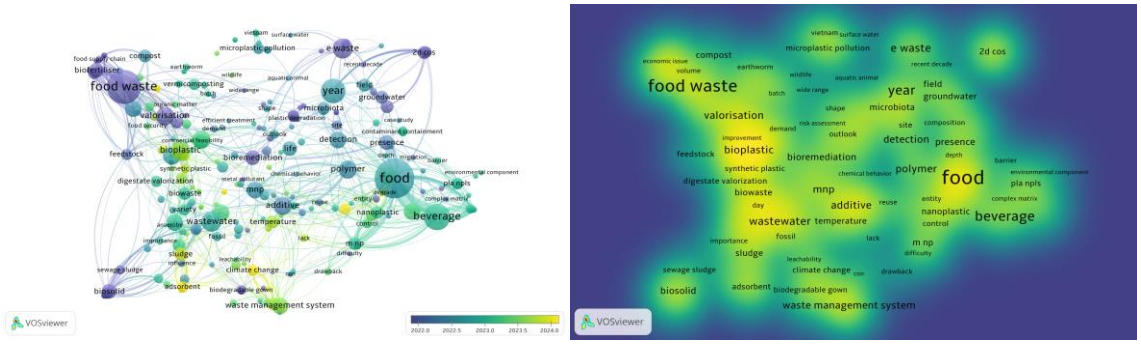

Figure 1: Overlay and density visualisation (Based on Elsevier, own edited by VOSviewer)

Recent research highlights the intersection of waste management and environmental challenges, stressing the need for integrated approaches to create resilient systems. Figure 1 shows keyword density in the current research landscape, with a strong focus on food waste generation, reflecting efforts to address its environmental impact. Keywords like bioplastic, bioremediation, and environmental risk management are increasingly relevant, relating to sustainable materials and methods for pollution control. Bioplastic offers an alternative to conventional plastics, while bioremediation uses living organisms to treat contamination. Waste treatment remains a major concern, with biodegradable materials receiving special attention as eco-friendly alternatives. These trends point to a comprehensive strategy addressing waste management and environmental sustainability.

The cluster analysis identified 13 distinct clusters (Figure 2). The first cluster consists of 47 items and primarily explores the biotechnological and organic aspects of the topic. This cluster emphasises the scientific investigation into organic processes and biotechnological applications relevant to the subject matter. The second cluster comprises 31 items and includes themes related to ecology and biology. This cluster focuses on understanding the ecological and biological impacts and processes associated with the research topic. The third cluster contains 27 items and encompasses topics such as micro-pollution, healthcare, and compost leachate.

The results of the cluster analysis indicate that compost leachate research is the third most significant area. The fourth cluster, which has 24 items, focuses on biodegradation, nanoparticle formation, risk management, and plastics. This cluster highlights the importance of studying material breakdown, nanoparticle formation, and associated risks. The fifth cluster, also with 24 items, concentrates on aquatic ecosystems and the risk of microplastic contamination, underscoring the growing concern about microplastics' impact on water environments. The sixth cluster, with 20 items, addresses soil protection, reflecting the significance of preserving soil health in environmental studies. The seventh cluster, containing 19 items, deals with waste management, suggesting that research on waste management challenges is not as prominent in current scientific directions. The eighth cluster, also with 19 items, examines the analytical aspects, focusing on methodologies and techniques used to study the subject. The ninth cluster, with 17 items, covers food waste, emphasising the importance of addressing this issue within environmental sustainability.

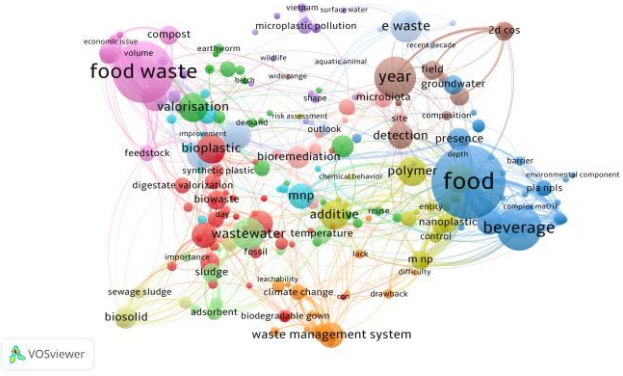

Figure 2: Network and cluster visualisation (Based on Elsevier, own edited by VOSviewer)

The tenth cluster, with 16 items, focuses on bioremediation and biostimulation, highlighting the use of biological methods to remediate contaminants and stimulate beneficial activity. The eleventh cluster, with 14 items, addresses sewage sludge and its chemical aspects, while the twelfth cluster, also with 14 items, investigates the impact of microplastics on aquatic ecosystems. The thirteenth cluster, with 10 items, focuses on waste pre-treatment, emphasising the processes involved in preparing waste for further treatment or disposal.

The examination of these clusters illuminates a multifaceted research field that grapples with the intricacies of waste management and its environmental ramifications. Each cluster offers distinctive perspectives that enhance our comprehensive understanding of the aspects of waste management, highlighting the connections between waste generation, environmental well-being, and sustainability. It must be emphasised that ecotoxicological parameters like heavy metal pollution and microplastics have not been extensively studied or regulated. The connections between various research domains highlight the necessity of interdisciplinary cooperation in addressing the complex challenges associated with waste. As the field of research progresses, fostering collaboration among these diverse disciplines will be crucial for formulating comprehensive strategies that promote sustainability and resilience in waste management practices. By bridging the gaps between these research clusters, scholars can cultivate synergies that deepen our comprehension and stewardship of waste, ultimately contributing to more sustainable and resilient ecosystems and communities.

4. Conclusions

A study conducted on waste and environmental research has revealed that the main topics of interest have evolved over time. Initially, there was a focus on food waste, compost, biodegradable plastics, leachate from compost, and microplastics. However, as research progressed, the scope expanded to include waste management, food waste management, and biodiversity. More recently, there has been a growing interest in climate change and the challenges posed by waste management systems, bioplastics, and sewage sludge. The study also identified 13 distinct thematic areas in the research landscape. These clusters covered a range of topics, such as biotechnology, ecological and biological concerns, micropollution, health, biodegradation, and more. Notably, research on waste management challenges ranked lower in terms of scientific priorities compared to bioenergy and waste management. However, leachate research, particularly the impact of biodegradable substances on environmental risk management, received significant attention. Overall, this study provides valuable insights into the evolving research landscape, highlighting critical areas of focus and emerging trends that are shaping the future of environmental sustainability research. To address the identified gaps, the study recommends: 1) Increasing research focus on waste management challenges, such as the development of more efficient and sustainable waste management systems; 2) Expanding leachate research to better understand the environmental impacts of biodegradable substances and improve risk management strategies; and 3) Fostering an integrated, multidisciplinary approach that leverages the interconnections between the identified thematic clusters to develop holistic solutions for environmental sustainability.

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