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RESEARCH TRENDS ON HYDROTHERMAL CARBONIZATION FOR MUNICIPAL SOLID WASTE MANAGEMENT

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RESUMO

A gestão de resíduos sólidos urbanos (RSU) constitui um desafio ambiental, demandando alternativas de tratamento e valorização. O interesse pela carbonização hidrotérmica (CHT) como uma rota termoquímica para a valorização da fração orgânica úmida dos RSU, convertendo-a em um material sólido carbonáceo denominado hidrocarvão, tem sido notado na literatura científica. Nesse contexto, este estudo apresenta um breve panorama dos avanços científicos relacionados à CHT aplicada aos RSU. Assim, foi realizada uma busca sistemática nas bases de dados Scopus e Web of Science para identificar as tendências de pesquisa. Os resultados indicam um crescimento da produção científica sobre CHT aplicada aos RSU a partir de 2016, com pico entre 2020 e 2023, seguido por um leve declínio nos anos mais recentes. Itália e China lideram em número de publicações, embora a comunidade científica esteja distribuída globalmente. A rede de coocorrência de palavras-chave revela uma abordagem de pesquisa integrada, centrada na otimização do processo, na diversidade de matérias-primas e na caracterização do hidrocarvão, com ênfase crescente em avaliação do ciclo de vida, economia circular e integração com a digestão anaeróbia. De modo geral, os resultados demonstram que a CHT de RSU é um campo de pesquisa estabelecido, com forte potencial para contribuir com a transição para sistemas de gestão de resíduos mais sustentáveis.

PALAVRAS-CHAVE: Carbonização hidrotérmica, Hidrocarvão, Biocarvão, Resíduos Sólidos Urbanos, Valorização de resíduos.

ABSTRACT

The management of municipal solid waste (MSW) poses an environmental challenge, requiring alternatives for treatment and recovery. Interest in hydrothermal carbonization (HTC) as a thermochemical route for the recovery of the wet organic fraction of MSW, converting it into a solid carbonaceous material known as hydrochar, has been noted in scientific literature. In this context, this study presents a brief overview of scientific advances related to HTC applied to MSW. Thus, a systematic search was conducted in the Scopus and Web of Science databases to identify research trends. The results indicate a growth in scientific output on HTC applied to MSW starting in 2016, peaking between 2020 and 2023, followed by a slight decline in recent years. Italy and China lead in the number of publications, although the scientific community is distributed globally. The keyword co-occurrence network reveals an integrated research approach, centered on process optimization, raw material diversity, and hydrocarbon characterization, with a growing emphasis on life cycle assessment, the circular economy, and integration with anaerobic digestion. Overall, the results demonstrate that MSW HTC is an established field of research with strong potential to contribute to the transition toward more sustainable waste management systems.

KEYWORDS: Hydrothermal carbonization, Hydrochar, Biochar, Municipal solid waste, Waste valorization.

INTRODUCTION

The municipal solid waste (MSW) management is one of the greatest environmental challenges. With rapid population growth and increasing consumption patterns, global MSW production is expected to continue to grow significantly in the coming decades, placing increasing pressure on collection, treatment, and final disposal systems. Inadequate management of this waste, particularly disposal in landfills and dumps, contributes significantly to greenhouse gas (GHG) emissions, especially methane (CH_4) and carbon dioxide (CO_2). In the context of a climate emergency, the search for solutions that minimize these emissions and add value to MSW has become imperative from both an environmental and a socioeconomic perspective (UNITED NATIONS ENVIRONMENT PROGRAMME, 2024) .

Among the various components of MSW, the organic fraction deserves special attention, as it accounts for the largest share by mass of waste generated in low- and middle-income countries, often exceeding 50% of the total composition (COOK et al., 2026). Various technological routes have been studied and implemented for the valorization of the organic fraction of MSW, with composting and anaerobic digestion being the most established approaches. Composting yields a stabilized humic product for agricultural use, while anaerobic digestion enables the generation of biogas for energy recovery and digestate as a biofertilizer. However, both technologies have limitations related to treatment efficiency, operational requirements, and, in the case of composting, low prospects for energy recovery, driving the search for complementary or superior alternatives (POLICASTRO; CESARO, 2022; ZAMRI et al., 2021).

In this context, hydrothermal carbonization (HTC) emerges as a promising alternative for the valorization of the organic fraction of MSW (Figure 1). HCT is a thermochemical process that occurs in an aqueous medium, typically at temperatures between 180 and 250 °C and corresponding autogenous pressure, with residence times ranging from hours to tens of hours. Under these conditions, the wet biomass is converted into a solid carbonaceous material called hydrochar, as well as a liquid phase containing soluble organic compounds and a gaseous phase. The resulting hydrochar exhibits physical and chemical properties markedly different from those of the original biomass (e.g., higher carbon content, greater calorific value, hydrophobicity, and a developed porous structure), which gives it a wide range of potential applications. In the energy sector, hydrochar can be used as a solid fuel, while in agriculture, its characteristics allow for its use as a soil conditioner, contributing to water and nutrient retention and to carbon sequestration in the soil. In environmental applications, hydrochar has demonstrated the ability to adsorb organic and inorganic contaminants, such as heavy metals, gases, and emerging contaminants. The final properties of the hydrochar and, consequently, its suitability for each of these applications are determined by the main HTC process variables: temperature, residence time, solid-to-liquid ratio, pH of the medium, and composition of the feedstock (CAVALI et al., 2023).

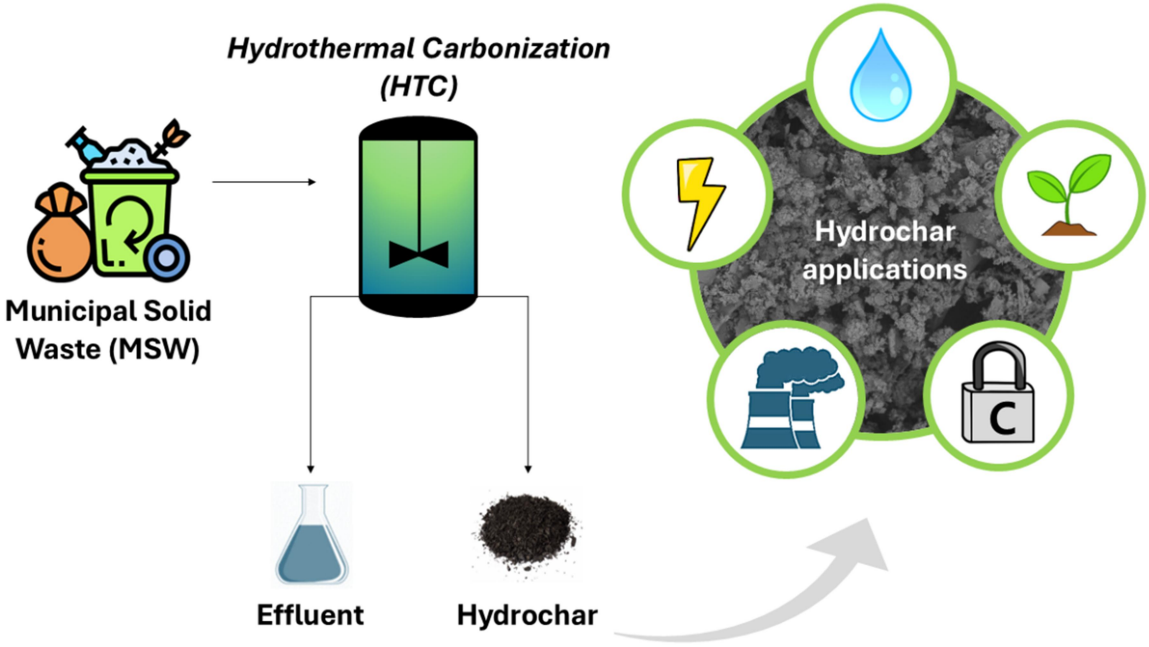

Figure 1: Hydrothermal carbonization (HTC) and potential hydrochar applications. Source: Authors.

OBJECTIVE

This study aims to present an overview of the research trends on HTC related to MSW.

METHODOLOGY

A systematic literature search was conducted in April 2026 using the Scopus and Web of Science databases (Figure 2). The search strategy employed the combined keywords "*hydrothermal carbonization*" AND "*municipal solid waste*" applied to titles, abstracts, and keywords. Only original research articles were included, while other document types (e.g., reviews, conference papers, editorials) were excluded to ensure consistency in the analysis. No restriction on publication year was applied, allowing the retrieval of the complete historical evolution of the topic across both databases. The retrieved records were exported in BibTeX format, merged, and processed in the R programming environment using the Biblioshiny interface (ARIA; CUCCURULLO, 2017). Prior to the bibliometric analysis, duplicate records were identified and removed from both databases using R-based tools.

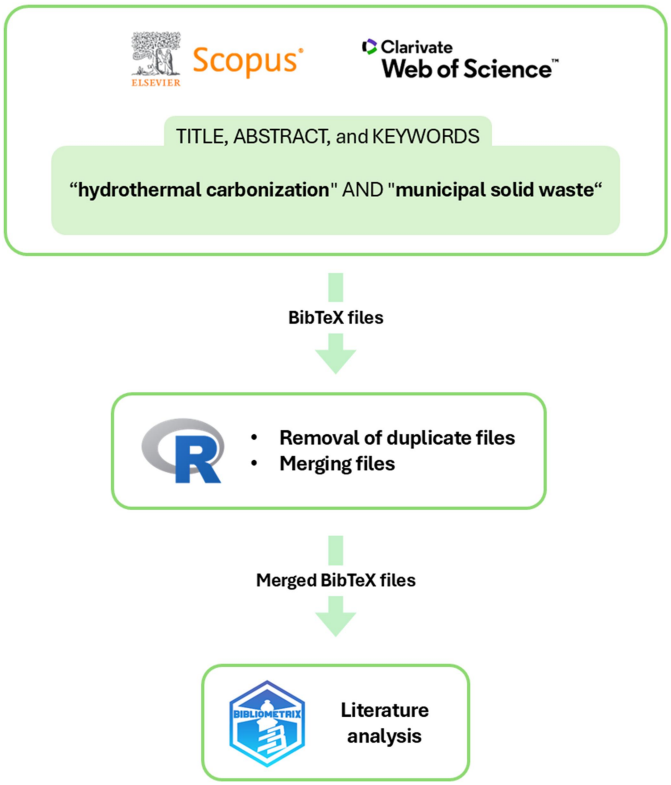

Figure 2: Systematic literature search and analysis of the results. Source: Authors.

RESULTS

The literature search performed in the Scopus and Web of Science databases resulted in 139 original research articles after the removal of duplicates. The temporal evolution of publications about HTC related to MSW is presented in Figure 3. During the initial period (2011–2015), scientific output was minimal, characterized by sparse studies. Beginning in 2016, there was a gradual increase in the number of publications, which intensified further through 2019. This suggests advances in understanding the mechanisms of the HTC process and the expansion of hydrochar's application possibilities. The period between 2020 and 2023 has been observed to demonstrate a more pronounced expansion, accompanied by a significant increase in scientific output and the attainment of the highest values in the historical series. This phenomenon may indicate the strengthening of the field and its growing relevance in the context of sustainable MSW management and energy recovery strategies. In recent years (2024–2026), there has been a slight decline in the number of publications. The results obtained demonstrate the transition of HTC related to MSW from an emerging research field in the beginning of the last decade to a well-established and continuously evolving area of research.

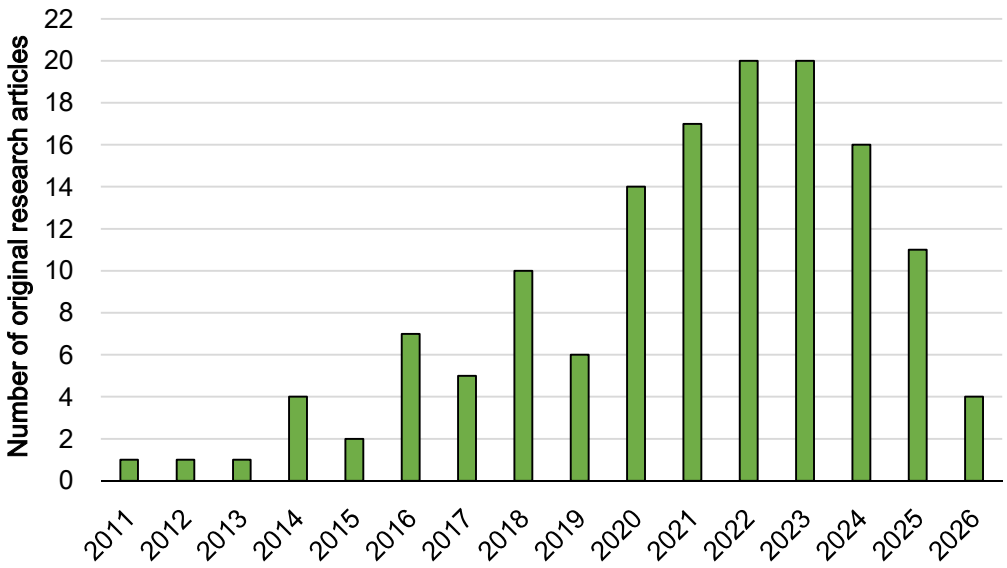

Figure 3: Number of original research articles on hydrothermal carbonization (HTC) related to municipal solid waste (MSW) retrieved from Scopus and Web of Science databases. Source: Authors.

Regarding the top ten countries with the highest number of original research articles published on HTC and MSW, it is presented in Figure 4. The distribution reveals that scientific output in this field remains relatively limited and concentrated, with no single country dominating in absolute terms. Italy and China are at the forefront of this field, yet the number of articles in these countries remains in the low dozens, suggesting that, despite their prominent position, the field is still in a stage of development and expansion. Countries such as Spain and Poland make intermediate contributions, while India and the United States have a moderate presence. This may be indicative of the diversification of research lines in waste treatment and recovery technologies. The geographical scope of the topic is reinforced by the inclusion of countries such as Bangladesh, Chile, Germany, and Indonesia, despite the modest publication volumes. The results suggest that research on HTC related to MSW is emerging on a global scale, with growth distributed across different countries, but still without a high density of scientific output in absolute terms.

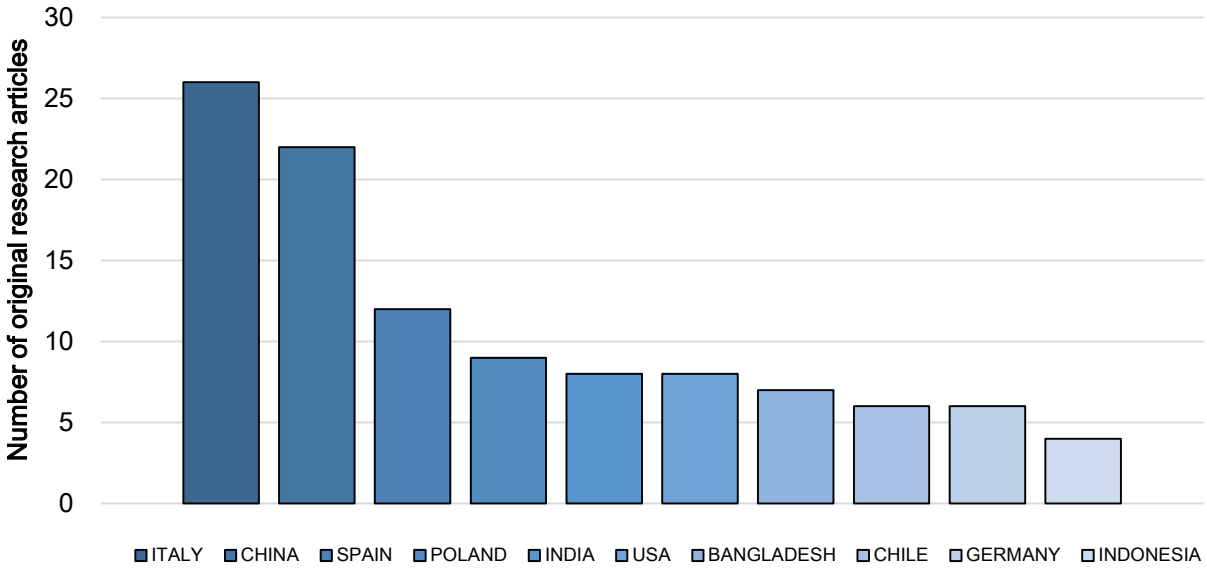

Figure 4: Top ten countries with the highest number of original research articles published on hydrothermal carbonization (HTC) related to municipal solid waste (MSW), based on data retrieved from the Scopus and Web of Science databases. Source: Authors.

Figure 5 presents the co-occurrence network of authors' keywords related to HTC and MSW. As expected, HTC exhibits a robust connection to MSW and hydrochar, thereby showing the literature's foundation of this topic on three fundamental pillars: the process, the feedstock, and the product. The strength of these connections indicates that most studies address all three elements simultaneously, reflecting an integrated approach that seeks to optimize both the operating conditions and the properties of the resulting material (HANTORO et al., 2020; LUCIAN et al., 2018; ŚLIZ et al., 2022)

The scope of raw materials is well represented, with terms such as "sewage sludge", "food waste", and "organic waste" indicating that research on HTC in the context of MSW is not limited to the dry fraction of municipal waste but extends to high-moisture organic subfractions. The presence of water in the waste is not a problem for HTC, but rather a technological advantage over conventional thermochemical routes (e.g., pyrolysis and gasification) (CAVALI et al., 2022; LIN et al., 2016). The presence of the "organic fraction of municipal solid waste" supports the focus on the organic fraction, whether source-separated or mixed, as a relevant substrate for hydrothermal processing (LUCIAN et al., 2018).

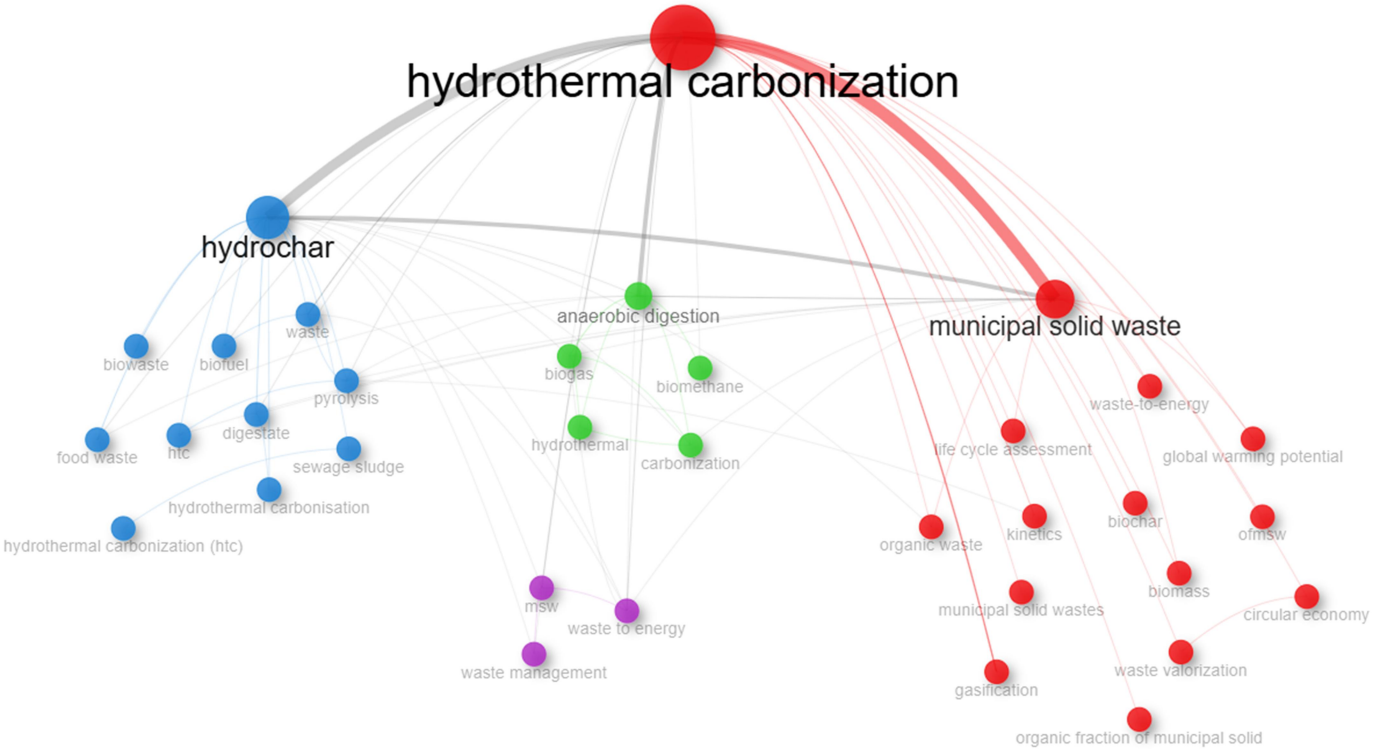

Figure 5: Co-occurrence network of authors' keywords related to hydrothermal carbonization (HTC) related to municipal solid waste (MSW). Node size represents the frequency of keyword occurrence, while link thickness indicates the strength of co-occurrence between terms. Colors denote clusters of related topics within the research field. Source: Authors.

Regarding competing and complementary technologies, the network includes "anaerobic digestion", "pyrolysis", "gasification", and "waste-to-energy" as recurring keywords, indicating that HTC is systematically studied in comparison with or in integration with other waste recovery pathways. The co-occurrence of "biogas" and 'biomethane' alongside "anaerobic digestion" suggests that process integration – particularly the recovery of HTC process liquor (effluent) via biological treatment – constitutes a promising line of research (ADAMS; STUART; KUMAR, 2021; LIN et al., 2016).

The evaluative dimension of the research is reflected in the inclusion of "life cycle assessment", "global warming potential", and "circular economy", indicating a growing trend toward a systemic environmental assessment of HTC within the context of municipal solid waste management. The co-occurrence of "waste valorization" and "circular economy" indicates that the field classifies HTC as a technology for material and energy recovery aligned with the principles of the circular economy (SHARMA et al., 2020). Finally, the presence of "waste management" and

"kinetics" points to two complementary research directions: the first reflects studies focused on the role of HTC in integrated waste management strategies, while the second indicates ongoing interest in the reaction mechanisms and process optimization that support the technology's scalability and industrial applicability (PUTRA et al., 2021; SADAB et al., 2023).

CONCLUSIONS

This bibliometric analysis reveals that research on HTC related to MSW has evolved, with a marked increase in scientific output between 2020 and 2023 and contributions from a globally distributed research community. The co-occurrence network of keywords reflects an integrated approach encompassing process optimization, feedstock diversity, and hydrochar applications, while the growing presence of terms such as "life cycle assessment" and "circular economy" signals a transition toward systemic environmental assessments. The consistent co-occurrence of HTC with anaerobic digestion highlights process integration as a particularly promising pathway for maximizing resource recovery from the organic fraction of MSW. Overall, HTC emerges as a potential technology to support the transition toward more sustainable, low-carbon, and circular waste management systems.

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