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Microwave-assisted pyrolysis in biomass and waste valorisation: Insights into the life-cycle assessment (LCA) and techno-economic analysis (TEA)

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ABSTRACT

Microwave-assisted pyrolysis (MAP) has been perceived as a promising technology for biomass and waste conversion due to its distinctive features, including fast, even, and precise heating. This results in higher energy efficiency when compared to conventional pyrolysis *via* thermal heating. However, the scaling up of MAP of biomass and waste poses challenges, with investigations ongoing to uncover not only the technological aspect, but also both the environmental impacts and economic feasibility associated with this process/technology. The possible environmental impacts associated with MAP processes can be analyzed through systematic life-cycle assessment (LCA), while the economic feasibility can be evaluated via techno-economic analysis (TEA). This paper presents an overview of the current research trend in MAP and the products produced, as well as the LCA and TEA of the pyrolysis technologies. The LCA study reported a 2.5 folds reduction in energy consumption and up to 62% reduction in global warming potential. TEA study revealed that conventional pyrolysis has a greater profit for long-term assessment due to a higher maturity and less complexity technology; however, MAP may be more economically feasible in the future owing to the increased maturity and more established technology. Finally, the challenges and future perspectives for LCA and TEA in MAP are elucidated.

1. Introduction

The depletion of non-renewable resources such as fossil fuel is always a global issue that urgently needs to be resolved. Furthermore, population growth has resulted in urbanization and industrialization, leading to a massive increase in waste production worldwide. The world has generated 2.01 billion tonnes of waste annually, and is forecasted to produce 3.40 billion tonnes of waste by 2050 [1]. Among the 2.01 billion tonnes of waste, more than 33% was not managed in an environmentally safe manner. There are various methods for waste disposal, however, most of them are not environmentally friendly. Landfilling is a widely practised method but poses environmental risks such as water and soil pollution due to leaking leachates. Incineration method is generally used for energy recovery but raises the concern of air

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emissions and ash management, while composting only apply to organic wastes. Recycling is environmentally beneficial, but the effectiveness depends on public participation and infrastructure. Therefore, waste-to-energy approach such as thermochemical conversion technologies (e.g., gasification and pyrolysis) are introduced for energy recovery with careful emission control, while recovering high-value products from biomass/waste materials.

Pyrolysis is a thermochemical conversion technology for biomass/waste materials by heating and decomposing them in a limited oxygen or inert environment to produce pyrolytic products such as biochar, bio-oil and syngas. Conventional pyrolysis is a well-established method that relies on indirect heating *via* external sources. However, it is relatively slow and causes uneven heating of the material, thus resulting in varying reaction rates and potentially causes incomplete conversion or runaway reaction. Microwave-assisted pyrolysis (MAP) is a novel and promising alternative to thermal decomposition processes by utilizing electromagnetic waves for rapid and uniform heating, ensuring higher energy efficiency and faster reaction rates [2]. The microwave radiation is absorbed by particles within materials and this results in vigorous vibration among them. This process subsequently generates heat internally, thereby providing uniform and volumetric heating. In contrast, in conventional heating, the heat is transferred from hot environment to the material being heated *via* conduction, forming a temperature gradient that could result in uneven heating of the material [3]. The selective heating mechanism of MAP allows better control of the pyrolysis processes, leading to enhanced products yield and quality. Besides that, MAP is capable of accommodating or processing a wide range of feedstock types (e.g., lignocellulosic biomass, plastic waste, aquaculture waste). The performance and efficiency of MAP processes can be affected by various factors, including microwave power, time, reactor design, particle size, presence of catalyst, etc. [3].

Life cycle assessment (LCA) and techno-economic analysis (TEA) are crucial tools for evaluating the sustainability and economic feasibility of certain process/technology, playing pivotal roles in guiding decision-making and optimizing the overall performance of this innovative technology. LCA is a tool in assessing the environmental impacts of a process throughout its entire life cycle, from raw material extraction to end-of-life disposal. With the systematic analysis of the factors and process inventories such as energy consumption, emissions, and resource usage, LCA provides a comprehensive understanding of the ecological footprint of the process [4]. LCA performed for pyrolysis technologies helps to identify areas where process/technology improvements can be made, guiding the development and implementation of more sustainable practices.

TEA is a pivotal tool for evaluating the economic viability of a process. TEA involves the systematic assessment of costs and revenues associated with the technology, considering the factors such as capital investment, revenue streams from the sales of products or energy generated, and the operational expenses [5]. TEA is important for stakeholder to make financial decision when implementing MAP at different scales. For instance, Neha et al. [4] performed LCA and TEA for MAP of plastic and food waste and revealed that MAP showed lower GWP (38.8 kg of CO_2 eq.) compared to landfill (200 kg of CO_2), and estimated that the breakeven point can be achieved within 4 years with a 7% of the internal rate of recovery. Integrating LCA and TEA in MAP aids in the identification of trade-offs and synergies between sustainability and economic viability. Ultimately, the full potential of MAP could be deployed commercially for waste recovery/conversion and energy generation.

Several reviews have been performed to evaluate the environmental impacts and economic feasibility of pyrolysis via LCA and TEA. Yu et al. [6] reviewed the LCA of biomass pyrolysis, focusing on the methodological issues of the assessment and type of biomasses for pyrolysis and revealed that the forest residue had lower GWP compared to agricultural wastes and microalgae in conventional pyrolysis. Another review by Andooz et al. [7] concluded that advanced pyrolysis (e.g., vacuum, catalytic, microwave, etc.) had an acceptable environmental impact and low GWP compared to conventional pyrolysis. Su et al. [8] reviewed the reaction mechanism and TEA of MAP of lignocellulosic biomass, microalgae and plastics, and reported a higher capital cost for setting up MAP system compared to conventional pyrolysis system due to the need of specific reactor and generator. Ren et al. [5] depicted that most of the research on MAP were conducted at laboratory and pilot scale. The advanced MAP such as catalytic and co-pyrolysis showed potential for GHG reduction and improved product quality, but further in-depth studies are required to fully comprehend and optimize the complexities associated with these approaches. In general, these reviews covered the LCA and TEA of conventional pyrolysis techniques. There are, to date, limited review focusing on MAP processes and their associated environmental impacts and economic feasibility.

To address these literature gaps, this review aims to provide an insight into the current research trends and technological progress of MAP, as well as the LCA and TEA of various types of MAP techniques, in pursuit of sustainable and economically feasible innovations for circular economy. The main objectives of this review are: (i) to compare the pros and cons of current MAP; (ii) to evaluate the recent LCA and TEA of MAP; and (iii) to identify the potential of upscaling MAP processes with high economic feasibility and low environmental impacts. This review is systematically structured as follows: Section 2: Bibliometric analysis; Section 3: Converting biomass and waste materials via MAP; Section 4: LCA of MAP; Section 5: TEA of MAP; and Section 6: Challenges and future perspective.

2. Bibliometric analysis

Bibliometric analysis is a statistical method to identify the research hotspots and trends quantitatively from relevant academic literature [9]. Therefore, it is important to define a suitable search protocol to obtain a maximum number of relevant papers. The search string was designed as ("microwave" OR "microwave-assisted" OR "microwave assisted") AND "pyrolysis" AND ("Life cycle assessment" OR "LCA" OR "life cycle") OR ("TEA" OR "technoeconomic" OR "techno-economic" OR economic"). A total of 88 articles were obtained from a primary run of the literature in the Scopus database (search string within the titles, abstracts, and keywords). The analysis only included research and review articles in English, where the non-relevant documents (e.g., conference paper, book chapter and letter) were excluded which led to a total of 72 articles remaining for further processing. VOS viewer software (version 1.6.11) was utilized to conduct the bibliometric analysis.

A keyword co-occurrence analysis was performed based on the keywords provided by the authors from these 72 documents, and the top 10 most frequent keywords (among 240 keywords) (Table 1). As shown in Table 1, techno-economic assessment, biochar, and life cycle assessment were the three most frequently used keywords of the authors. It shows that the research focuses more on studying the environmental impact and economic feasibility of biochar production compared to bio-oil production. Fig. 1 shows the link strength between the keywords. The LCA or TEA for MAP mainly focuses on converting biomass and plastic

Table 1
The top 10 most frequently occurring keywords in these 72 documents.

Keyword	Occurrences	Total link strength
Life cycle assessment	17	20
Techno-economic assessment	12	22
Biochar	10	20
Microwave pyrolysis	10	16
Pyrolysis	9	15
Microwave	6	9
Bio-oil	5	11
Biofuel	4	10
Wood vinegar	3	10
Biomass	5	9