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Biochar

REVIEW

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Multifaceted applications of biochar in environmental management: a bibliometric profile

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Abstract

Biochar is a carbon-containing material prepared through thermal treatment of biomass in limited supply of oxygen, and used for an array of applications including waste management, climate change mitigation, soil fertility improvement, bio-energy production, and contaminant remediation. The data related to biochar, its production, and the wide applicability were collected using Web of Science Core Collection Database (on 25/10/2022), while bibliometric network analysis was performed using VOSviewer software to analyse year-wise, author-wise, country-wise, and journal-wise publication trends, construct keyword co-occurrence maps, and identify research areas receiving greater focus. Further, the applications of biochar were reviewed and mechanistic insights were provided. Some of the findings include: > 50% of documents (> 13,000) getting published in the past 3 years, > 90% of documents (> 21,000) being research articles, ~ 50% of publications (> 10,000) being related to environmental sciences, pyrolysis being the most widely used (~ 40% articles) production technique (followed by carbonization, gasification, combustion, and torrefaction), China being the most active country in terms of publications (> 11,000), and biochar being mostly used for removing contaminants (followed by soil improvement, waste management, energy production, and climate change mitigation). Various strengths, weaknesses, opportunities, and threats (SWOT analysis) of biochar production and wide-ranging applicability were identified. Lastly, gaps were identified including the need for performing elaborate life cycle assessments, exploring machine learning and artificial intelligence for upgrading conversion technology and producing application-specific biochar, and investigating mechanistic aspects of soil-biochar interactions and nano-scale transformation of biochar. The study covers a broad spectrum of biochar applicability to identify areas receiving lesser attention, which could guide the future researchers for augmenting biochar research.

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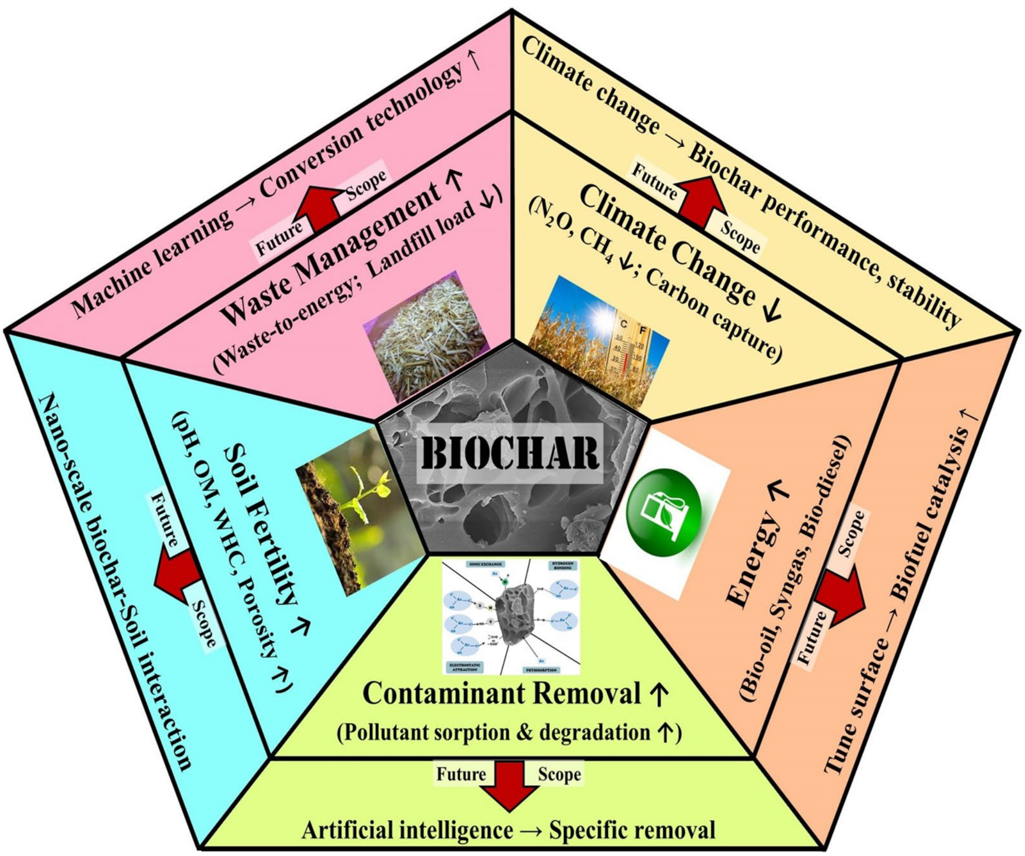
Highlights

- More than 75% biochar-related documents were published in the last five years itself.
- Most studies focussed on pollutant removal (>2000) and soil improvement (~1000).
- Focus on other applications: manage waste> produce energy> mitigate climate change.
- The Chinese dominate in publications, primarily enabled by extensive research funding.
- Artificial intelligence could be critical in producing application-specific biochar.

Keywords Sustainable development, Waste management, Climate change mitigation, Soil improvement, Energy production, Contaminant remediation

Graphical Abstract



1 Introduction

Unprecedented population growth and anthropogenic activities have resulted in generation of enormous quantities of waste, depletion of natural resources, plethora of environment pollution and triggering of climate change. Recently, biochar has emerged as a vital tool for minimizing the severity of these problems. Biochar is a solid carbon-containing material synthesized via thermal treatment of biomass wastes in a limited supply of oxygen (IBI 2015; Hossain et al. 2020). It can be produced from agricultural waste, kitchen waste, forest-based waste, industry-generated waste, or animal-derived waste (thereby enabling waste management), using methods including torrefaction, gasification, pyrolysis, and hydrothermal/flash carbonization (Hu et al. 2021a; Shaikh et al. 2022b). Pyrolysis is the most widely utilised method primarily due to its simplicity, high yield, and cost-effectiveness (Uday et al. 2022). It has the potential of increasing pH, organic matter, nutrient retention, cation exchange capacity, surface area, porosity, microbial community, and water holding capacity of soil (Hossain et al. 2020; Singh et al. 2022a). Correspondingly, biochar application helps augment soil fertility and plant productivity, eventually strengthening food security (Agarwal et al. 2022; Nath et al. 2022). Additionally, biochar application also helps in mitigating climate change by sequestering carbon and minimizing greenhouse gas emissions (Kumar et al. 2022a; Lyu et al. 2022); remediating organic and inorganic contaminants from soil, water and air via routes of adsorption and degradation (Gwenzi et al. 2021; Gao et al. 2022; Qiu et al. 2022); and producing and storing bio-energy via co-generation of bio-oil and bio-gas during biochar production and acts as a catalyst in the production of biodiesel (Kumar et al. 2020b; Osman et al. 2022). The wide applicability of biochar and the economic management of waste circumvent take-make-waste approach, which enables re-incorporation of valuable waste into the agricultural systems, thereby promoting a circular economy, achieving net zero emission goals in the future by several nations, and principally playing a key role in sustainable development around the globe (He et al. 2022; Kumar and Bhattacharya 2021; Li et al. 2022a). Biochar could also play crucial roles in "Environmental restoration", "Agricultural management", and "Carbon neutralization", which are critical for long-term global development strategies in the twenty-first century (Qin et al. 2022). Technologies such as artificial intelligence and machine learning have been incorporated to choose the suitable feedstock for effective biochar production and its possible applications (Lakshmi et al. 2021; Khan et al. 2022).

The wide-ranging applicability of biochar has propelled the research and publications related to biochar many folds in the past decade (Fig. 1). A bibliometric analysis could be performed with respect to biochar and its applicability, which could give a better view of the evolutionary trajectory of the biochar research (Abdeljaoued et al. 2020; Li et al. 2020a). Bibliometric analysis implies statistical assessment of scientific publications and literature including research articles, review articles, books, book chapters, conference proceedings, and others (Arfaoui et al. 2019). Bibliometric analysis is a powerful method of helping researchers and analysts for identification of research trends and gaps to suggest/recommend adequate directions for future research (Sossa et al. 2022; Zhao et al. 2022). For example, bibliometric mapping helps visualize similarity or relatedness between items of interest, with similarity meaning items possessing the same association strength, while relatedness referring to different types of relations (van Eck and Waltman 2010). Previously, bibliometric analysis was performed using softwares like CiteSpace, SciMAT, and VOSviewer utilising different bibliographic databases (Science Citation Index, Scopus, and Web of Science), where: (i) Belmonte et al. (2017) analysed the emerging role of biochar systems in water-energy-food

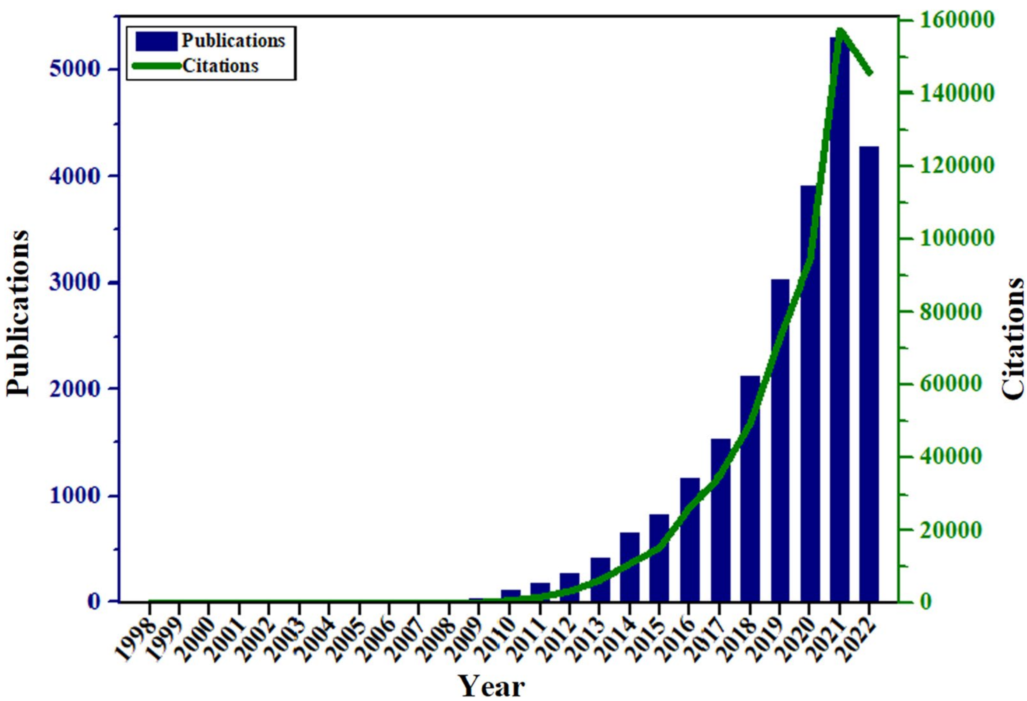


Fig. 1 Year-wise biochar publications with the number of citations

nexus via improvement of agricultural productivity resulting from biochar-supported rise in soil fertility; (ii) Ahmed et al. (2018) performed bibliometric analysis on global research in the field of biochar; (iii) Zama et al. (2018) investigated trends related to the research on contaminant remediation from soil using biochar; (iv) Arfaoui et al. (2019) analysed research trends in biochar amendment to arid soils using bibliometric study; (v) Li et al. (2020a) and Abdeljaoued et al. (2020) reviewed biochar-related studies and the evolving nature of biochar research in the previous decades; (vi) Yan et al. (2020) and Kamali et al. (2020) assessed bibliometric networking for effects of biochar application on soil; (vii) Qin et al. (2022) aimed at providing insights for opportunities and future research prospects with respect to biochar; (viii) Li et al. (2022b) reported the evolution of hydrothermal biochar; (ix) Boraah et al. (2022) analysed wood biochar performance in remediating contaminants from water; and (x) Wu et al. (2021) visualised research trends in the field of biochar for the year of 2020.

However, a preliminary analysis of the literature suggested that a bibliometric analysis covering the broad applicability of biochar in the fields of waste management, climate change mitigation, soil improvement, energy production, and pollution remediation was absent, with the few publications incorporating bibliometric analysis focussing on soil improvement and contaminant remediation. Further, any article covering SWOT (strengths, weaknesses, opportunities, and threats) analysis of biochar production and applicability was not observed during the mining of literature. Correspondingly, it would be extremely useful to perform a combined quantitative and qualitative in-depth review covering the broader spectrum of biochar applicability to guide and recommend the future researchers to perform specific studies related to biochar for solving the aforementioned global threats and achieving the goals of sustainable development. Therefore, the present study (i) utilises bibliometric analysis to statistically reveal the knowledge base and visually identify the prominent authors, countries, and journals in different fields; (ii) summarises the different applications of biochar along with identification of prominent authors, countries, and important keywords used in different studies related to the application; (iii) recognizes deficient areas needing additional improvements to popularize and commercialize biochar; (iv) incorporates a SWOT analysis to identify various strengths, weaknesses, opportunities, and threats of biochar production and its applicability in different fields; and lastly (v) furnishes future research directions needed in relevant areas for a better self-sustaining future.

2 Methodology

Data could be collected from databases, such as Web of Science (WoS), Scopus, Dimensions, Lens, or PubMed. Among these databases, WoS Core Collection Database was chosen for collecting data primarily because of the large spectrum of data covered, in-depth coverage of different publications (especially with reference to citation by source), and the ensured rigorous peer review system, in comparison to other databases (Zyoud et al. 2017; Li et al. 2020a; Jiao et al. 2021). The data were searched on 25th of October, 2022, where the search scope was inclusive of all types of articles available in the WoS database to ensure that the present investigation encompassed every possible publication related to the search query. During the search, important keywords were put inside double quotations to obtain desirable search results, and similar keywords were separated by OR to obtain wider results where different versions of keywords could have been used. For example, with respect to the management of waste by application of biochar, the search query was: Biochar "waste management" OR Biochar "management of waste". The different search queries used to retrieve the publications relevant to various biochar applications have been provided in Table 1, which eventually help recognize and analyse different areas of research with greater number of publications. The obtained data were downloaded using the "Tab delimited file" option available in the "Export" drop-down menu on WoS website.

Additionally, citation reports were also generated on WoS website to obtain the year-wise trend of documents published and the number of times they have been cited. The WoS website was also explored to identify the number of publications with respect to different authors, countries, affiliations, research areas, publishers, and journals. Lastly, the downloaded data were imported into the VOSviewer 1.6.17 software to make network maps for relationships between authors and countries, in addition to plotting co-occurrence maps of author keywords used in the publications (Pan et al. 2021; Zhao et al. 2021; Singh et al. 2022b). VOSviewer (Visualization of Similarities) is a free-to-use scientometric software developed by Ludo Waltman and Nees Jan van Eck, which has been used for creating network maps, with respect to different parameters including author, citation, organisation, country, and keyword co-occurrence (van Eck and Waltman 2010; Zhao et al. 2021). Also, the VOSviewer software helped sort the dataset in accordance with three different parameters consisting of total link strength, number of documents, and number of citations. In the obtained figures, the larger the size of the frame, the larger would be its dominance in the networks maps while the greater

Table 1 Search queries used for identifying various publications relevant for the biochar applications

Applications of biochar	Search query	Query link	Number of publications (accessed on 25/10/2022)
Waste management	Biochar "waste management" OR Biochar "management of waste"	https://www.webofscience.com/wos/woscc/summary/87a3bd53-14e9-46b5-94bb-50afea4a78fd-5863c4e4/relevance/1	1062
Climate change mitigation	Biochar "climate change" mitigation OR Biochar "climate change" management	https://www.webofscience.com/wos/woscc/summary/70d303ec-ed85-4d2d-afa0-99e8a6b1d958-586403c0/relevance/1	650
Soil quality improvement	Biochar "soil fertility"	https://www.webofscience.com/wos/woscc/summary/f148bec9-34ac-4e1f-bfa5-8e42d388a6ea-586435fe/relevance/1	1066
Energy production	Biochar "energy production" OR Biochar "energy conversion" OR Biochar "energy storage" OR Biochar "production of energy" OR Biochar "conversion of energy" OR Biochar "storage of energy"	https://www.webofscience.com/wos/woscc/summary/a7624222-4861-49f9-b9d1-9970bbd6dc2c-58646a9d/relevance/1	684
Contaminant remediation from soil	Biochar "soil remediation" OR Biochar "soil pollution" OR Biochar "soil treatment"	https://www.webofscience.com/wos/woscc/summary/9c2b62f4-2288-4093-b388-ea5629d1415e-5864949d/relevance/1	890
Contaminant remediation from water	Biochar "water removal" OR Biochar "water treatment" OR Biochar "water pollution"	https://www.webofscience.com/wos/woscc/summary/d2c2bad1-c8c9-4e6d-85e2-c807d0f97296-5864ba5e/relevance/1	1552
Contaminant remediation from air	Biochar "air removal" OR Biochar "air treatment" OR Biochar "air pollution"	https://www.webofscience.com/wos/woscc/summary/2c18a347-1acb-4f6c-bdde-00ef5aaea48a-5865040b/relevance/1	101

the number of lines originating from each frame (line represents link between two frames), the larger is its networking strength. With respect to the keyword co-occurrence maps, the larger the frame size, the greater is the frequency of the usage of a keyword. In addition to the different network mapping and trend analyses, different applications were reviewed by analysing the latest, most relevant and highly cited publications obtained on the WoS website and mechanistic insights were provided for each biochar application.

3 Results and discussion

3.1 Overall observations of bibliometric analyses

More than 23,800 publications have already been observed related to biochar on the WoS database (till 25th October, 2022), with first publication reported in 1998 on WoS database. Over the years, the number of publications shows an exponential trend. While 21,885 of these publications were research articles, 1490 were review articles. Biochar with its crucial properties is used in wide-ranging applications. Most of the focus was given to remediation/removal of contaminants (nearly 2500 publications), with maximum attention being given to removal from water (1549 publications), followed by soil (887 publications) and air (101 publications). Application of biochar for removal of pollutants was followed by its applicability for improvement of soil properties (1065 publications), management of waste (1056 publications), production of energy (684 publications), and mitigation of climate change (648 publications). Although biochar has been used for improving soil properties since ages (Sohi et al. 2010), the research trend shows that most of the focus has been given on the removal of contaminants, primarily from hydro-geosphere system.

Research trend demonstrated that ~ 75% of the documents were published in the previous 5 years: 2137 in 2018, 3034 in 2019, 3928 in 2020, 5236 in 2021 and 4172 in 2022 (till 25th October), which indicates that biochar has become a key area of research in the recent past. Such a research trend is also suggestive of the rising interest among researchers in various parts of world possibly due to the wide-ranging applicability of biochar and the potential of biochar in providing a sustainable solution to the menace of waste management, climate change, energy production, and pollution. As relevant studies continue to grow, in-depth research on biochar is expected to proliferate. Among the countries, China was associated with publishing the most number of articles (11,762), followed by USA (3556), India (1493), Australia (1420), and South Korea (1216). The highest share of China in publications is possibly because of the intensively active scientific programs in China growing rapidly in the recent past in addition to the higher investment in research and development by the Chinese government. Official statistics from 2020 have reported that China spends ~ 2.4% of its GDP on research and development, which could rise by 7% each year till 2025. China also released a National Medium and Long-Term Plan for the Development of Science and Technology (2006–2020), which aimed at transforming China into innovation-oriented country (Sun and Cao 2021). Moreover, establishment of "economic and technological development zones" and "special economic zones" in China helped augment impactful research in China. These changes could have helped China publish the maximum number of articles in comparison to other countries. With the trend observed among countries, Chinese institutes have also occupied the top two positions among the institutions publishing the maximum number of documents (1738 affiliated to Chinese Academy of Sciences and 546 affiliated to Zhejiang University), followed by Korea University (517).

In terms of research areas, a major portion of the documents were related to Environmental Sciences (10,403), Energy Fuels (3925), Environmental Engineering (3739), Chemical Engineering (3701), and Soil Science (2235). Among the researchers, Yong Sik Ok was the most active author and published the maximum number of documents related to biochar (612), with maximum focus on waste management (220) and contaminant removal from water (59). Yong Sik Ok was followed by Daniel Tsang (269), Yuan Zhang (264), Yu Wang (255), and Liang Wang (222). Such a trend of the contributing authors indicates that barring the top-most position, the Chinese dominate the list of the authors making the most of the scientific contributions. The observed extensive network links among the authors, countries and institutes suggest that scientific communication channels have been established world-wide which helps exchange information among scientific communities. However, it is crucial to note that there are certain scientific groups with low network links but commendable publishing credentials with very high scientific outputs.

Among the different publishers, Elsevier aided in publishing the maximum number of documents (12,102), and was followed by Springer Nature (3433) and MDPI (1789). Furthermore, identification of major journals could be helpful for scholars to select relevant impactful journals at the time of publishing articles. It could also help increase thought-process of scholars by evaluating the literature, broadening academic horizons, and expanding research ideas. Among the journals, Science of the Total Environment published the maximum number of documents relating to biochar (1400), followed by Bioresource Technology (1130), Chemosphere (1001), Environmental Science and Pollution Research (799), Journal of Hazardous Materials (666), Journal of Cleaner Production (556), Journal of Environmental Management (509), Chemical Engineering Journal (495), Environmental Pollution (415), and Biomass Conversion and Biorefinery (357). In terms of citations, the top five journals were Bioresource Technology (70,291), Science of the Total Environment (44,994), Chemosphere (42,196), Journal of Hazardous Materials (25,200), and Chemical Engineering Journal (24,976). Citation frequency of journals could be an important indicator of the attention given to it by other scholars and the relevance of the journal in the eye of other scholars. Sorting the journals in terms of citations per article, we observe the following trend (WoS website on 25th October, 2022): Bioresource Technology (62.2), Chemical Engineering Journal (50.46), Chemosphere (42.15), Journal of Hazardous Materials (37.84), Environmental Pollution (36.45), Journal of Environmental Management (33.39), Science of the Total Environment (32.14), Journal of Cleaner Production (28), and Environmental Science and Pollution Research (18.72).

3.2 Production of biochar

Several thermal treatment methods have been used to prepare biochar including torrefaction, combustion, gasification, carbonization, and pyrolysis. In most of the studies, biochar was produced using pyrolysis (9438 publications). Other methods used for production in decreasing order of usage include carbonization (2073), gasification (1317), combustion (1075), and torrefaction (485). It is crucial to note that treatment methods and fabrication conditions affect the physico-chemical properties of biochar prepared (Kumar and Bhattacharya 2021). Further, abundance of lignin in biomass could augment the yield of biochar production (Rangabhashiyam and Balasubramanian 2019). Importantly, nutrient-rich biomass would enable the production of biochar with high nutritional content, which could be vital for increasing the quality of degraded soils (Karim et al. 2019). Importantly, treatment temperature affects biochar production significantly (low temperatures are ideal for holocellulose-rich biomass, while high temperatures are excellent for lignin-rich biomass), apart from influencing its applicability (such as high temperature treatment of biomass for organic contaminant remediation and low temperature treatment for inorganic contaminant remediation purposes) (Yaashikaa et al. 2020; Qiu et al. 2022; Shahbaz et al. 2022).

Torrefaction involves heating of biomass (such as water hyacinth, rice husk, bagasse, peanut husk, and sawdust) at the temperatures of 200–300°C in absence of oxygen for ~ 1 h under inert atmosphere, where properties of high grindability, low volatile content, high heating value, high energy density, low moisture content, and biological degradation-resistant are obtained in the prepared biochar (Chen et al. 2021; Thengane et al. 2022). Torrefaction proceeds with drying below 100 °C, depolymerization and re-condensation of macromolecules below 180 °C, limited devolatilization below 250 °C, and extensive devolatilization and carbonization above 250 °C (Bates and Ghoniem 2014; Perera et al. 2021). Around 485 publications were related to torrefaction, with 111 documents published in 2021. Combustion is a process where biomass is burnt directly to produce biochar and generate thermal energy (Sri Shalini et al. 2021). Further, pre-treatment of biomass is a pre-requisite in combustion for obtaining a high yield of biochar. Combustion is accompanied by sub-processes like devolatilization, gas/solid phase combustion, and gasification, with benefits of energy production, waste reduction, and biochar obtained after combustion is non-hazardous and could be used for improving soil fertility (Lombardi et al. 2013). Combustion is influenced by temperature, turbulence, retention time, and intra-/extra-particle mass transfer resistance (Rozainee et al. 2010). Around 1075 publications were found related to combustion, and 206 documents were published itself in 2021.

Gasification involves treating lignocellulose-rich biomass thermally at the temperatures of 700–900°C with insufficient oxygen, which usually results in production of syngas (mainly containing CO and H_2 and smaller amounts of CO_2, CH_4, N_2, hydrocarbons, tar, ash, and sulphur compounds) and a low amount of biochar (You et al. 2017; Murugesan et al. 2022). It could be used for producing heat, liquid fuel, H_2, electricity, and chemicals like methanol and dimethyl ether (Dhanavath et al. 2018). Gasification results in 85% syngas, 10% biochar, and 5% bio-oil as products. Reactors used to produce syngas include fix bed gasifier, plasma gasifier, supercritical water gasifier, moving bed reactor, fluidized bed gasifier, packed bed gasifier, and cyclone gasifier (Arena 2012). Fluidized bed reactors are mostly used for producing syngas. Dual fluidized bed is reported to produce syngas free from nitrogen gas (Pröll et al. 2007). Gasification is a two-stage process, where drying, pyrolysis, and tar cracking occur during oxidation stage and gasification occur during reduction reaction stage (Keche et al. 2015). Around 1317 publications were observed related to gasification, and in 2021 itself, 247 documents were published. Carbonization is of two types—flash (thermal treatment of biomass, such as agricultural wastes, at the temperatures of 350–650°C for < 1 h at high pressure) and hydrothermal (thermal treatment of wet biomass, such as eucalyptus sawdust and barley straw, at high temperatures and pressure) (Cha et al. 2016; Nath et al. 2022). Hydrothermal carbonization has advantages of utilization of mild temperatures compared to other thermal processes and lesser emission of harmful gases like SO_x and NO_x which solubilize in water (Gao et al. 2016b). Hydrothermal carbonization begins with hydrolysis, followed by degradation of intermediate compounds (dehydration and carboxylation), formation of aromatic compounds (furfurals), and condensation polymerization (Gómez et al. 2020). While only 28 documents were published related to flash carbonization, 1232 publications were connected to hydrothermal carbonization.

Pyrolysis involves thermal treatment of biomass at the temperatures of 300–900°C in an oxygen-deprived furnace or kiln to obtain biochar, bio-oil, and syngas as products (Bolan et al. 2021). Absence of oxygen enables biomass to be heated above its thermal stability, resulting in maximum amount of highly stable biochar produced during pyrolysis (Li et al. 2020b; Wang et al. 2020c). Thermal treatment results in volatilisation of feedstock components and formation of oxygen-rich surface functional groups (such as hydroxyl, carboxyl, and carbonyl) (Foong et al. 2020; Leng et al. 2021). Pyrolysis is affected by heating technique, treatment temperature, heating rate, vapour residence time, and pressure conditions (Bolan et al. 2021; Perera et al. 2021). Slow heating rates increase biochar yields, while high heating rates decrease exposure time and secondary cracking reactions, thereby augmenting bio-oil yields (Bhoi et al. 2020). Low heating rates and long residence time increase retention time of vapour pyrolysis, leading to increased secondary char formation. While smaller particle size favours bio-oil production, larger particle size promotes the formation of lager amounts of biochar (Perera et al. 2021). High pressure (operating pressure > atmospheric pressure) increases vapour residence time, which in turn favours biochar yields (Qin et al. 2020). Pyrolysis could be classified as slow pyrolysis (biomass heated at the temperatures of 400–500°C with moderate rate of temperature rise), mild pyrolysis (or torrefaction, explained previously) and fast pyrolysis (biomass heated at the temperatures of 800–1200°C with rapid rate of temperature rise) (Premarathna et al. 2019; Lee et al. 2020). Pyrolysis begins with evaporation of unbound moisture at low temperatures, followed by devolatilization (releasing CO and CO_2 and acetic acid) at 100–200°C, extensive devolatilization (biomass decomposes into biochar, condensable, and non-condensable gases) at 200–600°C, and lastly secondary devolatilization (tars converted into biochar and non-condensable gases) at 300–900°C (Sun et al. 2016). In real-time situations, pyrolysis could be affected by presence of catalysts, biomass composition, degree of crystallinity, and polymerization of ligno-cellulosic components, which influence heat and mass transfer (Brennan Pecha et al. 2019). Fast pyrolysis is a complex process involving multi-scale, multi-phase hydrodynamics, heat transfer, and chemical reactions (Perera et al. 2021). For fast pyrolysis, fluidized bed reactors are mostly used enabled by high rate of heat transfer and superior temperature control (Bridgwater 2012). Further, slow steam pyrolysis (Giudicianni et al. 2013), microwave pyrolysis (Su et al. 2020), microwave vacuum pyrolysis (Wan Mahari et al. 2020), and flash pyrolysis (Gruss et al. 2019) have also been utilised for production of biochar. Biomass, such as crop residues, softwood chip, corn cobs, corn stover, sunflower oil cake, fruit waste, and vegetable waste, has been used for production of biochar via different types of pyrolysis (Windeatt et al. 2014; Kumar et al. 2020a, 2021a, 2022b). A total of 9438 publications were linked to pyrolysis, with 1323 pertaining to slow pyrolysis, and 1086 relating to fast pyrolysis. While 89 documents were associated with flash pyrolysis, 52 publications were connected to slow steam pyrolysis. The popularity of pyrolysis among the various production methods is indicative of its simplicity, cost-effectiveness, and a probable high yield obtained during pyrolysis (Li et al. 2020b; Bolan et al. 2021).

3.3 Applications of biochar

Variation in production technique/conditions and biomass/feedstock utilisation significantly affect the properties of biochar. Biochar possesses crucial properties such as alkaline pH, high carbon content, large surface area, adequate porosity, abundant surface functional groups, remarkable water holding capacity, high nutrient content, and sufficient ash content. These properties make biochar a huge prospect for wide-ranging applications (Igalavithana et al. 2017; Bolan et al. 2021; Osman et al. 2022). Some of the most important and highly-cited publications in different fields of biochar applications with relevant data have been provided in Table 2.

3.3.1 Waste management by using waste material as feedstock

Waste disposal has been a cause of concern with methods including landfill dumping, composting, incineration, and recycling. Improper disposal endangers human and ecosystem health, along with a strong probability of contamination of soil, water, and air and release of greenhouse gases into the atmosphere (escalating climate change) (Siddiqua et al. 2022). However, biomass wastes are valuable energy resources (high potential for energy production) critical for global sustenance (Tripathi et al. 2019). Waste-to-energy conversion would aid in minimizing wasteload, greenhouse gas emissions (from landfills), and dependence on coal/petroleum-based power plants. Technologies include incineration, torrefaction, plasma technology, gasification, pyrolysis, fermentation, liquefaction, and anaerobic digestion (Lee et al. 2019; Osman et al. 2021). Biochar has emerged as a highly potent waste management strategy with possible preference over composting, primarily emanating from high carbon storing capacity(> 1000 years), contaminant-remediating possibilities, soil quality-enhancing capabilities, and energy-producing capacities of biochar, while composting locks carbon hardly for 10–20 years (Oldfield et al. 2018).

Agricultural residues, produced in large quantities (including stubble, pulp, peel, husk, straw, leaves, stalk, stem, bagasse, and shell), mostly remain under-utilized (grazed by cattle, left to decompose, or burnt) (Wijitkosum 2022). Animal wastes (e.g. animal and poultry manures) were previously used to enhance soil fertility but led to water (and odor) pollution (Sarfaraz et al. 2020). Forestry residues (including wastes from deforestation, plantations, paper manufacturing, and wood processing) could be prone to wildfire, diseases and pest attack (Puettmann et al. 2020). Industrial wastes, including food industry waste (meat-based/confectionery), solid wastes (fruit, vegetables, pulp, or fiber), and pulp-paper industry waste, mostly end up in landfills (Kwon et al. 2020). Municipal solid wastes (comprising household wastes and sewage sludge) are generally dumped in water bodies or open fields (Gunarathne et al. 2019). Therefore, most of the biomass wastes either pollute our surroundings or remain under-utilized, and conversion of these wastes to useful resource like biochar could be highly beneficial for economical waste management. However, it is important not to jeopardize food security, fodder supply (for cattle and poultry), or biodiversity. Interestingly, thermal treatment of biomass waste kills the harmful micro-organisms present in the wastes, which could aid in minimizing their impact on human and environmental health (Wang et al. 2020a). Further, biochar production would aid in decreasing the waste overload in landfills (eventually decreasing the number of landfill sites) and landfill-associated problems (release of toxins, leachate and greenhouse gases) (Bolan et al. 2021).

Research in this area started since 2010 with 6 publications, which began growing exponentially from 16 in 2014 to 273 in 2021 (maximum number of publications). In 2022, 194 publications have been recorded already (Additional file 1: Fig. S1a). Most of the documents were

Table 2 Top-cited publications related to various applications of biochar along with production conditions, major findings, limitations, and recommendations

Biomass	Production	Application	Major Findings	Limitations and recommendations	References
Green-waste	Pyrolysis (450 °C)	Soil amendment	Increased radish yield; Maximumed yield when biochar was applied with N fertilizer; Increased soil pH, C, exchangeable cations; Decreased tensile strength of soil	Field experiments required; Could enhance C content and cation exchange capacity of soil	(Chan et al. 2007)
Waste biomass	Low-temperature pyrolysis	Carbon sequestration and waste management	Reduced greenhouse gas generation; Minimized solid waste	Could decrease environmental impacts but not reverse climate change; Could replace fossil fuels with renewable energy	(Johannes 2007)
Waste biomass	Pyrolysis	Carbon sequestration, soil fertility and waste management	Biochar affected microbial population and soil biogeochemistry; Biochar-mycorrhizal association contributed to plant production, ecosystem restoration, and carbon sequestration; Mycorrhizal abundance was influenced by plant-fungus signalling interference and detoxification of allelochemicals on biochar	Alteration in physico-chemical properties of soil; Potential negative impacts on some mycorrhizal fungi; Could be used for C sequestration	(Warnock et al. 2007)
Pinewood, rice husk	Hydrothermal liquefaction (300 °C)	Removal of Pb	Hydrothermal treatment resulted in irregular surface and enhanced O-containing functional groups; Adsorption fitted pseudo-second-order model; Thermodynamics suggested physical endothermic adsorption; Solution pH was key for Pb adsorption	No experiment for adsorbent regeneration and effect of co-existing ions; Could be used for waste minimization and contamination removal	(Liu and Zhang 2009)
Pecan shell	Pyrolysis (700 °C)	Agricultural soil amendment	Biochar increased organic C, pH, Mn, K, Ca, and P of Norfolk soil	Decreased acidity, S, and Zn; Could be used to improve soil fertility	(Novak et al. 2009)
Dairy manure	Pyrolysis (≤ 500 °C)	Contaminant remediation from aqueous solutions	Carbon content of biochar decreased from 36.8% at 100 °C to 1.67% at 500 °C; High efficiency for Pb (99.7%) and atrazine (77.3%) removal; Limited P release indicated its use as fertilizer	Chance of heavy metal enrichment in biomass; Potential for soil amendment for agronomic purposes and contaminant remediation	(Cao and Harris 2010)
Corn stover, yard waste, switchgrass	Pyrolysis	Increase in soil fertility	Increased N and C content to improve corn yield	Use of agricultural residues could reduce greenhouse gas emission	(Roberts et al. 2010)

Table 2 (continued)

Biomass	Production	Application	Major Findings	Limitations and recommendations	References
Paper-mill waste	Slow pyrolysis (550 °C)	Soil fertility improvement and waste management	Increased N uptake in wheat grown in fertiliser-amended ferrosol; Increased pH, CEC, exchangeable Ca, K and total C; Increased biomass in soybean	Reduced wheat and radish biomass; Could be used for vermicomposting	(van Zwieten et al. 2010)
Waste biomass	Pyrolysis	Carbon sequestration	Provided energy and increased crop yields; Variation in biochar amendment (0–80%) changed soil N_2O emission by − 4% to + 11%	Heavy metal enrichment in biomass; Could reduce biomass combustion thereby decreasing greenhouse gas emission	(Woolf et al. 2010)
Agricultural crop straw	Pyrolysis (350–450 °C)	Reduce greenhouse gas emission, soil quality, crop yield	Biochar amendment increased rice productivity; Increased C content, total N, soil pH and soil; Decreased N_2O emission	Biochar amendment decreased soil bulk density and rice rate; Could enhance soil fertility, reduce greenhouse gas emissions	(Zhanga et al. 2010)
Hardwood, corn straw	Pyrolysis (450 °C)	Removal of Cu and Zn	Adsorption data were well described by Langmuir isotherm; Adsorptions were endothermic; $=CH_2$ and $-CH_3$ groups were responsible for Cu and Zn adsorption	No real-time field experiment; Could be used for waste minimization and contaminant removal	(Chen et al. 2011)
Sugar beet tailing	Pyrolysis (300 °C)	Removal of Cr(VI)	-COOH and -OH groups involved; Removal governed by H-bonding, electrostatic interaction, surface complexation; Reduced Cr(VI) to Cr(III)	No experiment for adsorbent regeneration and effect of co-existing ions	(Dong et al. 2011)
Wastewater sludge	Pyrolysis (300–700 °C)	Soil fertility improvement and waste management	Increased N, P, K to enhance crop production; Enhanced mobility and bioavailability of trace elements; Concentration of all micronutrients (Ca, Fe, Mg, S, Cu, Zn) enhanced with pyrolysis temperature	Pyrolysis temperature affected-heavy metals (As, Se, Pb, Ni and Cd) concentration in biochar; Suitability for alkaline soils to reduce alkalinity	(Hossain et al. 2011)
Waste biomass	Pyrolysis (400 °C)	Carbon storage and greenhouse gas emission reduction	Increased CH_4 uptake in agricultural soil and water holding capacity; Could capture N_2O emissions	Mechanisms not discussed; Could help mitigate greenhouse gases emissions	(Karhu et al. 2011)
Rice straw	Pyrolysis (250–450 °C)	Improvement of soil fertility	Improved soil fertility and C sequestration; Maize biomass increased by 146% with NPK after biochar amendment	Maize biomass was increased by 164% without NPK after biochar amendment	(Peng et al. 2011)

Table 2 (continued)

Biomass	Production	Application	Major Findings	Limitations and recommendations	References
Agricultural residues (Sugar beet)	Anaerobic digestion (600 °C)	Removal of phosphate and waste management	Calcium ion released into solution which removed phosphate through precipitation; Phosphate also removed through interaction with functional groups	High biochar dose could alter soil properties; Spent biochar could be applied as fertilizer	(Yao et al. 2011)
Soybean stover, peanut shell	Pyrolysis (300–700 °C)	Removal of trichloroethylene	Adsorption of trichloroethylene was governed by Langmuir isotherm	No real-time field experiment were conducted	(Ahmad et al. 2012)
Dairy waste, sugar beet	Anaerobically digested (600 °C)	Removal of heavy metals	Effective aqueous please removal of heavy metal ions (Pb^{2+}, Cu^{2+}, Ni^{2+}, Cd^{2+}); Adsorption mainly due to surface precipitation;'Biological activation' produced high quality biochar for water treatment	No experiment for adsorbent regeneration and effect of co-existing ions; Could be used as sorbent for water purifiers	(Inyang et al. 2012)
Pig, cow manure	Pyrolysis (400 °C)	Removal of Cu(II), Zn(II), Cd(II) and Pb(II)	Effective aqueous phase Cu(II), Zn(II), Cd(II), Pb(II) removal; Adsorption followed pseudo-2nd order kinetics with intraparticle diffusion; Mechanisms- surface complexation and external mass transfer	Significant effect of competitive ions; Potential for wastewater treatment	(Kołodyńska et al. 2012)
Sewage sludge	Pyrolysis (500 °C)	Heavy metal bioavailability in Mediterranean agricultural soil	Decreased leaching of metals (Cu, Ni, Zn. Pb present in raw sewage); Reduced plant heavy metal availability; Increased soil respiration	Increment of soil respiration was lower; Biochar amendment could increase water holding capacity	(Méndez et al. 2012)
Switchgrass	Hydrothermal carbonization (300 °C)	Removal of Cu and Cd	Majority of functional groups were aromatic; Adsorption mechanism governed by surface complexation and electrostatic interaction	No experiment was carried out for adsorbent regeneration and effect of co-existing ions; Use in water purifiers	(Regmi et al. 2012)

Table 2 (continued)

Biomass	Production	Application	Major Findings	Limitations and recommendations	References
Dairy manure	Pyrolysis (200–350 °C)	Removal of Cu, Zn, and Cd	Isotherm modeling and chemical speciation were tested using Visual MINTEQ modelling; Adsorption capacity: Cu (48.4 mg g^{-1}) > Zn (31.6 mg g^{-1}) > Cd (31.9 mg g^{-1}); Surface adsorption through phenonic –OH complexation due to delocalized π electrons; Mineral components (PO_4^{3-}, CO_3^{2-}) important for sorption	No experiment for biochar regeneration; Remediation of contaminated water	(Xu et al. 2013)
Municipal sewage sludge	Pyrolysis (500–900 °C)	Removal of Cd(II)	Pyrolysis temperature alteredremoval efficiency; Biochar yield decreased and porosity increased with rise in pyrolysis temperature; Adsorption mechanism governed by surface precipitation and ion-exchange	No experiment for adsorbent regeneration and effect of co-existing ions; Effective for wide-ranging contaminants	(Chen et al. 2014)
Waste biomass	Pyrolysis (600–700 °C)	Remediation and soil fertility improvement	Improved soil fertility and enriched nutrients; Carbon sequestration due to carbon and ash content; Enhanced exchangeable cations; Improvedoverall soil quality	Heavy metal present in biomass; Could be used to resolve economic, health and environmental problems	(Tomczyk et al. 2020)

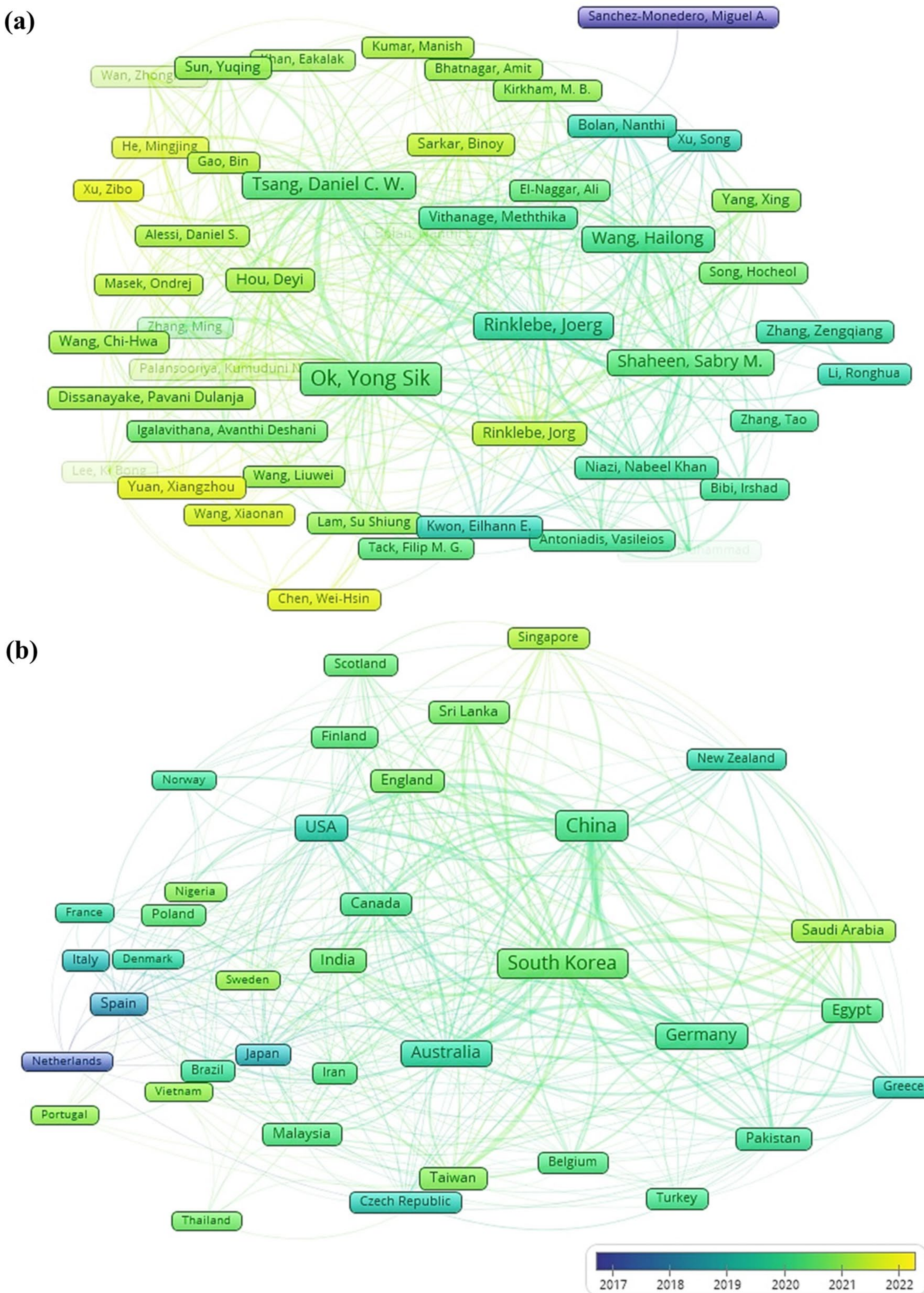


Fig. 2 Bibliometric network for waste management between **a** authors and **b** countries at minimum 10 document criteria

based on the field of Environmental Sciences (735), followed by Environmental Engineering (420), Energy Fuels (129) and Green Sustainable Science Technology (106). A maximum number of 220 documents was authored by Yong Sik Ok (citations-9872), followed by 153 by Jörg Rinklebe (citations-7783) and 104 by Daniel Tsang (citations-5847). Similarly, the maximum link strength (minimum 10 publications) was observed for Yong Sik Ok (582), followed by Jörg Rinklebe (352) and C.W Daniel Tsang (341) (Fig. 2a). With respect to documents published by the countries, China published the maximum number of documents (483), followed by South Korea (334) and Germany (207). Upon sorting the bibliometric data on the number of citations received for countries (minimum 10 documents), China received the maximum number of citations (17,014), while South Korea showed the maximum link strength (1119 for minimum 10 publications criteria) (Fig. 2b). Among the journals, Waste Management occupied the top spot actively involved in publishing articles (204), followed by Science of The Total Environment (70), Journal of Hazardous Materials (41), Journal of Cleaner Production (41), and Journal of Material Cycles and Waste Management (40). Co-occurrence of keywords (minimum occurrences-30) was analysed (Additional file 1: Fig. S2) and the following trend was observed: biochar (489 occurrences), pyrolysis (194), adsorption (155), biomass (143), and waste management (123). A large occurrence of keywords like adsorption, heavy metals, removal, kinetics, amendment, and others are indicative of utilization of waste-based biochars for soil/water remediation purposes in addition to management of waste. Further, keywords like sewage sludge, municipal solid waste, and food waste were also observed implying their utilisation in the biochar-based studies for management of waste and promotion of circular economy (another keyword).

3.3.2 Climate change mitigation by carbon fixation in soil and sink of greenhouse gases

Biochar, being an excellent medium for carbon sequestration, has immense potential to mitigate climate change (Wang et al. 2016; Kumar et al. 2022d; Osman et al. 2022). Carbon content in biomass is converted into highly stable biochar, which could resist degradation in soil for ~ 1600 years (Tomczyk et al. 2020). The high stability is facilitated by: (a) formation of organo-mineral complexes with organic matter in soil; (b) stabilization of colloidal suspension of biochar by humic acid in organic matter; (c) resistance offered to degradation by highly aromatic carbonaceous structures; (d) enhanced aggregation resulting from high microbial activity, which reinforces stability; and (e) downstream transport in soil profile minimizing its decomposition (Wiedemeier et al. 2015; Obia et al. 2017; Leng et al. 2019; Yang et al. 2019; Tsai and Chang 2020; Wang et al. 2022b). Further, stability could be influenced by pH, composition, surface area, porosity, moisture content, soil temperature, organic matter, abrasiveness, cropping pattern, and tillage (Sohi et al. 2009). Furthermore, biochar prepared at high temperatures possesses greater capacity for carbon sequestration. Above 650 °C, lignin is converted into polycyclic aromatic hydrocarbons which augments its hydrophobicity thereby increasing its stability (Tomczyk et al. 2020).

Moreover, biochar is a sink for greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, and decreases their concentration from atmosphere, as suggested by a huge number of studies, which eventually minimizes global warming (Yang et al. 2020; Rittl et al. 2021). However, studies have also reported increase in greenhouse gas emissions after biochar amendment (Edwards et al. 2018; Qi et al. 2020). Nevertheless, parameters like crop type, soil type, pH, moisture, biochar type, and fertiliser dose influence microbial activity, which enables greenhouse gas sequestration (Qi et al. 2018; Wu et al. 2018; Saletnik et al. 2019). Nitrous oxide emissions could be suppressed, after biochar addition, by: (a) improving soil structure and aeration thereby minimizing anaerobic soil volume and associated denitrification; (b) sorbing organic compounds like monoterpenes that trigger denitrification; (c) triggering ethylene release which inhibits microbial activity related to ammonium nitrification; (d) reduction of N_2O on surface by organic constituents, pre-sorbed organic molecules, or oxides like TiO_2 which catalyse N_2O reduction; and (e) sorbing nitrous oxide in addition to sorbing CH_4 and CO_2, NH_3 and other nitrogen compounds (Cornelissen et al. 2013; Cayuela et al. 2014; Chen et al. 2019a; Ribas et al. 2019). Methane emissions could be suppressed after biochar application by: (a) enhanced microbial/methanotropic activity which oxidises methane; (b) improved soil aeration thereby making it favourable for proliferation of methane-oxidising methanotrophs (compared to methane-forming methanogens); (c) hot-spot habitats provided to soil methanotrophic microbes in the porous framework of biochar; and (d) direct sorption of methane (Feng et al. 2012; Chen et al. 2018a; Qi et al. 2018; Wu et al. 2019). In a study, Rai and Reddy (2019) suggested incorporation of biochar-based landfill covers on a large-scale which could sorb methane released from landfills, thereby minimizing its emission sustainably. Removal of greenhouse gases is also enabled by mechanisms such as physisorption (involving van der Waals forces), precipitation, and size exclusion (Gwenzi et al. 2021). Interestingly, biochar could be amended to flooded soils (while cultivating paddy crops) for decreasing greenhouse gas emission (Kumar et al. 2022a). Further, co-production

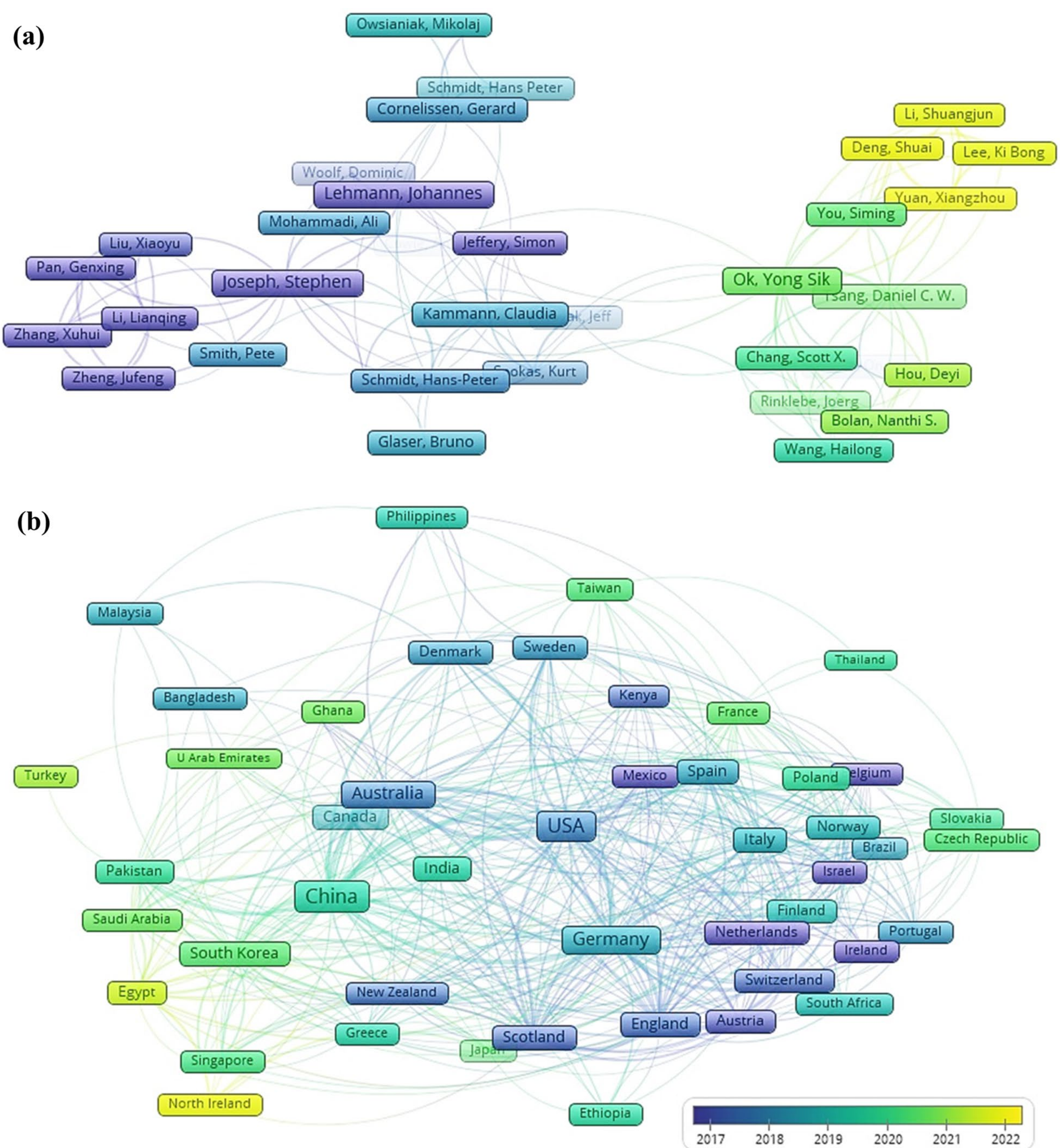


Fig. 3 Bibliometric network for mitigation of climate change between **a** authors and **b** countries at minimum 5 document criteria

of bio-oil and syngas during biochar preparation would assist in reducing fossil fuel burning which is generally associated with greenhouse gas emission.

Articles on climate change mitigation via biochar have been documented since 2007, with 1–5 articles published till 2009. From 2010 to 2015, the number of publications increased from 9 to 32, and later increased exponentially to 136 in 2021. In 2022, 102 documents have already been published (Additional file 1: Fig. S1b). Maximum research in this topic was related to Environmental Sciences (302) followed by Soil Sciences (98), and Agronomy (86). A maximum of 18 documents were published by Yong Sik Ok, followed by Stephen Joseph (17) and Johannes Lehmann (16) (Fig. 3a). Yong Sik Ok showed the maximum link strength for minimum 5 document criteria (43), followed by Stephen Joseph (41) whereas Johannes Lehmann showed link strength of only 14. When comparing author citation-wise, Stephen Joseph and Johannes Lehmann received 3078 and 3055 citations, respectively. When a minimum of 5 documents was fixed as the criteria for author-country relation, the maximum number of documents was authored by researchers from China (193), followed by United States (156) and Germany (87), with link strengths of 266, 278, and 251, respectively (Fig. 3b). In terms of number of citations, USA, China, and Australia received 10,454, 6551, and 5613 citations, respectively. Among the journals, Science of The Total Environment actively published the most articles (52), followed by Journal of Environmental Management (25), Global Change Biology Bioenergy (21), Agronomy Basel (17), and Sustainability (16). Co-occurrence of keywords were also analysed (Additional file 1: Fig. S3) and the following trend, with number of occurrences, was observed: biochar (341), black carbon (104), soil (102), and carbon sequestration (88). The keyword "climate change" showed 66 occurrences. A large occurrence of keywords like climate change mitigation, stability, sequestration, emissions, greenhouse gas emissions, N_2O emissions, and others were observed, which was in consonance with the search criteria (i.e., climate change mitigation). Further, keywords like organic matter, organic matter, and mineralisation pointed towards their role in climate change, while words like growth, yield, agriculture, and productivity implied the applicability of biochar for supporting plant growth and crop yield in addition to climate change mitigation. Moreover, keywords like energy, water, management, and life cycle assessment are indicative of biochar's wide ranging applicability utilised simultaneously in the studies.

3.3.3 Soil improvement by amendment

There has been a rise in climate change-associated extreme weather events (e.g., floods, droughts, and high temperatures), which are in association with increase in human population (and the resulting enhanced anthropogenic activity) and have deteriorated the soil systems by increasing soil contamination, erosion, compaction, and acidification (Boardman et al. 2019; Tao et al. 2019; Wang et al. 2021). Correspondingly, it has become an imperative to improve the properties of soil to boost the crop yield (Kumar et al. 2021b, 2022a). Amendment of soil with biochar improves its physical properties by increasing porosity, forming aggregates, and decreasing bulk density, thereby improving overall soil structure (Bolan et al. 2021; Basak et al. 2022). Aggregation is improved by helping aromatic carbon in biochar bind with organic matter, increasing hydrophobicity of soil, and boosting its resistance to physical disturbances like wetting-drying cycle (Gupta and Germida 2015; Wang et al. 2017). Aggregation is also influenced by presence of monovalent and multivalent ions in biochar, which interact with surface functional groups and minerals on organic matter such as $–COO^-$, Al-O^-, and Si–O^- (Dorji et al. 2020). Further, ions could assist in bridging organic matter and clay minerals, thereby improving aggregation. However, ions such as K^+ could increase dispersion and mobility of organic matter, thereby decreasing aggregation (Mukome et al. 2013). Increase in soil pH following biochar addition could augment flocculation of clay particles, thereby enhancing aggregation. Increase in organic matter could assist microbial activity which produces extracellular polymeric substances which help improve aggregate stability (Gupta and Germida 2015; Li et al. 2018). Microbial community structure in soil is improved by augmenting enzymatic activities, soil respiration, water retention, and nutrient content (carbon, nitrogen, and phosphorus), providing a habitat/niche for growth and colonization (and avoiding grazers), and increasing synergistic interactions with plant roots (Kumar and Bhattacharya 2023a). Moreover, biochar amendment decreases bulk density and increases porosity which augments soil aeration and diminish tensile strength of soil, consequently promoting microbial proliferation and root growth (Lehmann et al. 2011; Blanco-Canqui 2017). Biochar, with high porosity and augmented carbon content, favours plant growth-promoting bacteria (e.g. *Stenotrophomonas* sp., *Arthrobacter* sp., and *Bacillus* sp.) in rhizosphere and increases microbial diversity in soil (Wang et al. 2019; Zheng et al. 2019). A microbial layer is formed on roots which prevents uptake of toxic elements, mobilises S and P, degrades insoluble C, and induces indole-3-acetic acid (phytohormone) production, which eventually stimulate growth (Fox et al. 2014; Egamberdieva et al. 2016; Bertola et al. 2019; Liao et al. 2019). Additionally, pathogenic activity is suppressed by biochar amendment (aided by gene expression regulation, direct adsorption, or induction of plant resistance) (Graber et al. 2014; Jaiswal et al. 2017, 2018).

High surface area and hydrophilic domains in biochar enable soil to hold more water after amendment (Burrell et al. 2016; Sorrenti et al. 2016). Biochar addition improves electrical conductivity of soil which is primarily enabled by the presence of carbonates, phosphates, sesquioxides, silica, and other trace elements/minerals in biochar and the high ash content in biochar (Yu et al. 2013). Biochar improves pH of soil by induction of liming effect, complexation with O-functional groups, precipitation with Si, and surface complexation with Al (Shi et al. 2019). Alkaline pH of biochar enables it to neutralize degraded acidic soils (Geng et al. 2022). Biochar could sorb sodium ions from saline soils, thereby ameliorating saline/sodic soils (Gunarathne et al. 2020). The high sorption efficiency of biochar helps sorb NH_4^+, reduce nitrogen volatilization and leaching, increase nitrogen use efficiency and maintain soil nutrients (Xu et al. 2016). Biochar is a source of nutrients (such as Si, Mg, Ca, and P) and supplies nutrients to soil (El-Naggar et al. 2019b; Ye et al. 2020). Biochar addition enhances cation exchange capacity of soil, which aids in reducing leaching of nutrients (like NH_4^+ and K^+) and nitrogen loss through emissions (Domingues et al. 2020). Moreover, it reduces nutrient mobility and bioavailability, thereby acting as a nutrient sink (El-Naggar et al. 2019b). High carbon content in biochar makes it a suitable soil conditioner by augmenting organic content which enhances water (and nutrient) retention capacity of soil (Atkinson 2018; Karim et al. 2020). The increase in water retention (holding) capacity is also enabled by abundant residual pores, large internal surface area, hydrophilic surfaces, and improved soil aggregation and structure. Biochar amendment improves all the key water retention variables (field capacity, wilting point and plant available water) (Razzaghi et al. 2020). Following biochar amendment, an increase in soil nutrient supply, water retention, cation exchange capacity, total organic matter, microbial activity, erosion stability, and pollutant (organic and inorganic) immobilization helps increase soil fertility, which is followed by an increase in plant growth and crop productivity, and eventually helps manage food security (Edeh et al. 2020; Zhao et al. 2020; Wang et al. 2020c). Moreover, research groups have also applied biochar with fertilizers and/or compost to boost the yield of agricultural produce (Agegnehu et al. 2017; Ye et al. 2020).

The number of publications on the topic increased from 1 in 2008 to 9 in 2010, 100 in 2018, and 188 in 2021. In 2022, 146 documents have already been published (Additional file 1: Fig. S1c). The maximum number of documents was published in the field of Environmental Sciences (415) followed by Soil Sciences (266) and Agronomy (185). When the minimum criterion of 5 documents in author-author relation was fixed, Stephen Joseph emerged as the author publishing maximum documents (19), with link strength of 64 (Fig. 4a). He was followed by Xiaoyu Liu, Genxing Pan, and Yong Sik Ok publishing 17, 15, and 14 documents, respectively. Genxing Pan ranked second on the author list with high link strength (62). Yong Sik Ok received the most number of citations (4092) followed by Johannes Lehmann (3695), publishing 12 documents. China topped the list (documents-382, link strength-280), when the criteria of minimum 5 documents in author-country relation were fixed (Fig. 4b). USA was the second on the publication list (documents-134, link strength-145), while Pakistan was the second on the link strength list (documents-100, link strength-159). China topped the citations list (16,241) followed by USA (13,978) and Australia (9803). Among the journals, Science of The Total Environment actively published the most articles (57), followed by Agronomy Basel (42), Environmental Science and Pollution Research (27), Journal of Soils and Sediments (26), and Sustainability (26). Co-occurrence of keywords was also analysed (Additional file 1: Fig. S4) and biochar emerged as the keyword with the most number of occurrences (557), followed by soil fertility (223) and black carbon (198). A large occurrence of keywords like nitrogen, phosphorus, fertilizer, manure, compost, nutrient availability, and so on is in consonance with the search criteria (i.e., soil fertility improvement), while words like quality, growth, and yield denote use of biochar for promoting soil fertility and sustainable agriculture (another keyword). Keywords like nitrate, phosphate, adsorption, removal, and availability signify that biochars are used for recovering the nutrients from wastes and waste waters and applying them for improving soil fertility. Wheat and maize were observed to be the plants dominating the studies in this area. Lastly, terms like physical properties, chemical properties, pyrolysis temperature, and slow pyrolysis denote their significance for soil property enhancing capability for biochars.

3.3.4 Energy production, storage, and conversion

Thermal treatment of biomass produces highly affordable bio-energy (biochar, bio-oil and syngas) in varying amounts depending on treatment technique, treatment temperature, and feedstock (Kumar et al. 2020a). While fast pyrolysis produces bio-oil in large quantities, gasification generates syngas in abundance, and these techniques could be harnessed to produce bioenergy in accordance with the requirements. Further, gaseous emissions during thermal treatment could be recaptured and condensed into bio-oil. Bio-energy sources could be an adequate replacement of fossil fuels. High electrical conductivity, porosity and tunable surface (large area and abundance of surface functional groups) of biochar assist in energy production, conversion and storage including oxygen electro-catalysis, lithium/sodium ion batteries, supercapacitors, emerging fuel cell technology, and hydrogen storage (Liu et al. 2019). Biochar could be used as a carbon precursor in trans-esterification process for catalysing biodiesel production (Yu et al. 2011). High thermal stability enables biochar in catalysing plastic waste pyrolysis and removing impurities for enhanced oil quality (Ding et al. 2016). Further, the porous nature and high sorption capacity of biochar could enable carbon dioxide capture which could be later converted into (i) fuels via electro-catalytic reduction; and (ii) jet fuels via

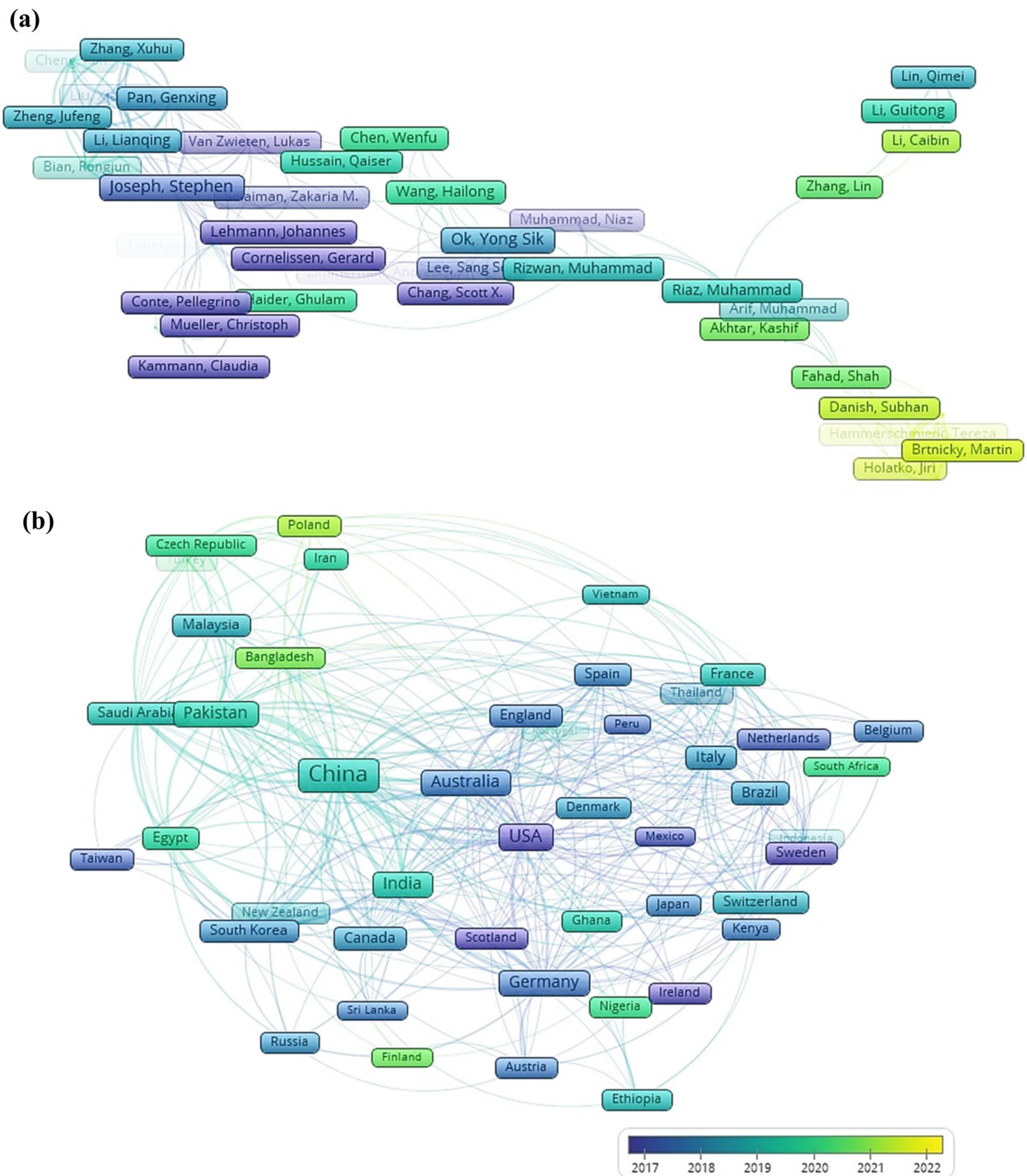


Fig. 4 Bibliometric network for improvement of soil fertility between **a** authors and **b** countries at minimum 5 document criteria

catalytic hydrogenation (Centi and Perathoner 2009; Yao et al. 2020).

Moreover, biochar-based materials (like acid/alkali functionalised or Fe/Ni-loaded biochars) or modified biochars (like sulfonated biochars) could act as excellent catalysts during production of biodiesel (Cheng and Li 2018). Biochar could cost-effectively help in removing tar (condensable hydrocarbons which cause catalytic bed fouling, reactor plugging, and deactivation of the catalyst) and toxic gases (such as hydrogen sulphide) from biogas during biomass gasification. Metal loading (Ni, Fe, or Co) could increase the removal of tar (≥ 92%) in comparison to unloaded biochar. For example, Ni-loading on biochar removed 96% tar in comparison to 90% removal by unmodified biochar (Wang et al. 2011). The removal of tar is primarily assisted by the inorganic portion of biochar (comprising of Ca, K, P, Fe, and Mg) which decomposes tar by breaking C–C and C–H bonds (Klinghoffer et al. 2012). Biochar has also been used as catalyst for improving the yield of syngas production. Corn stover-derived biochar augmented syngas production by > 3 times in comparison to syngas production devoid of catalyst (Ren et al. 2014). Moreover, biochar could be used for catalysing production of hydrocarbons from syngas (i.e. Fischer–Tropsch reaction) (Yan et al. 2013).

Research on the topic began in 2000, with 0–2 publications till 2009, which increased exponentially from 4 in 2010 to 26 in 2016 and 154 in 2021. 127 publications have already been reported in 2022 (Additional file 1: Fig. S1d). The majority of the research was focussed in the field of Energy fuels (313), followed by Environmental sciences (129), Thermodynamics (110), Chemical Engineering (110), and Mechanics (96). Yong Sik Ok published maximum number of documents (21) with link strength of 27 (Fig. 5a). He was closely followed by Eihann E. Kwon (20 documents) with the hightest link strength (50 for minimum 5 document criteria). Based on the number of documents, Sumin Kim published the third highest number of documents (15), followed by Young-Kwon Park (13). The top 3 authors based on number of citations were: Yong Sik Ok (841), Su Shiung Lam (712), and Hwai Chyuan Ong (503). However, Su Shiung Lam and Hwai Chyuan Ong possessed link strengths of merely 6. When countries were compared (criteria of minimum 5 documents), it was observed that China has published exorbitantly, with a total of 289 documents with link strength of 145, followed by the United States (96 documents and 79 link strength) and South Korea (78 documents and 95 link strength) (Fig. 5b). China and the United States received the maximum number of citations of 8167 and 3960, respectively. Among the journals, Energy Conversion and Management was the most actively participating journal publishing articles (95), followed by Bioresource Technology (26), Journal of Cleaner Production (20), Chemical Engineering Journal (17), and Renewable Sustainable Energy Reviews (16). Co-occurrence of keywords was also analysed (Additional file 1: Fig. S5) and the following trend, with number of occurrences, was observed: biochar (339), biomass (187), and pyrolysis (156). Terms like hydrothermal carbonization, gasification, and co-pyrolysis, indicates their utilisation for production with relevance to energy purpose. The keywords bio-oil, energy, energy storage, and supercapacitor are in consonance with the search criteria, while terms like porous carbon, nanosheets, and adsorption signify their role in energy storage and production. Terms like waste and sewage sludge denote the utilisation of waste biomasses for conversion (another keyword) into biochars specifically for energy purposes.

3.3.5 Contaminant remediation

Biochar has emerged as a cheap, reliable and highly potent method to remediate polluted soil, water, and air. Biochar decreases mobility and bioavailability of organic and inorganic contaminants primarily receiving assistance from physisorption (H-bonding, electrostatic interaction, surface sorption, or diffusion in pores) and chemisorption (ion exchange, complexation, precipitation, or π-π electron donor/acceptor interaction) events (Shaikh et al. 2021; Kumar and Bhattacharya 2022). Other mechanisms include chemical transformation (by reduction/oxidation), partitioning (in non-carbonized phase), or biodegradation (microbial mineralization). The remediation of pollution is discussed in subsequent sections:

3.3.5.1 Contaminant remediation from soil Previously, biochar has been used to remove organic contaminants, such as pharmaceuticals, antibiotics, agrochemicals, dyes, polycyclic aromatic hydrocarbons, persistent organic pollutants, volatile organic compounds, and endocrine disruptor compounds from soils (Kumar and Bhattacharya 2023b). Their immobilisation is affected by properties of soil (texture, pH, organic matter, clay content, and microbes), organic contaminant (molecular size and hydrophobicity/hydrophilicity), and biochar (aromaticity, alkalinity, surface functional groups, porosity, and surface area) (Ahmad et al. 2014). Increase in microbial colonization after biochar amendment assists in enhanced degradation of organic contaminants (Zhu et al. 2017). Further, biochar could also reduce the bioavailability of inorganic contaminants and immobilise these potentially toxic elements. The non-degradability of the inorganic contaminants makes them more toxic to living organisms (Bhattacharya et al. 2021). The inorganic contaminants immobilised using biochar include metal(loid)s like As, Cd, Cr, Cu, Ni, Pb, and Zn, along with other pollutants (H_2S, NH_3, NH_4^+, and NO_3^-) (Oliveira et al. 2017; Kumar et al. 2021a, 2022b).

Research on the topic began with 2 publications in 2010, 9 in 2013, 42 in 2016, 77 in 2018, and 196 in 2021. 157 articles have already been published in 2022 (Additional file 1: Fig. S1e). Maximum articles were published in the area of Environmental Sciences (710), Water Resources (195), and Meteorology Atmospheric Sciences (176). Yong Sik Ok published the maximum number

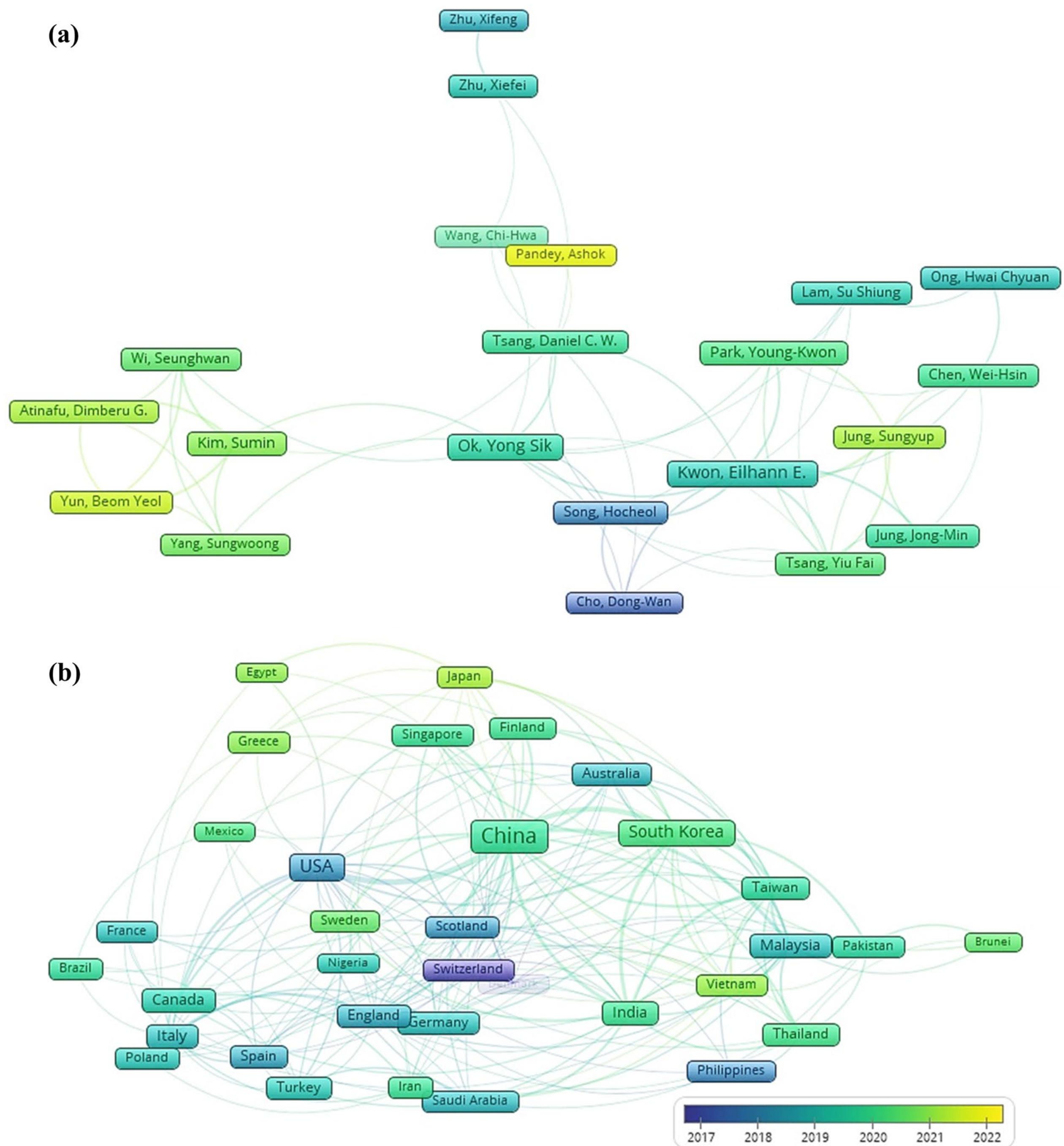


Fig. 5 Bibliometric network for energy production, conversion, and storage between **a** authors and **b** countries at minimum 5 document criteria

of documents (58), with maximum total link strength (143) (Fig. 6a). He was followed by Daniel Tsang, Jörg Rinklebe, Deyi Hou, and Hailong Wang who authored 37, 30, 24, and 20 documents, respectively. Yong Sik Ok also received the maximum number of citations (5657), while Daniel Tsang and Jörg Rinklebe received the second (3154) and third (2083) highest number of citations, respectively. China has published the maximum number of articles (547), followed by the United States (101), South Korea (88), Australia (68), and Germany (48) (Fig. 6b). When the countries were sorted link strength-wise (minimum 5 documents), the following trend was obtained: China (366) > South Korea (235) > Germany (165) > Australia (162) > United States (159). When

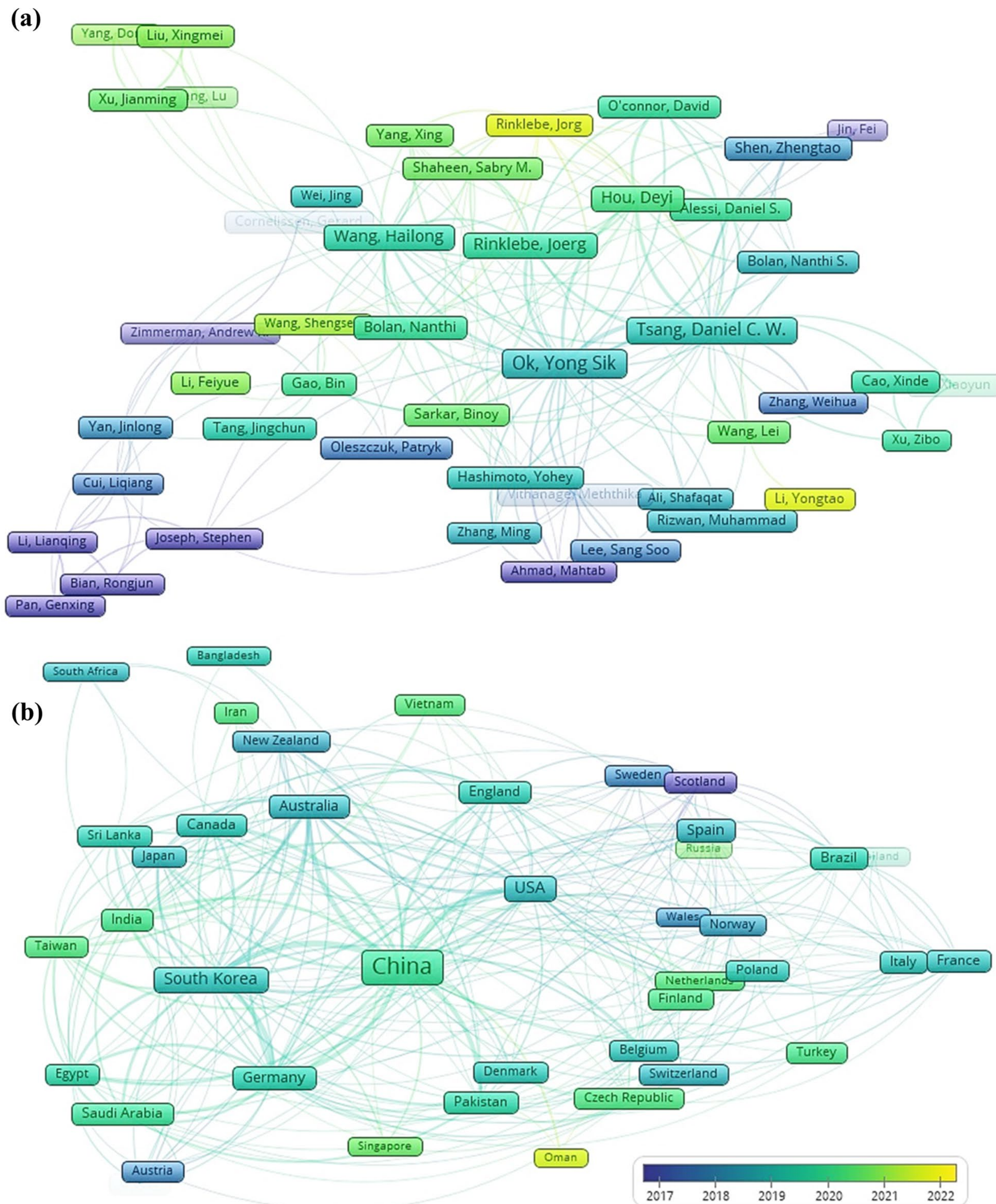


Fig. 6 Bibliometric network for remediation of contaminated soil between **a** authors and **b** countries for minimum 5 document criteria

the countries were sorted citation-wise, the following trend was obtained: China (17,520) > South Korea (6605) > United States (5342) > Australia (4301) > Germany (2601). Among different journals, Water Air and Soil Pollution was the most active (176 articles), followed by Science of The Total Environment (76), Chemosphere (71), Journal of Hazardous Materials (53), and Environmental Science and Pollution Research (45). Co-occurrence of keywords was also analysed (Additional file 1: Fig. S6) and the following trend, with number of occurrences, was observed: biochar (469), soil remediation (269), and heavy metals (220). Metals like zinc, cadmium, lead, and copper were mostly focussed on for decreasing their mobility, toxicity, bioavailability and immobilization (other important keywords). The keyword rice straw, biomass and waste occurred predominantly implying their utilisation for biochar production among the different wastes. A key term "polycyclic aromatic hydrocarbons" was also observed suggesting possible risks emanating from application of biochars in soils. Lastly, terms like nanoparticles and zero-valent iron were used indicating modification of biochar for improving contaminant remediation capabilities.

3.3.5.2 Contaminant remediation from water Biochar is also ideal for removing organic and inorganic contaminants from industry-generated wastewaters and waste streams. The removal of contaminants could be affected by differences in biochar (variation in feedstock and production conditions influence its properties), target contaminant (type and form), and operational parameters (solution pH, contact time, temperature, ionic strength and dose) (Ahmad et al. 2014; Oliveira et al. 2017). Biochar has been used to remove organic contaminants, like furans, phenolic compounds (e.g. catechol and naphthalene), pharmaceuticals (drugs and antibiotics), dyes (e.g. congo red, anionic brilliant blue, and methylene blue), persistent organic pollutants, agrochemicals (e.g. fertilizers, pesticides, and insecticides), volatile organic compounds, and endocrine disruptor compounds (Shaikh et al. 2020, 2022b, 2022a). Further, biochar has also been used to remove inorganic pollutants inclusive of cations (like Cd^{2+}, Cr^{6+}, Cu^{2+}, NH_4^+, Pb^{2+}, and Zn^{2+}) and anions (like F^-, NO_3^-, and PO_4^{3-}) (Mohan et al. 2014). Further, biochar also sorbs crude oil from oil spills (Navarathna et al. 2020).

Research on the topic began with 1–8 publications from 2009–13, which grew exponentially from 62 in 2016, 148 publications in 2018 to 371 publications in 2021. 290 documents have already been published in 2022 (Additional file 1: Fig. S1f). Most of the documents were published in the area of Environmental Sciences (738), Chemical Engineering (438), and Environmental Engineering (365). Yong Sik Ok has published the maximum number of documents (59) on the topic, with maximum total link strength (151) (Fig. 7a). He was followed by Yan Zhang, Guangming Zeng, Deyi Hou, and Daniel Tsang who authored 28, 26, 21, and 20 documents, respectively. Yong Sik Ok also received maximum number of citations (4102), while Guangming Zeng and Deyi Hou received the second (3581) and third highest (1612) number of citations. China has published the maximum number of articles (890), followed by the United States (189), South Korea (124), India (119), and Australia (76). When the countries were sorted link strength-wise, the following trend was obtained: China (437) > South Korea (265) > the United States (208) > Australia (168) > Germany (123) (Fig. 7b). When the countries were sorted citation-wise, the following trend was obtained: China (28,298) > United States (7578) > South Korea (5738) > India (3218) > Australia (2797). Among different journals, Desalination and Water Treatment published the most articles (184), followed by Science of The Total Environment (102), Bioresource Technology (79), Chemosphere (78), and Chemical Engineering Journal (71). Co-occurrence of keywords was also analysed (Additional file 1: Fig. S7) and the following trend, with number of occurrences, was observed: biochar (807), adsorption (605), removal (399), and sorption (282). Contaminants like dye (especially methylene blue), pharmaceuticals (especially antibiotics like tetracycline), ions (like phosphate and nitrate), and metals (like chromium, lead, copper, and cadmium) were focussed upon in the investigations to treat wastewaters, where they also performed isotherm and kinetic studies to optimize the removal (all terms used are keywords observed in the co-occurrence map). Terms like iron and magnetic biochar were also observed denoting their relevance for treatment of aqueous solutions.

3.3.5.3 Remediation of gaseous air pollutants Recently, biochar has also gained attention of research community for removing toxic pollutants (NO_x, CO_2, SO_2, ozone, H_2S, Hg, and volatile organic compounds) from air and gaseous streams. The mechanism of removal is primarily due to H-bonding, pore-filling, van der Waal interaction, electrostatic/covalent interaction, π–π electron interaction, and partitioning (with key role of volatile matter). NO_x, CO_2, and ozone is removed by biochar adsorption. While these gases could be removed by pristine biochar, removal efficiency could be enhanced by heteroatom doping or surface modification (Zhou et al. 2018a; Jung et al. 2019; Gwenzi et al. 2021). The obnoxious nature of H_2S and hazardous property of SO_2 makes its removal important, where biochar with well-developed porosity and surface functionality has efficiently removed them

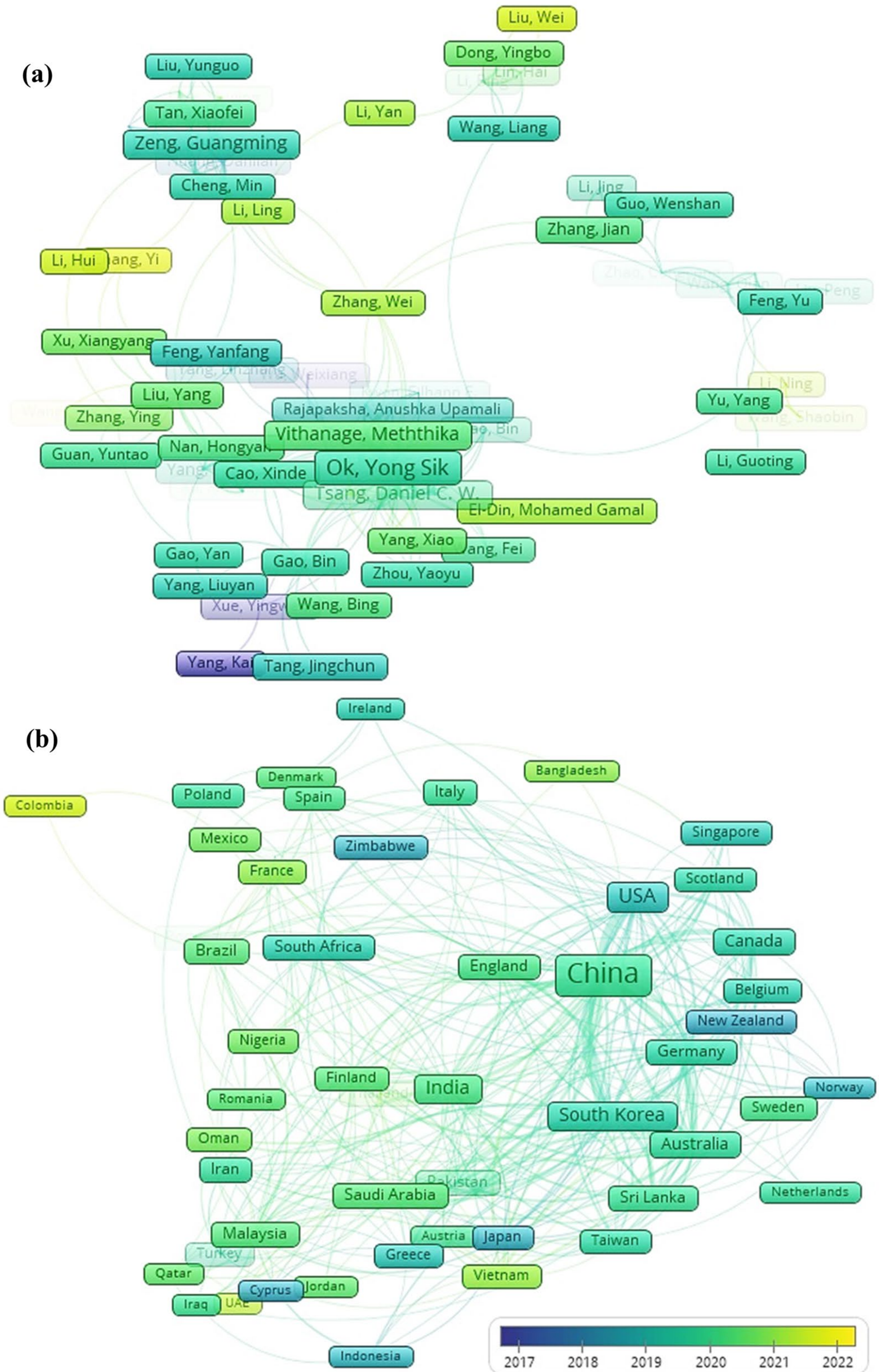


Fig. 7 Bibliometric network for treatment of polluted water between **a** authors and **b** countries for minimum 5 document criteria

(Braghiroli et al. 2019; Das et al. 2019). Polar volatile organic compounds (like aldehydes and ketones) are preferably removed by hydrophilic biochars, while non-polar volatile organic compounds (like aromatic hydrocarbons) are removed by biochars with low hydrophilicity (Zhang et al. 2017). Biochar-based materials could be used to thermo-catalytically and photo-catalytically remove volatile organic compounds by firstly (a) mass transporting it on adsorbent surface, (b) forming reactive oxidative species radicals, (c) triggering oxidative reaction between adsorbed volatile organic compounds and reactive oxidative species, and (d) desorption of products to regenerate the sorbent (Bolan et al. 2021).

Research on the topic began in 2010, with 0–5 publications till 2017, and grew from 8 publications in 2019 to 23 in 2020 and 2021. 2022 has already documented a total of 18 articles in this area (Additional file 1: Fig. S1g). Research articles were maximum in the field of Environmental Sciences (65), followed by Environmental Engineering (22) and Green Sustainable Science Technology (17). Compared to other topics, the maximum number of documents published was 6 by Huang Fei (link strength of 19 for minimum 3 document criteria) and Rongbo Xiao (link strength of 18) followed by 5 documents by Ren-ren Wu (link strength of 18) (Fig. 8a). A maximum of 255 citations were received by Xueyang Zhang (with 4 documents), followed by 124 citations by Fei Huang. Upon comparing countries in bibliometric analysis, the United States, China, and South Korea showed the hightest total link strengths of 29, 28, and 15, respectively (minimum 3 document criteria) (Fig. 8b). China with 49 documents received 1557 citations (maximum), followed by the United States with 25 documents (770 citations) and India with 15 publications (269 citations). While South Korea published 11 documents (cited 172 times), Canada was cited 339 times with only 3 publications. Among different journals, Science of The Total Environment published the most number of documents (10), followed by Chemosphere (7), Journal Of Cleaner Production (7), Bioresource Technology (4), and Industrial Crops And Products (3). Co-occurrence of keywords (minimum 5 occurrences) was also analysed (Additional file 1: Fig. S8) and the following trend, with number of occurrences, was observed: biochar (29), pyrolysis (11), adsorption (9), and air pollution (9). Terms like rice straw and rice husk could either be indicative of their role in increasing air pollution or their utilisation for biochar production (later used for minimizing air pollution). Keywords like temperature, pyrolysis, and slow pyrolysis indicate their role in biochar production, while the dominance of a key term "life cycle assessment" suggests its relevance for carrying it out especially in the scenario where pollution levels are increasing and biochar is being extensively utilised for minimizing pollution globally.

3.4 Modifications of biochar

Biochar could be modified to enhance porosity, surface area, and oxygen-containing surface functional groups through physical or chemical treatments (Kumar et al. 2022c). Through physical modifications, steam-modified biochar, heat-modified biochar, and ball-milled biochar are prepared (Li et al. 2014; Wei et al. 2020; Katiyar et al. 2021). Although physical modifications increase cation exchange capacity, surface area, porosity and mechanochemical properties of biochar, chemical modifications are preferred especially for contaminant removal purposes (Lima et al. 2015). The main chemical treatment of biochar includes alkali-modified and acid-modified biochar (Zhao et al. 2017; Jang and Kan 2019). The main advantages of chemical modifications are improved surface area, porosity and surface functionality, which help in removal of contaminants via ion exchange, π–π interaction, chemisorption, and hydrophobic/hydrophilic interactions (Wongrod et al. 2019; Benis et al. 2020b). Further, biochars could be impregnated with metals, metal oxides or nanomaterials to amplify magnetic properties, surface area, porosity, surface functionality, H/C, O/C and N/C ratios and availability of active binding sites, which help enhance electrostatic attraction, π–π interactions, chemisorption, and complexation (Cho et al. 2017; Sizmur et al. 2017; Shaikh et al. 2022c). Among the modifications, impregnated biochars are widely used nowadays because of their high specificity, increased surface area, high reactivity, enhanced adsorption efficiency, augmented mineral content, and abundant surface functional groups (COOH, OH, C–O, C=O, and others) (Shaikh et al. 2022b). The main impregnated biochars are Fe-modified (Singh et al. 2020), Al-modified (Jung et al. 2015a), Mn-modified (Liang et al. 2017), Bi-modified (Zhu et al. 2016), Zn-modified (Van Vinh et al. 2015), La-modified (Sun et al. 2021), Mg-modified (Jung and Ahn 2016), Co-modified (Wang et al. 2012), Ca-modified (Agrafioti et al. 2014), Ni-modified (Wang et al. 2013), and multi-metal-modified biochar (Lin et al. 2019; Kumar et al. 2022c). Apart from these modifications, methods include ball milling (Panahi et al. 2020; Qu et al. 2022), gas/steam treatment (Yek et al. 2020), microwave pyrolysis (Duan et al. 2017), electro-modification (Jung et al. 2015b), ultrasonic treatment (Luo et al. 2019), ozonation (Huff et al. 2018), carbonaceous modification (Inyang et al. 2015), chitosan modification (Zhang et al. 2015), clay/silt/silica treatment (Chen et al. 2017), H_2O_2 modification (Huff and Lee 2016), microbe modification (Dalahmeh et al. 2018), and nutrient enrichment (Kumar

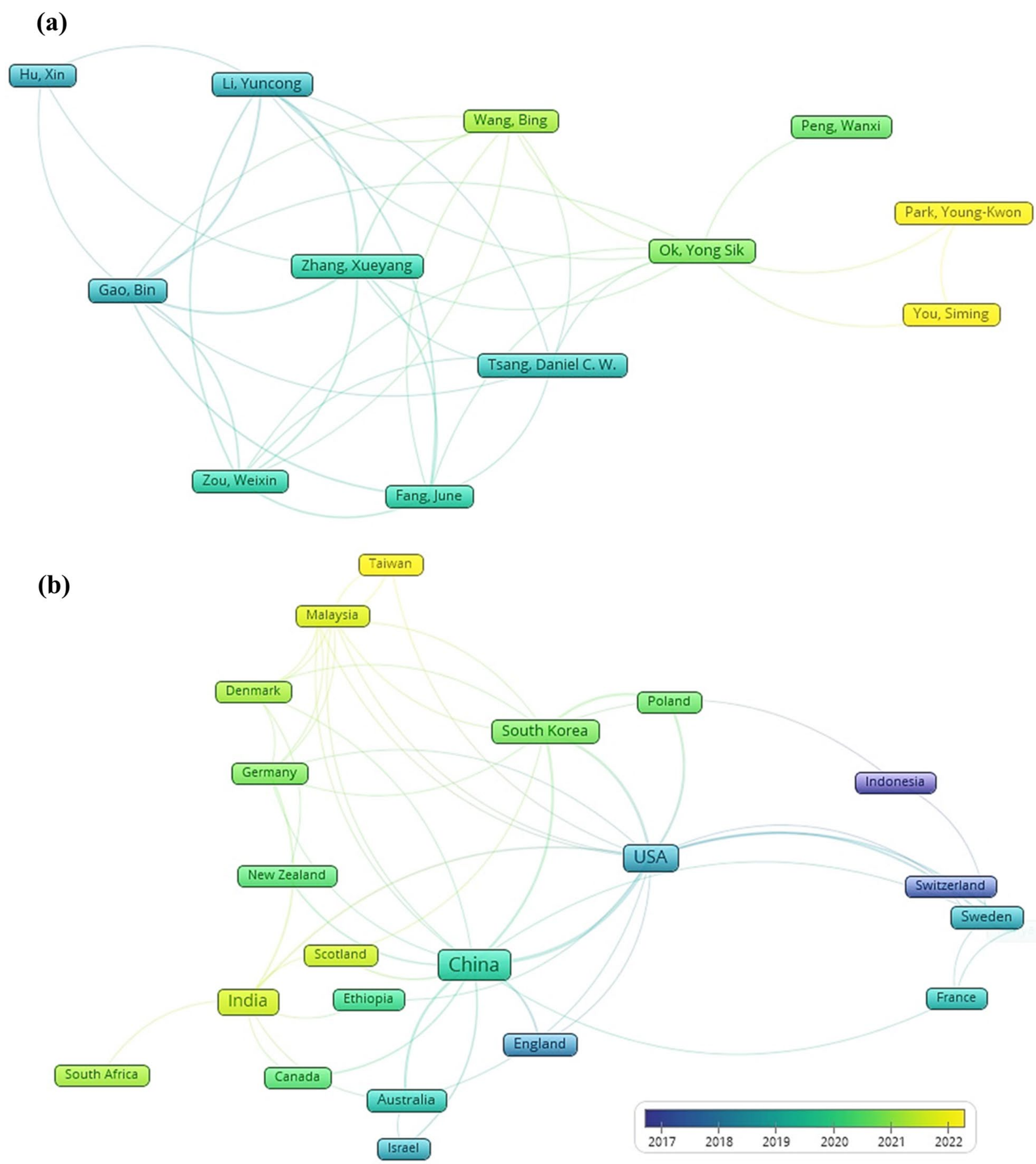


Fig. 8 Bibliometric network for treatment of contaminated air between **a** authors and **b** countries for minimum 3 document criteria

et al. 2022c). Biochar-based materials have also been used in areas like catalysis, energy storage and conversion, and as electrodes in supercapacitors, primarily enabled by increase in surface area, pore structure, and surface chemistry (Cheng et al. 2017; Xiu et al. 2017). Modified biochars could be added to soil systems to increase their pH, electrical conductivity, porosity, cation exchange capacity, microbial activities, nutrient profile, organic matter, hydraulic conductivity, and gas exchange properties, and therefore successfully used as soil enhancers (Gupta et al. 2022; Hafeez et al. 2022).

Research on modified biochars began with 0–10 publications till 2012, and grew exponentially to 269 publications in 2018 and 837 in 2021. 2022 has already documented 754 articles in this area (Additional file 1: Fig. S1h). Research articles were maximum in the field of Environmental Sciences (1540), followed by Environmental Engineering (610) and Chemical Engineering (599). The maximum number of documents was published by Yong Sik Ok (98 documents with link strength of 95, which was maximum among authors for minimum 10 document criteria), followed by Yan Zhang (61 documents) and Bin Gao (58 documents with link strength of 68-s on author list) (Fig. 9a). A maximum of 8125 citations were received by Yong Sik Ok, followed by 5722 citations by Bin Gao and 3742 citations by Guangming Zeng (37 publications). Upon comparing countries in bibliometric analysis, China, South Korea, and the United States showed the hightest total link strengths of 723, 309, and 294, respectively (for minimum 10 document criteria) (Fig. 9b). China with 2063 documents received 53,755 citations (maximum), followed by the United States with 373 documents (18,808 citations), South Korea with 219 publications (11,479 citations) and India with 200 publications (5507 citations). Among different journals, Science of The Total Environment published the most number of documents (220), followed by Chemosphere (168), Bioresource Technology (157), Environmental Science and Pollution Research (137) and Journal of Hazardous Materials (110). Co-occurrence of keywords was also analysed (Additional file 1: Fig. S9) and the following trend, with number of occurrences, was observed: biochar (1215), adsorption (1079), and removal (724). Metals (like arsenic, zinc, cadmium, lead, chromium, and copper), dyes (like methylene blue), and antibiotics (like tetracycline) were mostly focussed on for removal via adsorption or degradation. Modifications involved grapheme, carbon nanotubes, chitosan, microbes, and iron, as suggested by other keywords. Modified biochars were used for treating waste waters and recovering nutrients like ammonium, nitrate, and phosphate.

3.5 SWOT analysis of biochar production and applicability

Different strengths, weaknesses, opportunities, and threats were analyzed and are given in the following passages along with a figurative representation (Fig. 10).

3.5.1 Strengths

- Management of solid waste has become a challenging issue, and biochar has been reported to decrease biomass waste-load and landfill-associated problems (Dahal et al. 2018). Moreover, biochar also helps in waste-to-energy conversion, thereby harnessing the energy stored in the waste biomasses (Gunarathne et al. 2018; Li et al. 2022a).
- Biochar sequesters carbon and acts as a sink for CO_2, CH_4, and N_2O, which aids in mitigating climate change (Osman et al. 2022). Biochar systems could reduce 3.4–6.3 Pg of CO_2 equivalent emissions worldwide (~50% constituting CO_2 removal), while it could minimize emissions by 95% when biochar is used for replacing renewable energy (Lehmann et al. 2021). Further, biochar-based landfill covers have been used to sorb CO_2 and CH_4 emissions from landfill (Rai and Reddy 2019).
- The O-containing functional groups on biochar are responsible for redox potential of biochars, with carbonyl and quinone primarily involved in electron accepting roles and phenolic OH involved in electron donating roles of biochar (Klüpfel et al. 2014; Yuan et al. 2017; Zhang et al. 2019c). Therefore, biochars could also help in aerobic oxidation and anaerobic mitigation of methane, enabled by the electron acceptor role of biochars which affects methanogens and methanotrophs (Zhang et al. 2019b; Nan et al. 2021). The electron donating/exchange capacity of biochar could also help in N_2O reduction, enabled by biochars with high H/C, ash content, low surface area and lower lignin in feedstocks (Pascual et al. 2020).
- Production of sustainable and renewable energy is crucial in the scenario of ever-rising environmental pollution for future technological requirements, where utilisation of biochar has shown promising results for energy production, conversion, and storage (Kumar et al. 2020a). Porous biochar with high capacitance and stability could be used for sustainable energy storage (Gao et al. 2020), while biochars were used for fabricating supercapacitors enabled by high surface area, porosity, energy density and capacitance (Su et al. 2018; Zhou et al. 2018b; Lu et al. 2020).
- Biochar improves soil productivity by decreasing nutrient leaching, ameliorating saline/sodic soils, and increasing soil pH, organic matter, microbial community, erosion stability, and plant resistance to pathogens (Purakayastha et al. 2019; Dai et al. 2020; Tenic et al. 2020). Further, biochar-based fertilizers could be prepared by methods including mixing (Shin and Park 2018; Adekiya et al. 2020), impregnation (Khan et al. 2021; Sim et al. 2021), co-pyrolysis (An et al. 2020; Chen et al. 2020), and encapsulation/coating (Chen et al. 2018b; Jia et al. 2020).

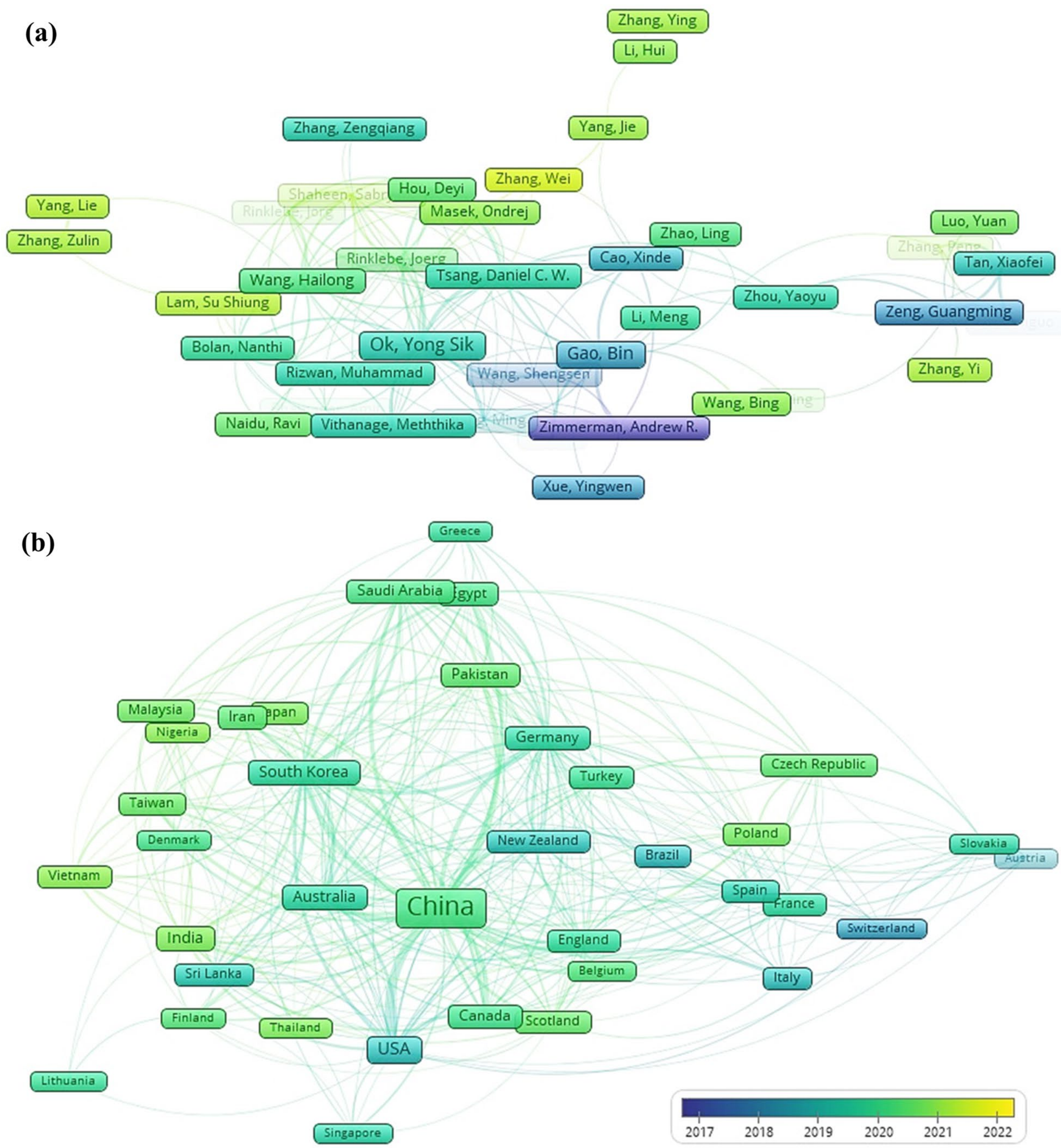


Fig. 9 Bibliometric network for modified biochars between **a** authors and **b** countries for minimum 10 document criteria

- Biochar also decreases mobility and bioavailability of organic and inorganic contaminants, which remediates polluted soils (Guo et al. 2020b; Ji et al. 2022) and treats wastewater (Vyavahare et al. 2019; Qiu et al. 2021), oil spills (Kandanelli et al. 2018; Navarathna et al. 2020), and foul air (Gwenzi et al. 2021).

3.5.2 Weaknesses

- The proliferation of biochar applicability could face initial funding/cost barriers during feedstock procurement, production, storage, and transportation (McHenry 2009).

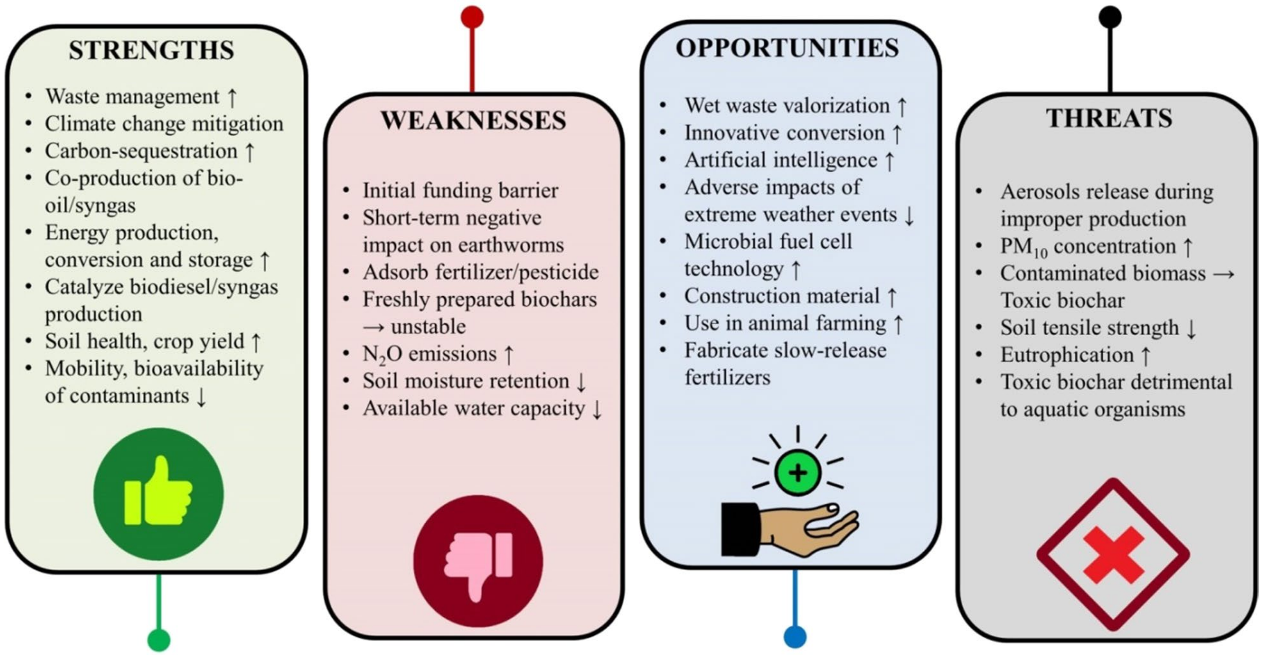


Fig. 10 SWOT analysis of biochar production and its applications

- Application of biochar could have short-term negative impacts on earthworms (Weyers and Spokas 2011). However, a recent study pointed out that earthworms could act as biological vectors enabling enzyme adsorption on biochar, thereby combining beneficial effects of both biochar and earthworm eventually assisting production of vermichar (Sanchez-Hernandez et al. 2019).
- Biochar amendment has been reported to minimise the compaction of soil systems, but the alleviation of soil compaction lasts less than 2 years and frequent biochar application could cause compaction of soil systems (Blanco-Canqui 2021).
- Biochars could also decrease soil moisture retention and available water capacity, possibly due to the clogging of soil micropores by minerals/ash components of biochar (Herath et al. 2013; Carvalho et al. 2016). Biochar amendments increase soil pH, but the rise could limit supply of nutrients like NH_4^+, cause micronutrient deficiency or adversely influence cation exchange capacity of soils (El-Naggar et al. 2019a; Zhang et al. 2019a).
- N_2O emissions could increase following biochar application due to stimulation of nitrification or there could be a rise in CH_4 and CO_2 emissions after biochar amendment due to the increase in microbial activity in soils (Edwards et al. 2018; El-Naggar et al. 2018; Ribas et al. 2019).

3.5.3 Opportunities

The different possible opportunities related to biochars have been discussed in details in "Future perspectives" section, but some of them have been summarised in the following points:

- Biochar production could incorporate wet waste valorization or more innovative conversion systems to augment energy/resource recovery and minimize gas emission (Li et al. 2022a).
- Machine learning and artificial intelligence could be harnessed to design and assess waste conversion processes, and characterize biochars for specific applicability (Lakshmi et al. 2021; Li et al. 2022c).
- Biochar could successfully ameliorate adverse impacts of climate change-triggered extreme weather events including floods, droughts, and elevated temperatures (Haider et al. 2020; Xiong et al. 2020; Jahromi et al. 2020).
- Biochar could assist production of electricity via microbial fuel cell technology enabled by high surface area and energy density (Huggins et al. 2014; Patwardhan et al. 2022).
- Surface properties of biochar could be fine-tuned for specific applications (Mendonça et al. 2017; Hafeez et al. 2022; Kumar et al. 2022c).
- Biochar not only decreases waste load and avoids waste biomass burning-derived greenhouse gas emis-

sion (Lyu et al. 2022; Pradhan et al. 2022), it also presents a great potential to decrease fertilizer usage and mitigate climate change (Lehmann et al. 2021; Xiao et al. 2022).
- Biochars could be used to fabricate highly efficient slow-releasing fertilizers (via co-pyrolysis, co-application, or co-composting), enabled by high surface area, porosity and surface functionality (Marcińczyk and Oleszczuk 2022; Wang et al. 2022a).

3.5.4 Threats

- Improper/inefficient production techniques emit gaseous aerosols and extremely harmful compounds including dioxins/furans, polycyclic aromatic hydrocarbons, persistent free radicals, per-/poly-fluoroalkyl substances, potentially toxic elements and volatile organic compounds presence in the biochar feedstocks, while smaller/lighter biochar particles are transported to atmosphere via winds ultimately increasing PM_{10} concentrations and endangering human health (Lyu et al. 2016; Gelardi et al. 2019; Zhang et al. 2019d). Deposition of PM_{10} in lungs could damage alveoli or entry into blood could cause pathological problems like rhinitis and bronchitis or produce reactive oxygen species (Yang et al. 2017; Lyu et al. 2018; Odinga et al. 2020). Biochars could also act as vectors for different types of toxic contaminants, such as carcinogens, reproductive toxins, and neurotoxins) (Gelardi et al. 2019).
- Biochar could reduce soil's tensile strength or contaminated biomass-derived biochars could release pollutants (heavy metals, polycyclic aromatic hydrocarbons, dioxins, environmentally persistent free radicals, perfluorochemicals, and volatile organic compounds) into the environment or enhance the bioavailability of toxic elements thereby endangering plant productivity (Xiang et al. 2021).
- Nutrient-rich biochars when applied on a large-scale, could eventually release NH_4^+ and PO_4^{3-} into the aquatic systems resulting in eutrophication (Park et al. 2015; Chen et al. 2017). There could be co-transportation of pollutants with spent biochars posing risks to aquifers and surface water (Chen et al. 2019b; Song et al. 2019).
- Presence of toxic substances in biochar could be detrimental to aquatic organisms, with maximum impact observed on crustaceans (Oleszczuk et al. 2013). There could be generation of hydroxyl radicals or other reactive oxygen species in aquatics, which damages organs of aquatic organisms (Odinga et al. 2020). Algae could also be detrimentally affected because of the deterred photosynthesis following shading effects of micro/nano-biochar or toxicity related to biochar (Bjorkl et al. 2017; Freixa et al. 2018).
- Biochars could have detrimental impact on soil microorganisms, resulting from pH alterations which affects signalling compounds (Zimmerman et al. 2011; Gao et al. 2016a)
- Biochar could negatively affect arbuscular mycorrhizal fungi, possibly due to disturbed signal transduction, changed nutrient levels, increased pH, adsorbed signaling molecules, altered cell–cell communication, or promoted hydrolysis (Odinga et al. 2020).
- Biochar could threaten soil organisms due to the presence of neurotoxic persistent free radicals, which might inhibit movement and defecation in the organisms (Lieke et al. 2018; Pan et al. 2019). Biochars could adsorb pesticides, heavy metals, or polycyclic aromatic hydrocarbons, which might enter gut of earthworms and mites, or change pH enhancing mortality in earthworms (Odinga et al. 2020).

4 Future perspectives

- *Feedstock collection and preparation*: Management of wet waste by their valorization into biochar could be achieved through alternate strategies such as use of novel catalysts or integrating upgraded reactor designs and configurations (Li et al. 2022a; Pradhan et al. 2020). However, factors like environmental sustainability and energy savings must also be incorporated. More innovative conversion systems could be explored to accomplish greater energy and resource recovery from waste and diminish associated emissions (Hyland and Sarmah 2014; Gabhane et al. 2020).
- *Biochar production and modification*: Data-driven machine learning and artificial neural network (ANN) modelling have been suggested to design waste conversion processes, assess the performance of the conversion technologies, and characterize the biochar for estimating its potential applications (Fózer et al. 2021; Khan et al. 2022). These models could be amalgamated with life cycle assessment (LCA) to ensure efficiency in economy, energy, and environment-friendliness (Cheng et al. 2020).
- *Biochar application in soil*: Studies could focus on gaining mechanistic insights in interactions occurring between soil, microbial community, plants, climate and agricultural management activities, which critically influence greenhouse gas emis-

sions. Consequent to amendment of soil with biochar, large amount of organic carbon could increase microbial activity (microbial biomass and enzyme production), which might increase mineralisation of biochar or the carbon itself could get leached away (via irrigation or rainfall), eventually lowering the contents of recalcitrant biochar, which minimizes its long-term sequestration potential (Sheng et al. 2016; Xiao et al. 2014). Further, studies could be carried out to explore the transportation and transformation of biochar particles at nano-scale or studies could even explore wider applications of nano-biochar (Chausali et al. 2021; Guo et al. 2020a).

- *Biochar application in climate change-exposed soils*: Climate change-associated warmer climate, drought-related water-deprived situations, flood-triggered water-logged conditions, and highly salt-affected environments could mineralise biochar and affect its stability in agro-ecological regions worldwide (Kumar et al. 2022a). Correspondingly, it becomes critical to perform investigations in such a direction to ensure global sustainability. Biochar could influence pH, temperature, aggregate structure, bulk density, porosity, water holding capacity, biological activity, and nutrient cycling of soil differently depending on the texture of soil or variation in environmental conditions, which need to be examined urgently especially under climate change regime (involving drought, flood, salinization, or elevated temperature conditions) (Ali et al. 2017; Saifullah et al. 2018; Mansoor et al. 2021). Moreover, long-term impact of biochar on the properties of soil should be explored to determine the fate of biochar along with possible ecological and health consequences.
- *Biochar interaction with soil systems*: The soil microbial community potentially affects the properties of soil and its suitability for growing crops (Usero et al. 2021). The interaction between biochar and microbes has still not been discussed adequately in previous studies and focus could be given on those specific biochar properties which alter the soil microbial structure. With respect to removal of contaminants, prior studies have provided probable mechanisms involved in remediation (Zhu et al. 2017; He et al. 2019), but the coordination between such mechanisms (working independently or complementing each other) needs additional investigation.
- *Biochar application for supporting microbial growth and energy production*: Properties of biochar such as high porosity, surface area, and surface functionality support microbial growth and biofilm production which is necessary for producing electricity in microbial fuel cells (Nastro et al. 2021; Patwardhan et al. 2022). Interestingly, biochar with appropriate nutrients could be preferably used to help boost microbial growth and biofilm production (Hu et al. 2021b). Biochars prepared at relatively high temperatures could be used as effective inoculant carrier for many microbial species, sufficiently enabled by high survival rates, sustainability, and simplistic low cost of production (Egamberdieva et al. 2018).
- *Biochar-based catalysts*: They could be used for biofuel production apart from synthesis of chemical products (like glucose, xylose, and furfural) or for pollution control (such as degradation of organics, ozonation of ammonia and reduction of NO_X) but the experiments are still at laboratory scale (Xiong et al. 2017). However, objective-oriented synthesis and modification would be essential for industrial applications and large-scale biofuel production. The surface functionalization mechanisms could be investigated and fine-tuned, and their relationship with catalytic functions in biochar could be examined (Yang et al. 2022).
- *Biochar application for pollution control*: Artificial intelligence (AI) could be exploited to screen biochar for various applications, especially pollution control, based on the physico-chemical properties of biochar, which could be affected by feedstock variation, production conditions, and thermal treatment temperature (Lakshmi et al. 2021; Medeiros et al. 2022). AI could also help in producing biochar with desirable properties by choosing the biomass type and operating conditions (Ke et al. 2021; Garg et al. 2022). Biochar is rich in persistent free radicals which generates OH radicals and helps activate H_2O_2 which eventually aids in degrading organic contaminants like *p*-Nitrophenol (Fang et al. 2014, 2015). However, the catalytic activity and the potential of biochar in promoting degradation of adsorbed contaminants haven't been given adequate attention by researchers (Tian et al. 2020; Jin et al. 2022). Although the adsorptive removal of contaminants has been extensively studied, the reductive removal is still in the nascent stage and should be appropriately attended to by the scientific community (Seo et al. 2022).
- *Other applications of biochar*: Biochars could be used as construction materials (e.g., binding agents in asphalt mixtures or filler material in mortar/concrete), enabled by their binding, corrosion resistive, building insulating and humidity regulating properties, and the technology could be scaled up with the advent of 3D printing (Gupta et al. 2018, 2020; Muthukrishnan et al. 2019, 2020; Bolan et al. 2021). Biochar could be used in animal farming to augment

feed intake, cattle health, udder health, and protein and fat content in milk, and decrease allergies, stress, and mortality rates (Chu et al. 2013; Joseph et al. 2015; Lan et al. 2016; Teoh et al. 2019).

- *Modified biochars*: Studies were limited to lab-scale setups and must be proliferated for pilot-scale commercial and industrial applications (Benis et al. 2020a; Hafeez et al. 2022; Kumar et al. 2022c). Further, the stability of modified biochars must be assessed to identify composites with longer lifetime, even under scenarios of climate change (Kumar et al. 2021c, 2022a). Contrasting results were reported when impact of ageing was analysed on removal efficacy assessment of biochars, triggering the need for extensive studies for confirming adsorption/ performance of aged modified biochars (Shen et al. 2018; Wang et al. 2020b).

5 Conclusions

The data available on WoS Core Collection Database were explored and bibliometric network analysis was performed. With the first publication on biochar in 1998, more than 20,000 documents have been reported. More than 50% of these documents have been published in the previous three years, and 90% of these publications were research articles. Analysis suggested that pyrolysis was the most widely used technique for production of biochar. Further, biochar was mostly used for removal of contaminants from the polluted environments. While China was associated with publishing the maximum number of documents, Yong Sik Ok emerged as the most active author. Extensive network links were observed among the authors suggesting well-established worldwide scientific communication channels. While Science of the Total Environment published the maximum number of documents, Bioresource Technology received the maximum number of citations. Exploration of the wide applicability of biochar through bibliometric analysis suggested that global research on biochar has increased tremendously in the recent past. Biochar could be produced from a wide variety of waste biomass, which enables waste management. Biochar could enable food security management by augmenting soil fertility and plant productivity, mitigate climate change by sequestering carbon and minimizing greenhouse gas emission, produce bio-energy (i.e. bio-oil and syngas), and remediate contaminants from soil, water, and air. The wide applicability suggests the key role biochar could play in sustainable development worldwide. Artificial intelligence, data-driven machine learning and artificial neural network modelling could play a critical role in producing and screening application-specific biochar. Moreover, it is crucial to incorporate life cycle assessment (LCA) for assuring environmental sustainability and determining the fate of biochar along with probable ecological and health consequences. Although the study has covered the bibliometric analysis of nearly all the important applications of biochar and the most important routes through which it could be produced, certain applications like its use as construction material or in animal farming or as a catalyst for energy production were not covered in details. Moreover, the wide range of activation and modification methods of biochar provides a huge scope for performing elaborate bibliometric analysis. Future bibliometric analysis could also cover trends of wide range of feedstocks utilised for production of biochar to suggest appropriate biomasses for the fabrication of high yielding application-specific biochar.

Supplementary Information

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Additional file 1: Figure S1. Year-wise trend for publications and citations for (a) waste management, (b) mitigation of climate change, (c) improvement of soil fertility, (d) energy production, conversion, and storage, (e) remediation of contaminated soil, (f) treatment of polluted water, (g) treatment of contaminated air, and (h) modified biochars. **Figure S2.** Keyword co-occurrence map for waste management for minimum 30 occurrences. **Figure S3.** Keyword co-occurrence map for mitigation of climate change for minimum 30 occurrences. **Figure S4.** Keyword co-occurrence map for improvement of soil fertility for minimum 30 occurrences. **Figure S5.** Keyword co-occurrence map for energy production, conversion, and storage for minimum 30 occurrences. **Figure S6.** Keyword co-occurrence map for remediation of contaminated soil for minimum 30 occurrences. **Figure S7.** Keyword co-occurrence map for treatment of polluted water for minimum 30 occurrences. **Figure S8.** Keyword co-occurrence map for treatment of contaminated air for minimum 5 occurrences. **Figure S9.** Keyword co-occurrence map for modified biochars for minimum 30 occurrences.

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Author contributions

AK: Conceptualization, investigation, resources, data curation, writing—original draft preparation. TB: supervision, conceptualization, resources, writing—review and editing. WAS: Investigation, resources, visualization, writing—review and editing. AR: Writing—review and editing. SC: Visualization, writing—review and editing. MV: Visualization, writing—review and editing. JKB: Visualization, writing—review and editing. All authors read and approved the final manuscript.

Availability of data and materials

The manuscript does not have any associated data.

Declarations

Competing interests
The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work done in this paper.

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