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Emerging trends and research frontiers of biochar derived through microwave assisted pyrolysis: A scientometric review

Mari Selvam S., Paramasivan Balasubramanian *

Agricultural and Environmental Biotechnology Group, Department of Biotechnology and Medical Engineering, National Institute of Technology Rourkela, Rourkela 769008, Odisha, India

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ABSTRACT

Microwave-assisted pyrolysis (MAP) is one of the proven energy-efficient techniques in biomass thermochemical conversion with better characteristics than conventional heating. Despite the benefits, the scale-up and commercialization of MAP-derived products are still facing challenges. Investigation of research evolution and timely status leads to an understanding of emerging trends and loopholes that aids to make process effective and viable. Scientometric analysis has been conducted on biomass microwave pyrolysis for biochar and other biofuel production shedding light on research hotspots and gaps. The findings indicate that MAP research predominantly focused on energy-based applications compared to agriculture-oriented studies. Major research hotspots included utilization of biochar for contaminant removal, catalytic microwave pyrolysis, and energy-based applications. This study provokes the researchers and stakeholders to understand research evolution and loopholes which aids in exploration of new strategies and process designs to ensure sustainability of MAP while promoting global social and material well-being.

1. Introduction

With an abundant supply of biomass resources on a global scale, researchers are exploring more ways to derive bioenergy products that could serve as feasible alternatives to conventional non-renewable energy sources. Pyrolysis or thermochemical decomposition of biomass in a closed container under anoxic conditions is one of the effective techniques for converting the biomass to produce range of solid, liquid, and gaseous products (Yu et al., 2019). Biochar is the carbonaceous solid product of the pyrolysis process that has ascertained applications as soil amendment (Lian et al., 2021); wastewater remediation (Emenike et al., 2022); heterogeneous catalyst for production of biodiesel (Behera et al., 2020); anaerobic digestion (Wang et al., 2019). This is owing to the excellent physical and chemical properties of biochar (Širić et al., 2022).

Microwave assisted pyrolysis (MAP) is one of the efficient techniques in resource recovery from waste materials to produce sustainable products with higher conversion efficiency (Abomohra et al., 2021). The detailed review by Garcia-Nunez et al. (2017) have summarized the recent developments in biochar reactor designs and production technologies and reported that MAP is a promising technology for the advancement of managing the wastes through effective volumetric heating and energy transfer process. Microwave reactors are designed in a manner such that the heat transfer occurs as a result of flipping dielectric poles in the materials due to changes in the direction of alternating current of the microwave (Suriapparao et al., 2015; Jing et al., 2021). These reactors have high heating efficiency, and could even produce biochar from lignocellulosic biomass with appreciable moisture content. Many researchers (Haeldermans et al., 2019; Nzediegwu et al., 2021; Potnuri et al., 2022) have stated better product yield and improved physicochemical characteristics of the pyrolytic products produced through microwave compared to conventional pyrolysis in an electrical furnace/kiln. The porosity and surface characteristics of biochar have been improved significantly after MAP due to removal of residual volatiles and development of surface pores (Wallace et al., 2019; Allende et al., 2022). Microwave-derived biochar has more finite porosity compared to conventionally produced biochar under similar conditions and thereby leading to increased water-holding capacity (WHC) than the latter (Mohamed et al., 2016).

The industrial-scale feasibility of microwave pyrolysis depends on the market price of the commercial product, ensuring that the overall expenses are lower than the potential profits (Liew et al., 2018a). Foong et al. (2020) have reviewed the key concepts and challenges associated

* Corresponding author.
E-mail address: biobala@nitrkl.ac.in (P. Balasubramanian).

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with microwave pyrolysis and emphasized the necessity of enormous research on reactor design and biomass pyrolysis in microwave since the technology is in the development stage and yet to achieve industrial commercialization. The market estimations of microwave pyrolysis indicate that its growth rate is increasing at 5.6. % with a projected market value of 0.255 billion USD by 2028 (TheExpressWire, 2022) and is smaller compared to overall biochar market which is predicted to exceed 6.3 billion USD by 2031 (Cavali et al., 2022). Most of the commercial pyrolysis plants producing biomass-derived products is relying on conventional systems (Haeldermans et al., 2020).

By analyzing these sporadic results on microwave pyrolysis, exploration of the loopholes that limit the scale-up feasibility, process commercialization, and product quality to achieve better market price has to be outlined. For a better understanding of the potential of microwave biochar application, the research evolution has to be delineated in order to interpret the emerging research trends, hotspots and gaps associated with the scientific arena. Scientometric analysis of research area aids to determine the recent trends of a scientific field and identification of deficiencies that helps the researchers to implement the desirable advances to develop the technology for commercialization (Behera et al., 2022a). Scientometric analysis of biochar application has been carried out by Wu et al. (2019) and Kamali et al. (2020) to detail the research trends and gaps associated with conventional biochar. Jiao et al. (2021) illustrated that microwave pyrolysis would become research trend in future however the extensive description of scientific status of MAP-derived biochar has not been described. Abdeljaoued et al. (2020) have carried out bibliometric analysis of biochar technology with a detailed description of publication records in accordance to country, journals, and institutes and further elaborated the research evolution. As per these observations, a detailed systematic analysis of scientific status of microwave pyrolysis for biochar production and its application is lacking. Henceforth in this study, the authors have carried out the scientometric analysis of research documents published with respect to microwave pyrolysis to analyze the current trends in this scientific field. The research hotspots and gaps associated with microwave biochar application have been identified. The future scope and opportunities have also been illustrated. This study will facilitate for the scientists and stakeholders to identify deficiencies and areas in which further improvements are needed to accelerate the commercialization of microwave biochar for multiple applications.

2. Methodology for scientometric analysis

2.1. Data collection and processing

The publications related to microwave pyrolysis for biochar production and its applications have been imported from scientific database for the period of 2000–2021 to systematically study the research growth and trends for past two decades. The documents were extracted using the combination of relevant keywords including “microwave”, with “biomass”, biochar”, “bio-char”, char”, “pyrolysis”, “carbonization” by means of boolean operators. The search carried out on Feb 11, 2022, was restricted to the appearance of keywords in title of the manuscripts as this could significantly aid in analyzing the comprehensive research framework of the field (Kamali et al., 2020). The documents collected were then processed in Citespace software to convert these documents into uniquely formatted files after removal of duplicates. The data collected were then analyzed using different node types such as country, keyword, subject category and cited documents.

2.2. Parameters used in scientometric analysis of microwave pyrolysis

The parameters involved in the scientometric analysis of microwave pyrolysis for biochar production and application were 1). Betweenness centrality which reveals the importance of a node through its shortest path between other nodes; 2). Citation burst indicating the frequency of a topic over a period of time; 3). Sigma is an integrated parameter measuring the centrality and burst strength of a node. The nodes were then clustered based on research similarity and sub-categorized based on log-likelihood ratio algorithm. By analyzing these clusters and timeline networks, the evolution of research and its potential hotspots could be interpreted. A detailed description of these parameters could be found elsewhere in Kamali et al. (2020) and Tundup et al. (2021).

2.3. Data interpretation in scientometric analysis of microwave pyrolysis

To interpret the research evolution with the emerging trends and research loopholes, several analysis like cooperative network analysis, co-citation analysis, timeline network of co-word analysis have been carried out (Behera et al., 2022b). With respect to macro-level cooperative network analysis, the cooperation of global countries to enhance the research related to MAP-derived biochar has been studied. The knowledge base and distribution of topics with its research frontiers have been determined through co-citation analysis. Based on co-citation analysis, cluster network and thematic framework of the MAP research have been outlined. Timeline network of co-word analysis has been used to represent core concepts or themes of the article reflecting the evolution of MAP-derived biochar research and knowledge domain. Comprehensive interpretation of these analyses has been made to illustrate the research evolution, trends and challenges associated with MAP-derived biochar research (Shi and Yin, 2021).

3. Results and discussion

3.1. Publication outputs

The distribution of research publications related to microwave pyrolysis for biochar production and application has been given in Fig. 1. The publication counts during early 2000 were relatively low and increased rapidly after 2010 following a polynomial model (with R^2 of 0.9836) revealing the increased research concern towards the field. The number of publications increased with relative growth rates of 0.20 and 0.18 for the period between 2000–2010 and 2011–2021 respectively indicating the consistent growth of the research field over the last two decades. These documents include research articles, reviews, proceedings, and others. The cumulative number of publications also indicates the growing research interest in this field, representing it as a research hotspot in pyrolysis technology. This emphasizes the need for continuous improvement to ensure the sustainability of the process.

3.2. Analyzing the major contributing countries in microwave biochar related research

Global research network related to microwave biochar arena consisted of 71 nodes and 200 links based on their collaboration derived from 1891 documents (Fig. 2). The impact of contribution was estimated based on the number of documents, link strength and citations. The advent of manuscripts related to microwave pyrolysis for biochar production in China (Peoples R China), began in the late 2000s. However, European countries such as Spain, Belgium, Germany and South Korea published the research findings during the initial period of study considered. After 2010, the research documentation on this topic increased rapidly worldwide. China is the leading country in the research of MAP-derived biochar research with contribution percentage of 35.1 % and centrality of 0.47, followed by United States of America (USA), with research contribution of 12.20 % and a centrality score of 0.29. The similar research productivity was also visualized by Wu et al. (2019) and Jiao et al. (2021) for conventional biochar research where China and USA were the foremost contributing countries identified through scientometric study conducted for time period between 1998–2018 and 2006–2018 respectively. Followed by China and USA, Malaysia, England, India and Canada have contributed 12.2 %, 7.17 %,

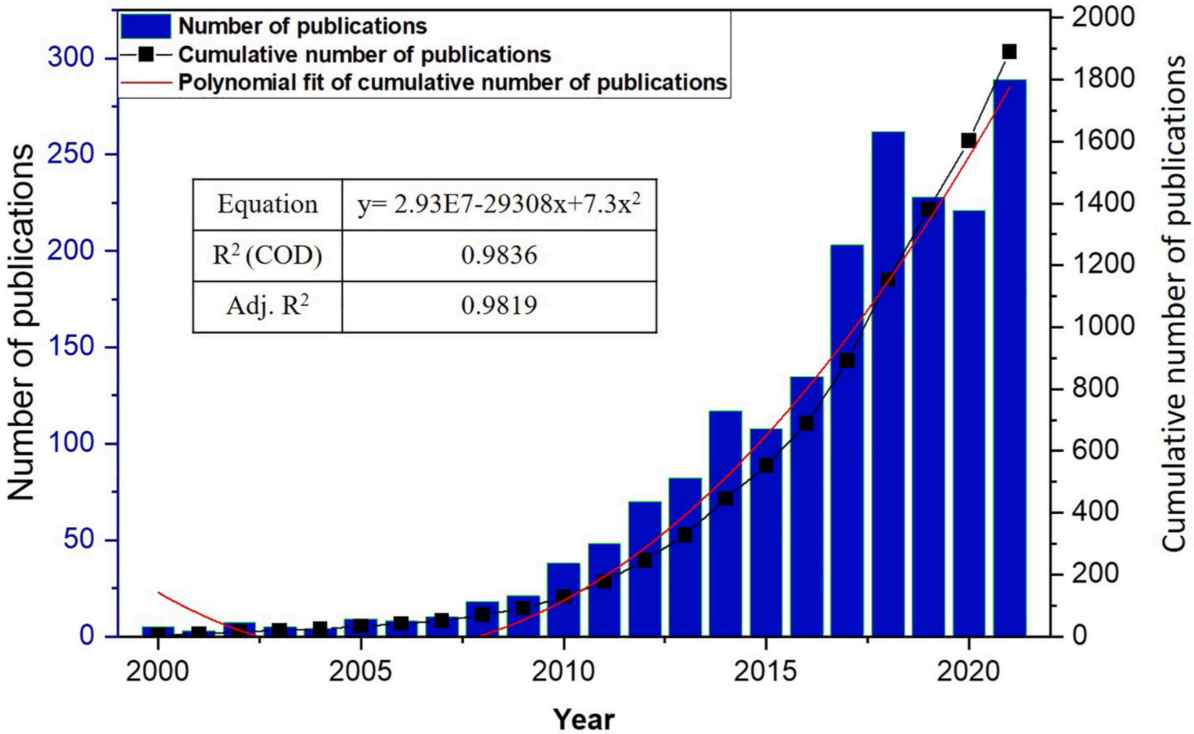

Fig. 1. Distribution of research publications related to microwave assisted pyrolysis for biochar production.

Fig. 2. Network distribution of major collaborating countries based on microwave assisted pyrolysis research for biochar production.

5.9 % and 3.9 % respectively between the period considered in this study. The nodes corresponding to China, USA, Malaysia and England had purple rings on outer edge that indicates the high betweenness centrality affirming the popularity and their crucial contribution in this field. The contribution hierarchy of few entries listed in Table 1 is similar to the list for conventional biochar research reported by Jiao

Table 1
Contributing countries in terms of publications on microwave pyrolysis for biochar production.

Country	Count	Contribution %	Burst	Centrality	Sigma
Peoples R China	558	35.12	–	0.47	1.00
USA	194	12.21	–	0.29	1.00
Malaysia	114	7.17	–	0.31	1.00
England	94	5.92	–	0.30	1.00
India	62	3.90	–	0.10	1.00
Canada	51	3.21	4.11	0.02	1.07
Spain	47	2.96	6.79	0.08	1.72
Taiwan	41	2.58	–	0.01	1.00
Italy	35	2.20	4.72	0.06	1.30
Australia	32	2.01	–	0.03	1.00
South Korea	26	1.64	–	0.01	1.00
Brazil	23	1.45	3.63	0.14	1.62
Germany	21	1.32	–	0.12	1.00
Pakistan	20	1.26	3.57	0.01	1.04
France	16	1.01	–	0.08	1.00
Japan	16	1.01	3.14	0.00	1.00
Sweden	16	1.01	–	0.01	1.00
Thailand	13	0.81	–	0.01	1.00
Egypt	13	0.81	–	0.00	1.00
Iran	12	0.75	–	0.02	1.00

et al. (2021) however the countries like Australia and South Korea contributed 2.01 % and 1.63 % respectively and recorded the research findings in early 2000s. Despite the increased number of publications and centrality documented by India compared to Canada and Spain, total citations and sigma values were lower than the latter. Sigma value revealed that the research findings reported by Spain and Canada are structurally essential and innovative (Chen et al., 2012). The total link strength of these countries reveals the contribution of each country and its impact on others in the field of microwave biochar research.

3.3. *Analyzing the subject categories in microwave biochar related research*

The information regarding the network of subject categories of published documents on microwave pyrolysis for biochar production and its application has been given in Fig. 3. It could be understood that majority of publications appear to fall under the subject category "Energy and Fuels" since it has highest recorded contribution of 13.5 % than others (Table 2). Then follows "Engineering", "Chemistry", "Biotechnology and Applied Microbiology", "Environmental Sciences and Ecology" and "Agriculture". This is contrasting to the result of conventional biochar research reported by Li et al. (2018) and Wu et al. (2019), wherein, "Environmental Sciences and Ecology", and "Agriculture" were the top-cited subject categories. This is due to the fact that MAP-derived pyrolytic products are mostly used for energy and fuel-based applications. The initial research involved the studies on comparative evaluation of conventional and microwave heating for the production of biofuel from biomass (Domínguez et al., 2006; Dominguez et al., 2007). Gronnow et al. (2013) have reported that energy requirements for MAP are higher than conventional treatment, however, the bioenergy produced through MAP offsets its efficiency. The authors recommended the combination of conventional treatment and catalytic MAP for efficient biochar production. The research to improve the pyrolytic product quality for efficient utilization in energy-based applications has been focussed later. Xiao et al. (2015) described the approach for the enhancement of steam gasification of biochar through microwave heating. The presence of alkali and alkaline earth metals increased carbon conversion efficiency during microwave-assisted gasification of

Table 2
Information regarding the categories of published documents on microwave pyrolysis for biochar production.

Subject category	Count	Contribution %	Degree	Centrality	Sigma
Energy & fuels	542	13.58	25	0.20	1
Engineering	459	11.50	33	0.28	1
Chemistry	374	9.37	36	0.38	1
Engineering, chemical	364	9.12	23	0.09	1
Biotechnology & applied microbiology	162	4.06	13	0.08	1
Environmental sciences & ecology	160	4.01	19	0.13	1
Agriculture	160	4.01	9	0.02	1
Environmental sciences	160	4.01	19	0.13	1
Agricultural engineering	152	3.81	5	0	1

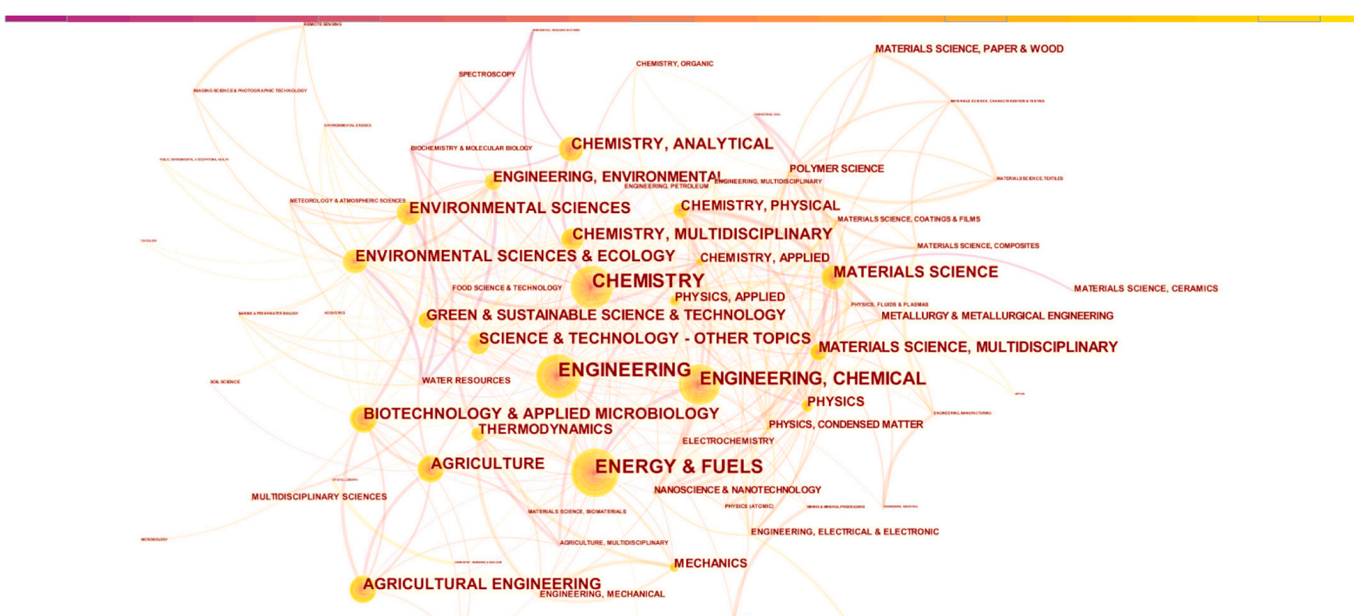

Fig. 3. Network domain of major subject categories in microwave assisted pyrolysis research for biochar production.

biochar. The background mechanism was found to be promotion of M-O-C intermediate formation, dipole rotation and hotspot generation, significantly improving gasification activity. Huang et al. (2017) produced biochar with heating value of 30 MJ kg^{-1} and fuel ratio of 3.7 which is higher than those of bituminous coal. By using silicon carbide and AC, its effects on pyrolytic product quality have also been investigated by Fodah et al. (2021a). The energy return on investment of the process was found to be 36 %–55 % indicating it as a promising technique for energy- and fuel-related applications. Thus, MAP holds potential for energy and fuel applications, with research emphasizing improved product quality and efficiency.

MAP is considered as one of the effective waste disposal techniques employed to create a circular economy and environmental sustainability. Different wastes like waste tires (Undri et al., 2013), horse manure biowaste (Mong et al., 2020), plastic wastes (Rex et al., 2020), carbon composites (Hao et al., 2021) have been significantly converted into energy and/or value-added products through MAP thereby promoting sustainable waste management and reducing the environmental burdens. MAP-derived biochar has been used to mitigate various organic and inorganic pollutants to treat wastewater and contaminated sites (Ahmed and Theydan, 2014; Liew et al., 2018b; Lam et al., 2019). Antunes et al. (2017) evaluated the regeneration efficiency of silver adsorbed biochar for methylene blue (MB) adsorption. The authors found that biochar prepared from bio-solids showed an adsorption capacity of 43.9 mg g^{-1} of silver and could further remove 50 % of MB showing a promising application for wastewater treatment. Kong et al. (2019) adopted self-purging microwave pyrolysis for producing oil palm shell biochar that possessed a surface area of 410 m^2 g^{-1} and an adsorption capacity of 20 mg g^{-1} for textile dye adsorption. The utilization of MAP-derived products contributes to Sustainable Development Goals (SDGs) by advancing energy and fuel-based research. The research addresses various SDGs, including affordable and clean energy (7), industry, innovation and infrastructure (9), responsible consumption and production (12), climate action (13), partnerships for goals (17).

The subject categories “Agriculture” and “Agricultural Engineering” have low centrality values, indicating that further research exploration is needed in studies related to potential application of MAP-derived biochar in agriculture. Researchers are currently focusing on engineered biochar by employing various strategies to increase the product value and the characteristics such as water retention capacity and soil fertility enrichment (Mohamed et al., 2016; Lam et al., 2019). The potential of MAP-derived biochar for adsorption of different heavy metals that deteriorate the soil fertility has been studied by different authors. For instance, the reduction of heavy metal risk by microwave pyrolysis of sludge has been analyzed by Liu et al. (2016) and Raček et al. (2018). Shukla et al. (2019) used rice husk biochar to remediate the wastewater and potential of soil nourishment was determined through extractable nutrient contents. Lam et al. (2019) have reported herbicide removal of 11 mg g^{-1} of biochar activated by combination of MAP and steam treatment. This technique potentially mitigates the herbicide contamination in agricultural land. Several research groups have investigated the fabrication of biochar-based hydrogel composites under microwave irradiation to increase nutrient release and water retention. Microwave irradiation aids in structural alteration of biochar and promotes the cross-linkage of biochar –hydrogel composites. The water retention capacity increased significantly by 10 %–30 % based on different synthesis methods (Elsaeed et al., 2021; Wu et al., 2021). Co-microwave pyrolysis of different sludge sources increases the heavy metal immobilization in biochar by conversion of metal halides to stable crystalline compounds promoted by inorganic minerals in the sludge (Chen et al., 2021a). The study of microwave-derived biochar and its uses for improving soil fertility and tackling heavy metal pollution aligns with various SDGs, notably addressing hunger (2), promoting well-being (3), ensuring clean water (6), fostering innovation (9), encouraging sustainable production (12), and supporting biodiversity (15). However, studies on influential parameters associated with microwave heating for constructing a prototype for large-scale biochar production for soil amendment and other environmental applications need to be explored further.

3.4. Analyzing the co-cited documents in microwave biochar related research

The co-citation analysis of documents related to MAP-derived biochar research are listed in Table 3. The evolution and knowledge base of research could be interpreted from these manuscripts since the articles indicated the major changes carried over in the research field in relation to analysis of product profile, physicochemical characterization of biochar and its application as adsorbent, catalytic reforming and other environmental applications. By analyzing the co-cited documents listed in Table 3, initially, Dominguez et al. (2007) and Menéndez et al. (2007) emerge as the most co-cited articles, explaining the significance of microwave pyrolysis for increased production of H_2 biofuel from coffee hull. The authors also discussed about the beneficial use of microwave heating over conventional heating. In addition, the recovery of energy in form of H_2-rich fuel gas and utilization of biochar for contaminant adsorption have also been carried out, however, the practicality of the research was uncertain at that time (Huang et al., 2008). Later, the influence of process parameters on the pyrolytic product yield has been determined which revealed that microwave pyrolysis could take place rapidly using large-sized feedstock and most of the mineral content would be retained in the biochar (Lei et al., 2009). The studies carried out in an earlier period were mostly batch-type processes, and the temperatures were maintained at intermediate rates. Borges et al. (2014) produced biochar from wood sawdust and corn stover using fast microwave-assisted pyrolysis (fMAP) in semi-continuous process mode using silicon carbide as microwave absorbent. The produced biochar had more than 50 % carbon content and the bio-oil had higher hydrogen and nitrogen contents. The utilization of fMAP-derived biochar offers the potential to enhance soil carbon and replenish few minerals, signifying it as a technology for improving product values and its commercialization (Xie et al., 2014). The most co-cited articles related to microwave pyrolysis primarily focused on energy recovery from biomass, with strong emphasis on utilization of syngas and bio-oil overshadowing the attention on biochar (Suriapparao et al., 2018). This result is similar to scientometric study of conventional biochar research reported by Wu et al. (2019), where the keyword “bio-oil” had higher centrality value depicting the research of interest owing to sustainable bioenergy production. Further exploration of biochar produced from MAP is necessary to increase its product value for energy-related or value-added product-based applications.

3.5. Analyzing the research hotspots and emerging trends

The keywords are the most predominant parameters in explicating the research evolution of a field. The co-occurrence network of keywords has been given in Fig. 4. The merged network consisted of 726 nodes and 4659 links connecting different keywords related to microwave pyrolysis for biochar production. The keywords, “biomass”, “microwave pyrolysis”, “bio-oil”, “activated carbon”, “sewage sludge” have higher frequency, centrality, and burst values (Table 4), indicating the key role of microwave pyrolysis in converting the biomass into value-added products. These keywords acted as a basis for emergence of different research perspectives in thermochemical conversion techniques. Analyzing the citation burst (Table 5), the keyword “microwave pyrolysis” shows a higher citation burst of 7.49 after 2010, reflecting the remarkable focus on this research area. While the keyword “fuel” has a lower centrality score compared to other keywords, its sigma value (an integrated value of centrality and citation burst) is of 1.21 which indicates the significant attention on the research area of producing biofuels from renewable resources. Following these keywords, “rice straw”, “product” have higher centrality values and citation bursts between 2008 and 2016, signifying the increased attention in utilizing

Table 3
List of most cited documents on microwave pyrolysis for biochar production.

References	Strength	Begin	End	2000–2021
Dominguez A, 2007, J Anal Appl Pyrol, V79, P128	13.40	2007	2012	
Menendez JA, 2007, Energ Fuel, V21, P373	6.40	2007	2012	
Yu F, 2007, Appl Biochem Biotech, V137, P957	8.33	2009	2012	
Dominguez A, 2008, Chemosphere, V70, P397	7.21	2009	2012	
Huang YF, 2008, Bioresour Technol, V99, P8252	12.73	2010	2013	
Budarin VL, 2009, Bioresour Technol, V100, P6064	8.53	2010	2014	
Lei HW, 2009, Energ Fuel, V23, P3254	7.57	2010	2014	
Wan YQ, 2009, J Anal Appl Pyrol, V86, P161	12.19	2011	2014	
Huang YF, 2010, Bioresour Technol, V101, P1968	12.00	2011	2015	
Du ZY, 2011, Bioresour Technol, V102, P4890	11.02	2011	2016	
Chen MQ, 2008, J Anal Appl Pyrol, V82, P145	10.29	2011	2013	
Fernandez Y, 2009, J Anal Appl Pyrol, V84, P145	6.31	2011	2014	
Menendez JA, 2010, Fuel Process Technol, V91, P1	12.16	2012	2015	
Salema AA, 2011, Bioresour Technol, V102, P3388	11.69	2012	2016	
Zhao XQ, 2010, J Anal Appl Pyrol, V89, P87	9.68	2012	2014	
Menendez JA, 2011, Carbon, V49, P346	6.42	2012	2016	
Hu ZF, 2012, Bioresource Technol, V107, P487	9.04	2013	2016	
Luque R, 2012, Energ Environ Sci, V5, P5481	8.49	2013	2017	
Yin CG, 2012, Bioresour Technol, V120, P273	11.25	2014	2017	
Motasemi F, 2013, Renew Sust Energ Rev., V28, P317	10.98	2015	2018	
Bridgwater AV, 2012, Biomass Bioenerg, V38, P68	6.97	2015	2017	
Borges FC, 2014, Bioresour Technol, V156, P267	6.47	2015	2018	
Mushtaq F, 2014, Renew Sust Energ Rev., V39, P555	8.16	2016	2019	
Xie QL, 2014, Bioresour Technol, V172, P162	7.00	2016	2018	
Lam SS, 2017, J Clean Prod, V147, P263	6.16	2018	2021	

agricultural residues to derive bioenergy products under microwave irradiation, ranging from the batch to continuous processes (Jun et al., 2010; Suriapparao and Vinu, 2015). For instance, Huang et al. (2015a) co-pyrolyzed sewage sludge and rice straw and suggested that biochar could be used as an alternative for coal owing to increased fixed carbon content and calorific value. Mineral content of rice straw also exhibited a catalytic effect on biomass pyrolysis and resulted in increased biochar production (Wang et al., 2018). However, electricity consumption is still a limiting factor concerning the energy balance of the process. Hence, reliable and sustainable energy sources like solar systems are being used to minimize the cost associated with energy consumption. Fodah et al. (2021b) reported a net energy recovery of 71 % using solar photovoltaic power with CO_2 mitigation up to 55 tons in 30 years and carbon credit of \$ 30 ton^{-1}.

The co-occurrence of keyword network was divided into 24 clusters based on the research similarities. The clusters have been given in Fig. 5 labelled by log-likelihood ratio algorithm. The top cluster #0 "catalytic temperature" consisted of 130 nodes linking the core keywords of cluster. Catalytic microwave pyrolysis is one of the major research hotspots where the selection of catalyst like zeolites, metal oxides, carbon materials (Bu et al., 2012; Lam et al., 2015; An et al., 2020); process modes involving ex-situ, in-situ pyrolysis, reactor configuration (Dai et al., 2017; Jing et al., 2021) optimization of process parameters (Zhou et al., 2019; Chen et al., 2021b), regeneration are being investigated to improve the MAP efficiency and product quality. To illustrate further about the research hotspot, the studies related to this cluster were focused to analyze the product distribution and its characteristics by effect of different catalysts being added to MAP process. Wan et al. (2009) analyzed the product selectivity of microwave pyrolysis using chloride salts and metal oxides as catalysts. The catalyst facilitated "in-situ upgrading" of pyrolytic vapors increasing the yield of bio-oil and decreasing the biochar yield. The portion of catalyst added could also be used to regulate the microwave temperature and also influences the product distribution and its properties (Salema and Ani, 2012). Utilization of char as a microwave absorber for pyrolysis has been studied for various biomass sources. The findings revealed that addition of char as microwave absorber facilitated the pyrolysis process instead of drying, leading to significant reduction of time and energy consumption than conventional heating. Its synergistic effect is inevitable in improving the heating performance of the pyrolysis unit (Menéndez et al., 2002; Du et al., 2011). Use of activated carbon (AC) as a catalyst has also been employed in the production of biofuels, resulting in higher phenolic content (Yerrayya et al., 2018). Catalytic effect of char is more effective under the influence of microwave than conventional process in reforming the pyrolysis volatiles (Dong et al., 2018). The coke formation on catalyst is reduced in co-catalysis mode owing to the cracking of long-chain hydrocarbon where the polymerization reactions are alleviated (Dai et al., 2017). Luo et al. (2020) used ash/ organics as catalyst for microwave pyrolysis of four kinds of sewage sludge, where the authors observed that the yield of biochar was negatively correlated with organic content and positively correlated with ash content of sewage sludge. During the continuous process of pyrolysis, the longer retention time can increase the amount of char trapped in the carbon bed, that in turn promotes the heterogeneous reactions which influence the product distribution (Fodah et al., 2021a; Suriapparao and Vinu, 2021). Dong et al. (2021) analyzed the role of metal ions in microwave pyrolysis. The authors reported that after demineralizing biomass and introducing calcium chloride salts, biochar yield increased significantly. The retention of calcium in biochar played a crucial role in promoting condensation reaction through cross-linking of biomass components, increasing the biomass matrix density. Moreover, higher percentage of calcium ions contributed to improved surface area and pore volume of the biochar with uniform pores. However, the existing studies reported lack of optimization knowledge in terms of catalyst type, susceptor loading, MAP process conditions for producing superior characteristic biochar in large scale and to be used for different applications. Traditional and non-traditional catalytic microwave absorbers need further development and testing in terms of enhancing biochar quality.

The second largest cluster was #1 microwave pyrolysis encompassing 102 nodes with silhouette value of 0.726. The keywords related to this cluster were of "microwave pyrolysis", "sewage sludge" with higher frequency whereas the keywords like "gas turbine", "microwave organic matter interaction", "combined reforming" had lower frequency and centrality values. As mentioned earlier, the initial research on microwave pyrolysis involved processing of sewage sludge to produce energy-based products as shown in Table 4 for correlation. The main research hotspots corresponding to the cluster "microwave pyrolysis" include the exploration of different feedstocks like sewage sludge (Fernández and

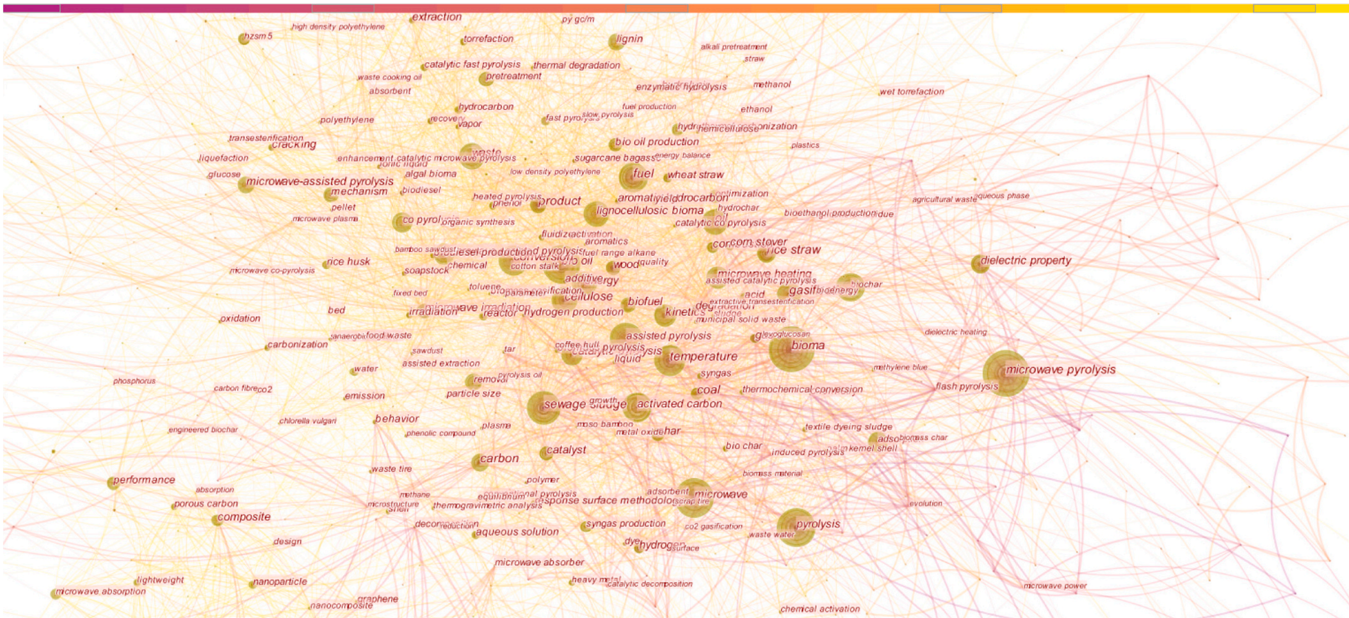

Fig. 4. Co-occurrence network of keywords related to microwave assisted pyrolysis research for biochar production.

Table 4
List of keywords related to microwave pyrolysis research.

Keyword	Frequency	Degree	Centrality	Sigma
Biomass	362	75	0.06	1.0
Microwave pyrolysis	302	84	0.10	2.0
Microwave	214	47	0.03	1.0
Pyrolysis	206	43	0.03	1.0
Bio-oil	179	57	0.03	1.0
Activated carbon	168	56	0.05	1.0
Assisted pyrolysis	164	42	0.01	1.0
Sewage sludge	148	80	0.08	1.7
Temperature	141	70	0.05	1.0
Biochar	136	22	0.01	1.0
Conversion	133	68	0.05	1.0
Lignocellulosic biomass	130	57	0.03	1.0
Waste	117	43	0.02	1.0
Fuel	105	64	0.04	1.2

Table 5
Citation burst of keywords related to microwave pyrolysis.

Keywords	Strength	Begin	End	2000–2021
Sewage sludge	6.85	2002	2009	
Microwave absorber	4.52	2005	2011	
Rice straw	6.47	2008	2016	
Oil	4.35	2008	2014	
Fuel	4.98	2010	2015	
Enzymatic hydrolysis	3.92	2010	2016	
Gas	7.27	2011	2014	
Microwave plasma	5.82	2011	2015	
Microwave pyrolysis	7.49	2012	2013	
Algal biomass	4.47	2012	2013	
Metal oxide	4.19	2013	2014	
Wheat straw	4.34	2015	2016	
Hydrothermal carbonization	4.44	2016	2017	
Dye	3.97	2016	2018	
Waste tire	5.17	2017	2018	
Enhancement	3.98	2018	2019	
Light weight	6.18	2019	2021	
Facile synthesis	4.82	2019	2021	
Electromagnetic wave absorption	4.7	2019	2021	
Microsphere	4.3	2019	2021	

Menéndez, 2011), waste oil (Lam et al., 2012), bamboo leaves, waste coffee grounds, sugarcane bagasse (Huang et al., 2016), oil palm (Nomanbhay et al., 2017), plastic wastes (Jing et al., 2021), and various agro-residues for biochar production through MAP. The researchers have analyzed the background mechanism of thermal degradation of the biocomponents with respect to the process conditions and the characteristics of produced biochar. Feedstock type and pyrolysis temperature are the most influential factors affecting the biochar yield and its physicochemical properties. The effect of these factors on biochar yield along with morphological and functional changes of resulting biochar has been studied by various authors (Lei et al., 2009; Wallace et al., 2019; Sahoo and Remya, 2020; Nzediegwu et al., 2021). The authors interpreted that due to selective and volumetric heating, the physicochemical and thermal properties of biochar were significantly enhanced. The dielectric properties of different biomass and microwave absorbers depend on process temperature that simultaneously affects the process yields (Salema et al., 2013; Motasemi et al., 2014; Antunes et al., 2018). The determination of dielectric properties of oil palm biomass has been carried out by Tripathi et al. (2015) in order to understand the material interaction in the microwave environment and the authors recommended the usage of low-frequency microwave owing to higher dielectric constant and penetration depth. Carbonaceous absorbers like activated carbon promote the carbonization reaction better than glycerol which thereby lead to higher stability and enhanced morphological features (Antunes et al., 2018). With higher microwave power, structural integrity of biochar pores becomes higher in terms of cracking and residual tar present inside the biomass (Wallace et al., 2019). The mode of microwave pyrolysis from batch to continuous operation possesses advantages like less energy consumption and higher energy efficiency provided with increased number of pyrolysis cycles compared to batch process. The primary mechanism is identified to be continuous feed input with instantaneous heating to higher temperatures. In addition, function of auger reactor in transport and mixing of feed by conveying to the chamber enhance the mass and heat transfer between the feed and pyrolysis products. Further, it promotes the secondary reforming reactions thereby reducing thermal loss (Luo et al., 2021). The assessment of its application as solid fuel/ soil amendment is based

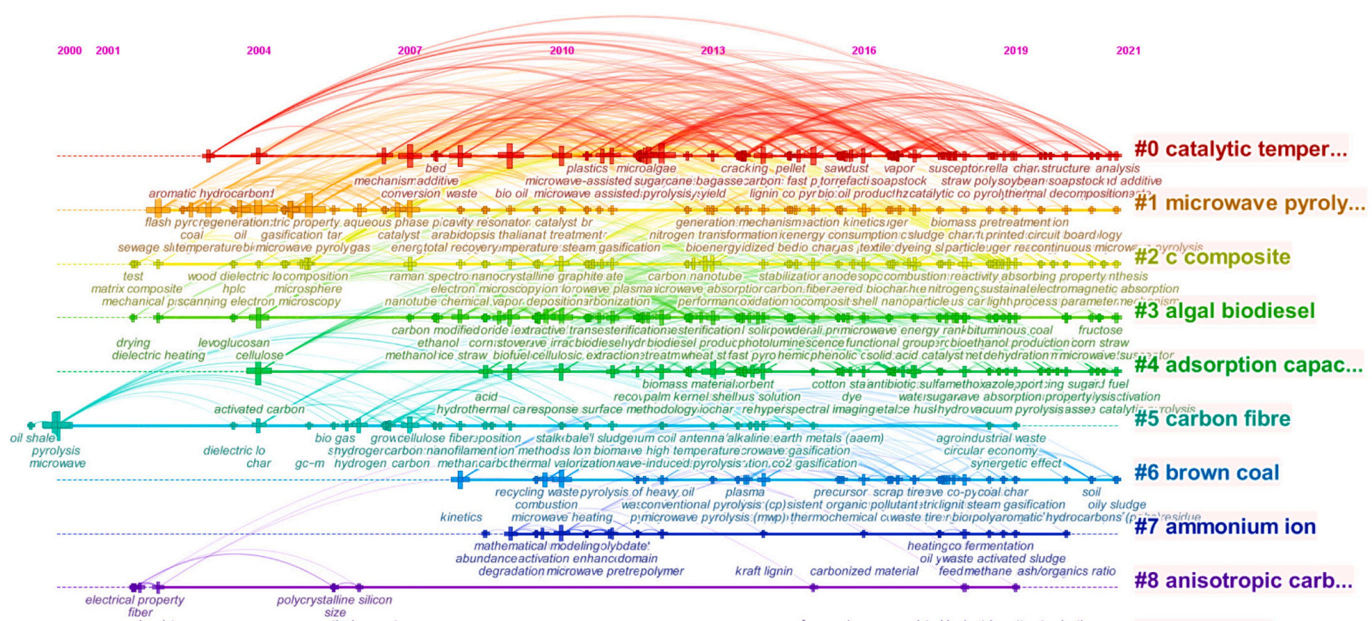

Fig. 5. Timeline network evolution of keywords related to microwave assisted pyrolysis research for biochar production.

on its stability, polarity, hydrophilicity and gross calorific value which is influenced by pyrolysis temperature and biomass composition (Nzediegwu et al., 2021**)**. In relation to this cluster, the comparative evaluation of microwave pyrolysis over conventional pyrolysis in terms of heating behaviour and product characteristics has been discussed (Wu et al., 2014; Abdelsayed et al., 2018). Research on microwave pyrolysis advances innovative techniques for converting biomass waste into valuable products, supporting industrial innovation and infrastructure development. It also contributes to responsible consumption and sustainable production practices, clean energy, climate action, and sustainable land use. However, MAP technology is still at lab scale level and should be extended to industrial scale. The studies on biochar production in continuous mode have to be explored further for assessing the biochar properties for various applications. The long-term stability and characteristics of MAP-derived biochar need further investigation, especially for soil applications.

Over past decade, development of carbon-based nanomaterials for lightweight and high-performance electromagnetic absorbers has been explored which is another major research hotspot. The exemplifications of research pertaining to this cluster are delineated in following studies. Synthesis of carbon-based microwave absorbers was carried out by Du et al. (2010) using anion exchange resin. Later low-cost biomass was used for synthesis of microwave absorber materials. Utilization of microstructured biomass after enhancing the material component as low-cost and high-performance microwave absorbers help in interference issues of electromagnetic radiation. Zhao et al. (2019) have improved the electromagnetic wave absorbance capability of rice straw by incorporating a magnetic substance (Ni^{2+}) and activating it with KOH to transform into a hierarchically porous magnetic carbon material. The improved microwave absorber property is owing to higher dielectric loss through polarization relaxation, conductive loss, multi reflection, and synergistic loss. Huang et al. (2020) synthesized TiP_2O_7 composite with biomass carbon as a capable material for microwave absorption. It could be further improved by incorporating carbon nanomaterials. Sun et al. (2020) demonstrated that high-aromatized biochar produced from biomass (oak tree) with higher lignin content (55 %) under CO_2 environment possessed higher microwave absorptivity and organic contaminant removal efficiency than biochar produced from apple tree biomass with 35 % lignin. The biochar was observed to induce localized overheating and promoted the removal of 2,4-D. Zhang et al. (2021) reported that microwave-derived composite of biochar-carbon-nanotube-NiO exhibited a high capacity of 674.6 mAh g^{-1}. The presence of carbon nanotube and NiO enhanced the capacitive performance and specific capacity of the electrode. Omoriyekomwan et al. (2017) reported that microwave pyrolysis plays a significant role in formation of carbon nanotubes on biochar. The carbon nanotube-coated biochar has high potential for removal of heavy metals from wastewater. The mechanism of CNF formation is based on self-extrusion model growth, where tar polymerization and subsequent carbonization cause volatiles to condense owing to lower external temperature. This leads to resolidification and formation of nanospheres on biochar surface, protruding outwards (Zhang et al., 2018). The research on synthesis of novel materials through MAP assists the scientific community in innovative product development for environmental and energy applications contributing to several SDGs related to advancement of industry practices, benefitting life below water and on land, and climate action.

Cluster #4 represents another research hotspot involving adsorption capacity of MAP-derived biochar for adsorbing organic contaminants, antibiotics, and dyes. The carbonization and activation of biochar through microwave has been done through either single or two-step processes to enhance the adsorption capacity of biochar. Adsorption of antibiotics (Ahmed and Theydan, 2014), dyes (Liew et al., 2018b**;** Yek et al., 2020), organic contaminants (Cunha et al., 2018) and wastewater treatment (Duran-Jimenez et al., 2017; Shukla et al., 2019) achieved through MAP-derived biochar are the instances explicating the development of this research hotspot. Many researchers have optimized the parameters involved in determining the adsorption behaviour of biochar and affirmed that under optimized conditions, the adsorption capacity is improved significantly through MAP. Lam et al. (2017) reported that under optimum microwave power of 550 W and time of 5 min, higher amount of activated carbon was achieved with adsorption capacity of 28.5 mg/ g of malachite green. Yap et al. (2017) synthesized magnetic coconut shell biochar through microwave under optimal conditions at 800 W, 20 min and 0.5 impregnation ratio. The synthesized biochar was able to uptake cadmium and lead with removal efficiencies of 4.77 mg g^{-1} and 4.96 mg g^{-1} respectively. Few studies have calculated the cost associated with the preparation of adsorbent and its adsorption of contaminants. For instance, Zbair et al. (2018) prepared an adsorbent through MAP from almond shell for ultrasound-assisted adsorption of antibiotic sulfamethoxazole. The cost for the adsorption process was found to be 15.6 USD kg^{-1} under optimal conditions and had a regeneration capacity up to 5 cycles with 6 % reduced removal efficiency. The authors reported that with the influence of microwave power, the carbon structure is expanded internally and simultaneous intensification of devolatilization occurs. With the influence of microwave time, drastic development of elementary pores was observed. Cluster #4's research on MAP-derived biochar and its ability to adsorb organic contaminants, antibiotics, and dyes contributes to multiple SDGs, primarily focusing on clean water, innovation, responsible consumption, ecosystem preservation, and partnerships. The enviro-economic assessment of MAP-derived biochar for adsorption application is limited which hinders the stakeholders and policymakers for making the process sustainable.

Over the years, various studies have reported the comparative efficiency of MAP-derived biochar with conventional produced biochar. This field of study is currently a research focal point, encompassing investigations into comparative efficiencies across diverse feedstock types and the amalgamation of various technological approaches. The net result of these studies indicates that MAP process could be achieved at reduced temperatures and with minimum formation of tar compared to traditional pyrolysis (Menéndez et al., 2007; Wu et al., 2014). In order to attain an equivalent composition in a biochar sample, the microwave process necessitates a temperature that is 157 °C lower compared to the temperature required for the gradual pyrolysis process (Gronnow et al., 2013; Masek et al., 2013). Microwave heating demonstrated a higher efficiency in maintaining the porous structure of the biochar compared to traditional pyrolysis. The surface area of MAP-derived biochar is significantly higher than conventionally produced biochar with a range of 14 %–57 % which is also influenced by other process parameters (Wu et al., 2015; Halim and Swithenbank, 2016; Abdelsayed et al., 2018). Haeldermans et al. (2019) reported that microwave pyrolysis of medium-density fiberboard at 300 W–400 W with microwave absorber showed higher aromaticity and higher stability due to a higher H/C ratio compared to conventionally produced at 350 °C–450 °C. Huang et al. (2015b) reported that the adsorption capacity of MAP-derived biochar (80 mg g^{-1}) for CO_2 was 14 % higher compared to conventional pyrolysis-produced biochar. Yek et al. (2020) reported that microwave activation represents an energy-efficient approach for producing biochar with enhanced surface area, contrasting with the conventional carbonization method requiring higher temperatures. However, the enviro-economic analysis of the comparison between two methods for production and application of biochar is limited and has to be evaluated to make the MAP process viable as that of conventional pyrolysis.

The uncertainty of process economics of MAP confines the technology commercialization, and it is one of the critical shortcomings compared to conventional pyrolysis. The scale-up strategies for the MAP reported in the literatures are limited and sufficient data available for implementation in real-case scenarios is deficient. Between 2010 and 2015, the techno-economic studies related to MAP systems were at a small scale due to untested large-scale prototypes, selection criteria for fixing biofuel prices, and higher contingency factors (Wang et al., 2015). Conventional pyrolysis is more viable than MAP however the increase in the selling price of MAP-derived biochar could make the technology feasible (Haeldermans et al., 2020). Reducing power/ energy consumption by varying the utilities can minimize production costs and make the process viable. Fodah et al. (2021b) have used solar power as a heat source for MAP, which has saved 11.17 % of energy consumption. The net energy recovery is also higher than conventional electricity. Combination of microwave-assisted vacuum pyrolysis and catalytic activity of activated carbon bed resulted in a bio-oil yield of 84 % from co-processing of plastic waste and used cooking oil. The cost of production of oil is USD 0.25 L^{-1} and that is lower than conventional diesel price (Lam et al., 2019). The equipment cost leading to capital cost investment for microwave pyrolysis is higher (Ge et al., 2021). However, the higher capital cost could be offset by co-products' credits. Yang et al. (2018) have reported that utilization of H_2 as bio-jet fuel offsets the production cost of biochar and the required heating for the process is sustained by on-site energy production. In spite of various TEA studies reported, the continuous reactor for processing agro-residues under microwave irradiation has to be validated economically with further investigations on process optimization, energy utilization, and sustainability. These indications reveal the research evolution and emerging hotspots related to microwave-assisted biochar production and application research.

3.6. Challenges and future perspectives

Main challenges associated with MAP-derived biochar research are the sustainable implementation and economically viable technology. In regard to sustainable implementation, the technical issues related to optimal operation of microwave for controlling the heating rate, and maintenance of constant temperature have to be considered before process scale-up and commercialization (Foong et al., 2020). One of the challenging tasks in reducing production costs are selecting materials with dual properties as both microwave absorbers and catalysts, which can influence the composition and product value of MAP biochar (Lin et al., 2021). Similarly, selection of microwave absorbers that enhance the product generation while providing simultaneous benefits to soil must also be considered. Another major issue is measurement and control of temperature where conventional thermocouple is not accurate and utilization of an infrared thermometer gives the surface temperature rather than reaction core temperature (Nhuchhen et al., 2018). Information on reactor design for obtaining higher power density and significant heat transfer in direct and hybrid heating of biomass with catalyst, as well as energy-saving equipment for biomass pyrolysis is still limited. This in turn affects the quantitative prediction of capital investment and operating cost of MAP systems. The presence of toxic recalcitrant compounds like persistent free radicals, and small molecular organic compounds like polychlorinated biphenyls, dibenzo-p-dioxins, polycyclic aromatic hydrocarbons, furans, etc. (Godlewska et al., 2017) in biochar is considered toxic to the environment. Economic viability of microwave pyrolysis is lower than conventional pyrolysis owing to capital investment cost, and technical stability (Haeldermans et al., 2020). Intensive studies on MAP have been conducted to improve its performance at the lab scale and to understand the technical issues related to its economic feasibility. However, the complexity of configurations in catalytic pyrolysis, along with scarce data on economic performance in large-scale operations despite several studies reporting continuous modes of operation to check its feasibility of scale-up, are factors that limit the commercialization potential. In catalytic MAP, the formation of coke on the catalyst surface declines its effectiveness and poses serious problems in upgrading bio-oil. Establishment of market for MAP-derived biochar considering the environmental protection legislation by improving its quality and product value is lacking (Alhashimi and Aktas, 2017).

Based on above mentioned challenges, the following future opportunities aid in making the MAP process for scale-up and commercialization. The economic sustainability of microwave-assisted pyrolysis of biomass depends on using a sequential process having lower energy return on investment along with co-product allocation to achieve better returns. The research gaps and future recommendations related to MAP research are as follows:

- ➢ Overall future research priorities must involve process optimization to increase performance efficiency and yield. Further, appropriate characterization techniques must be used to study the physicochemical features of biochar delineating their applications deriving maximal benefits.
- ➢ There is a need to establish a clear empirical relationship through mathematical modelling based on the underlying mechanism of microwave pyrolysis conditions, and raw material composition on the product yield. Computational approach of using machine learning models, simulations on MAP for deriving the energy/ value-added products are limited and it has to be explored.
- ➢ Molecular interactions between the biomass and catalyst under microwave heating has to be investigated further with considerations to

reduce the cost related to catalyst selection and loading, along with environmental benefits.

- ➢ Studies on the long-term potential of microwave-derived biochar in enhancing soil fertility are scarce and should be achieved through field studies.
- ➢ Most of the studies reported were on lab-scale level implemented in batch mode explicating the need for steps for adopting the scale-up of MAP in beneficial terms.
- ➢ The detailed quantification of MAP process in producing high-quality biochar and its potential in offsetting the CO_2 is needed in terms of overall carbon intensity of process.
- ➢ There is a need for an in-depth analysis of mechanisms associated with microwave absorption in multicomponent systems. Consequently, an extensive exploration of different biomass-derived absorbing materials with characteristics like higher temperature resistance, and hydrophobicity is necessary. In a nutshell, combination of various technologies such as nanotechnology and chemical synthesis can be employed to produce high-performance microwave-absorbing materials from cost-effective resources.
- ➢ Utilization of mixture of similar/ different types of feedstock for microwave-assisted co-pyrolysis to produce high-quality biofuels has to be explored further accounting to reduce process economics. Application of pyrolytic products for soil amendment, energy storage, chemical production, power generation has to be studied in a biorefinery perspectives considering the environmental benefits.
- ➢ It is essential to balance the optimum applicability of biochar to avoid undesired toxicity impacts on the environment. To avoid constraints linked with the merit of the technology during the process scale-up, it is essential to conduct more economic and life-cycle impact assessment studies. Analysis of the environmental hotspots along with economic extremities must be carried out during the semi-pilot level studies considering the microwave biochar production and thereby their differential application scenarios.

4. Conclusion

Scientometric analysis of research publications related to MAP-derived biochar has been carried out. China and USA were found to be the most prominent countries having highest contribution percentage in MAP biochar research. Compared to other subject categories, "Energy and Fuels" has been more focused affirming the potential of technology for producing advanced biofuels from biomass whereas "Agriculture" needs further significant attention. The major research trends and hotspots were associated with exploration of different feedstock and possible mechanism of thermal degradation for high quality biochar production with low energy requirements, identification of significant catalyst for improving the heating performance, increasing the adsorption behaviour of biochar for various contaminants, formation of nanostructures on biochar for different environmental applications. Scale-up of MAP in continuous mode for high quality biochar production to be used for various applications has to be more focused in future research. Enviro-economic assessment studies of MAP technology for sustainable energy and/or value-added product generation has to be considered for making process viable. MAP-derived biochar positively impacts communities by improving soil health, reducing pollution, and boosting crop yields. Its social implications include fostering healthier ecosystems, sustainable farming, knowledge sharing, and community empowerment, contributing to the advancement of SDGs. Thus, the study aids researchers in understanding current research trends and identifying the loopholes that can guide the enhancement of sustainability in MAP-derived biochar production and its applications.

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CRediT authorship contribution statement

Mari Selvam S.: Conceptualization, Data curation, Software, Formal analysis, Writing – original draft. **Paramasivan Balasubramanian:** Conceptualization, Formal analysis, Writing – review & editing, Funding acquisition, Supervision, Validation.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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