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Advances in agricultural crop residue utilization for biogas production and sustainable energy solutions

Jean Agustin Velasquez-Pinas [a,*], Cristian Wedgwood [a], Diego M. Yepes Maya [b], Larissa Ampese [c], Tania Forster-Carneiro [c], Thomas Prade [a]

[a] Department of Biosystems and Technology, Swedish University of Agricultural Sciences - SLU, Box 190, 234 22 Lomma, Sweden

[b] Institute of Mechanical Engineering, Federal University of Itajuba – UNIFEI., Av. BPS, 1303, Itajubá, MG, Brazil

[c] School of Food Engineering, University of Campinas (UNICAMP), Rua Monteiro Lobato, n.80, 13083-862, Campinas, SP, Brazil

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ABSTRACT

The valorization of agricultural and agro-industrial residues is critical for advancing the circular bioeconomy and achieving global energy transition goals. This study presents a comprehensive bibliometric analysis of scientific literature on biogas production from these residues to gain insights into the intellectual structure, trends, and influence of this research field. By addressing the central question—What are the emerging research trends, thematic hotspots, and key intellectual contributions in the field of crop residues for biogas production over the last five years?—this paper maps the conceptual evolution and key actors shaping the domain. Based on a dataset of 1004 documents from the Web of Science Core Collection (2021–2025), VOSviewer and the Bibliometrix R-package were used to analyse publication volume, collaboration networks, and thematic clusters. This analysis reveals significant and sustained growth in publications, with China and India emerging as the most influential countries, supported by leading institutions such as the Chinese Academy of Sciences. Keyword co-occurrence analysis reveals a shift from a narrow focus on anaerobic digestion to integrated circular economy frameworks. Emerging research hotspots include biorefinery concepts, biochar applications, and the use of life cycle assessment (LCA) to evaluate environmental performance. The findings underscore a maturing field that has evolved from a singular focus on energy generation to a holistic, systems-level approach aligned with Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production).

1. Introduction

Every year, more than 5 billion tonnes of agricultural residues are produced worldwide [1]. The term *crop residues* refers to biologically derived material left over after harvesting and processing of the main product. In some cases, these include stalks, stubble, leaves, roots, stems, and/or straw, which may not have any commercial value that would justify their removal from the field [2]. Fundamentally, there are two primary pathways for valorizing these agricultural residues. Direct incorporation (on-field option) involves reintroducing residues into the field. This significantly contributes to the soil organic carbon (SOC) pool and facilitates nutrient recycling, which are crucial for maintaining and improving long-term soil health, water retention, and reducing erosion [3–6]. Conversion into valuable products (off-field option), where residues are collected as valuable feedstocks and reintroduced into the wider production chain using several processes like biorefineries and anaerobic digestion to yield energy (biogas, biofuels) and valuable compounds (e.g., biochar, biochemicals), thereby driving the transition towards a circular bioeconomy [7–9].

On the other hand, some agricultural practices used in some places to dispose of agricultural residues can be considered unsustainable. For instance, the burning of crop residues in India contributes to environmental degradation through short-term emission of greenhouse gases, particulate matter, volatile organic compounds, and other pollutants [10]. In China, it is estimated that between 2019 and 2021, 12,236 Gg of carbon monoxide (CO) were emitted, though no consensus exists among different studies regarding the exact figures [11]. However, addressing this issue requires an understanding of farmer behavior and economic constraints. Smallholder farmers often resort to open burning due to the high costs of mechanical clearing, short turnaround times between crop

* Corresponding author.
E-mail address: jean.velasquez@slu.se (J.A. Velasquez-Pinas).

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cycles, and the lack of viable markets or financial incentives for residue valorization. Countries in the European Union have stricter policies concerning the burning and use of crops and crop residues. For example, the Renewable Energy Directive (RED II) promotes the use of agricultural biomass for biofuel and biogas production, while introducing sustainability criteria [12].

The valorization of agricultural and agro-industrial residues for the production of value-added products plays an essential role in integrating production chains into circular economy (CE) schemes [13]. In recent years, researchers worldwide have shown growing interest in exploring new alternatives and possibilities for producing value-added compounds, such as bioactive phenolic compounds [14,15], biochar [16,17], biofuels such as second-generation ethanol [18,19], biopolymers [20], and nanomaterial [21], among others. Agricultural residues can also be directly used as cattle feed [22] or as bedding material in livestock housing [23].

On the other hand, an interesting alternative for the use and recovery of both agricultural and agro-industrial residues is anaerobic digestion (AD), a consolidated and expanding technology worldwide. AD technology not only produces energy but also digestate, a nutrient-rich byproduct that can enhance soil health and contribute to nutrient recirculation [24,25]. This dual functionality positions AD as a pivotal technology in sustainable agricultural practices and the circular economy.

There is increasing interest in identifying new feedstock sources, such as residues from food production chains and agricultural byproducts, which are mainly incorporated as co-substrates [26,27] to maintain an adequate nutrient balance within the digester. However, some challenges remain, such as the heterogeneity in composition and spatial distribution of residues, which complicates the implementation of sustainable policies for their utilization and valorization. Transportation and residue density are additional factors worth considering in economic and environmental feasibility assessments. Strategies such as the use of intermediate crops or cover crops [28] for biogas production can also be an interesting option, provided they are economically viable and their environmental benefits are accounted for within sustainability frameworks that include economic, environmental, and social dimensions.

In this context of growing interest in the utilization of agricultural and agro-industrial residues, biogas has been extensively investigated as a sustainable energy production option within circular economy frameworks. Accordingly, the present study seeks to provide a comprehensive overview of the state of research on *agricultural crop residues for biogas production* through a bibliometric approach. This analysis not only maps the evolution of scientific interest in the topic but also identifies key actors, collaboration networks, and leading institutions, while highlighting emerging areas, trends, and potential research directions. To achieve this, bibliometric techniques were applied to publications from the last five years (2021–2025), providing a snapshot of current knowledge and future directions in the valorization of agricultural and agro-industrial residues for biogas production.

2. Methodological approach

This research used bibliometric analysis tools to examine relevant information on the selected research topic. The research topic was defined by the authors' interest, focusing on understanding bibliometric information on the development of the use of agricultural and agro-industrial residues for biogas production, the countries and institutions involved in generating scientific knowledge, and trends and emerging themes.

The database selected for data collection was the Web of Science Core Collection (Clarivate), chosen for its comprehensive coverage of high-impact scientific literature and its highly reliable citation metadata, both of which are required for robust bibliometric mapping. An initial analysis was conducted to identify appropriate search terms. Logical operators OR, AND, and NOT were applied to refine and discriminate the information to be collected (supplementary material SM1). The selected documents consisted of scientific publications (articles and reviews) published between 2021 and 2025. Data extraction was completed on March 31, 2025. Agricultural and agro-industrial residues for biogas production were considered for the analysis. This comprehensive scope was deliberately chosen to capture the full spectrum of the agricultural value chain, encompassing both on-field crop residues left after harvest and off-field by-products generated during subsequent agro-industrial processing operations. In addition, terms such as *intermediate crops* and *cover crops* were included as sustainability strategies, which also focused on biogas production.

The document exclusion process involved applying an additional filtering criterion using logical operators to eliminate publications on methane emissions from the agricultural sector. This step was required because, in the present study, *methane* is defined as the recovery and utilization of organic materials through anaerobic digestion processes, rather than methane emissions arising from agricultural activities influenced by climatic, environmental, or management factors. The final dataset comprised 1004 documents, including 842 research articles and 162 review papers. To address the potential thematic bias and disproportionate influence of review articles—given their integrative nature and typically high citation counts—the citation impact analysis was strategically divided. The research impact of reviews and original research articles was evaluated in separate sections. This ensured that the citation metrics of primary research were not skewed by review papers, while still allowing reviews to be retained in the broader VOSviewer clustering to accurately reflect the comprehensive intellectual and thematic structure of the field.

Subsequently, the documents were downloaded in raw format, extracted as *.txt files, and afterward analyzed using software tools designed to process large volumes of information [29]. For this purpose, VOSviewer version 1.6.20 was used, which provides a graphical mapping of the collected information in the form of clusters and networks, facilitating its interpretation [30,31]. In VOSviewer, keyword co-occurrence mapping was conducted by weighting terms based on their frequency and co-occurrence links, allowing for the identification of prominent thematic clusters. On the other hand, the Bibliometrix R-package version 2023.12.1 Build 402 was used to analyse publications through mapping and bibliometric analysis, supporting the understanding of the processes underlying trends in research topics [32]. Several specific analytical techniques were applied in Bibliometrix to achieve the research objectives: a three-fields plot (Sankey diagram) was generated to visualize the proportional correlations between author-keywords, publication countries, and journals; the thematic evolution was assessed by dividing the dataset into specific time slices (utilizing 2022-2023 as cutting point) to accurately track shifts in research priorities over the 5-year period; and ubiquitous search terms (such as "anaerobic digestion" and "biogas") were deliberately excluded from specific keyword frequency counts to reveal underlying, nuanced research topics that would otherwise be overshadowed.

Regarding the evaluation of geographical contributions, it is important to clarify that the country-level analysis and collaboration networks refer strictly to the institutional affiliations of the authors, rather than the geographical location where the empirical research was conducted. Furthermore, to accurately assess international collaboration dynamics, country affiliations were systematically categorized into Single-Country Publications (SCP) and Multiple-Country Publications (MCP). Fig. 1 presents the structured methodological framework of the analysis, visually detailing the logical sequence adopted to examine the global evolution, the most productive countries and institutions, and thematic evolution. The selected search terms and the analytical criteria applied in both VOSviewer and Bibliometrix are detailed in the Supplementary Material (SM1).

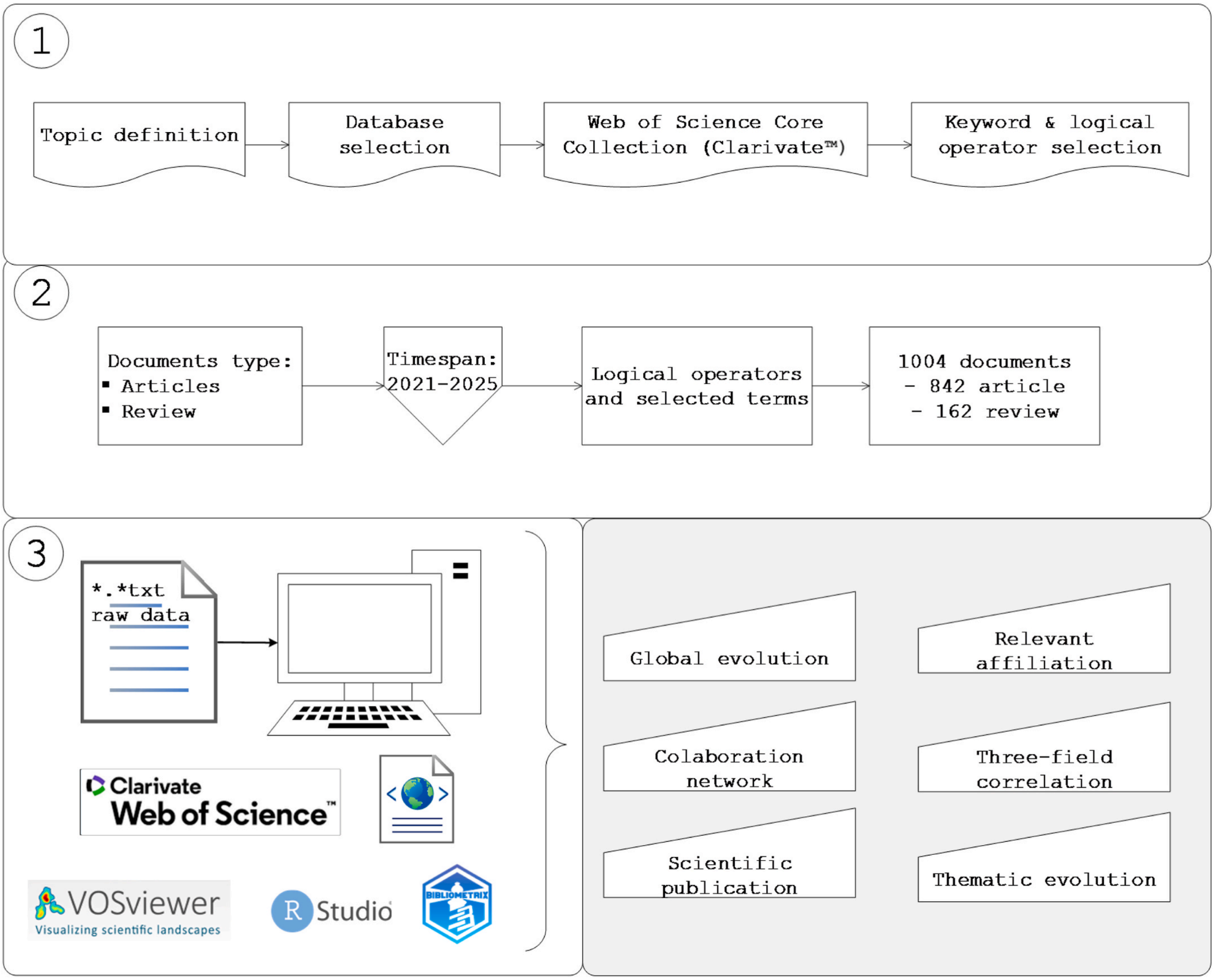

Fig. 1. Detailed methodological framework of bibliometric analysis on the research topic.

3. Results and discussion

3.1. Global coverage and leading contributing countries

3.1.1. Global growth of publications

Research on the utilization of agricultural and agro-industrial residues for biogas and methane production through anaerobic digestion technologies has increased exponentially over the past two decades (Fig. 2). This increase reflects a clear global interest in valorizing organic waste streams as sustainable energy sources, aligned with current decarbonization and circular economy policies [33,34].

The last five years represent a turning point for this research field. In 2022 and 2023, publication counts reached 214 and 236, respectively, accounting for nearly 18% of all indexed records (2498 documents) combined. This momentum was maintained in 2024, with 230 contributions (9.2% of the total), thereby confirming the field's consolidation as a priority area on the international research agenda. Although the 2025 data remain partial, 60 publications had already been recorded by March, representing 2.4% of the total. When extrapolated for the entire year, the trend suggests a continuation of the upward trajectory observed over the last decade.

Since 2000, a total of 2424 documents have been published, averaging approximately 200 per year over the last five years, representing

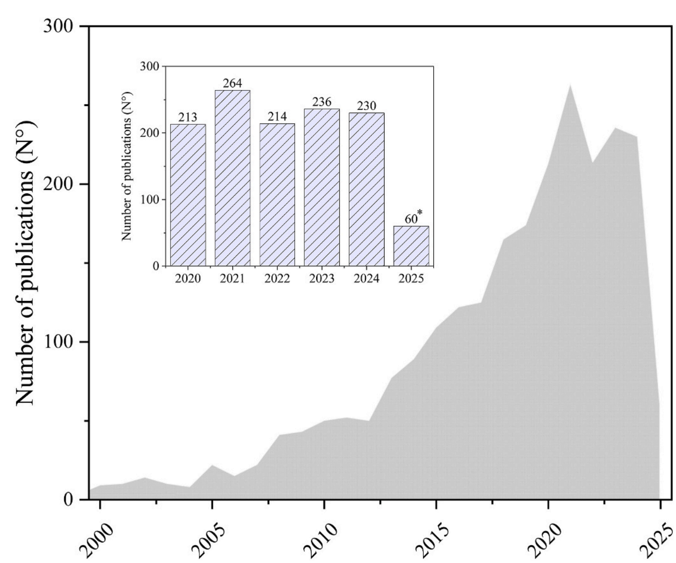

Fig. 2. Growth of publications in the research topic (* include partial data).

41% of all outputs since the beginning of the century. This acceleration underscores the increasing scientific and policy relevance of anaerobic digestion technologies for waste-to-energy systems [35]. An analysis of the selected subset of 1004 documents for the last five years reinforces this pattern. Between 2022 and 2024, this subset represented more than two-thirds of all records in the category. Beyond the quantitative expansion, these years also mark a qualitative strengthening of the field. The concentration of outputs in recent years suggests that the domain has reached a stage of scientific maturity, characterized by increased methodological sophistication and growth of global collaboration networks.

The growing interest in the use of residual agricultural biomass, particularly for methane production, can be attributed to recent policies that promote biomethane as a strategic renewable fuel. In the European Union, for instance, the REPowerEU plan encourages the deployment of anaerobic digestion and biomethane production as means to enhance energy independence while mitigating greenhouse gas emissions [36]. These developments have undoubtedly stimulated academic output and contributed to positioning this topic at the intersection of energy transition, waste management, and climate change mitigation.

3.1.2. Collaboration between countries and key countries by cluster

Asia, specifically China and India, dominates the global research output (Fig. 3a). Together, China and India contribute over a third (37.15%) of the publication output. This reflects massive national investments in renewable energy, environmental remediation, and research on the circular economy in these countries [37,38]. The United States and Germany represent the traditional powerhouses of scientific research, maintaining strong, high-output positions. Italy, Brazil, and Spain form a strong second tier, demonstrating significant regional interest and capacity in this research domain.

The international collaboration network exhibits a scale-free, hierarchical structure, with a few countries acting as global hubs while most contributors remain in the periphery, producing marginal outputs.

This asymmetry is evident in the collaboration clusters (Fig. 3b), where the cluster colors identify distinct research communities and the nodes reflect the strength of the existing collaborative ties. Countries such as China, India, the USA, Germany, Italy, and Brazil dominate both publication volume and research influence. Their consolidated infrastructure, funding capacity, and critical mass of researchers enable them to publish independently, while also making them the most sought-after partners in multinational projects. These collaborative clusters reflect the direct impact of macro-level funding frameworks that drive cross-border research, e.g., such as the European Union's Horizon Europe programs and China's Belt and Road Science and Technology Innovation Action Plan [39].

The cluster analysis (Table S1) further dissects this landscape into five groups. The red cluster comprises European and Latin American countries (e.g., Germany, Spain, Brazil, Poland, Colombia), underscoring historical cooperation within EU frameworks and South–North partnerships. The green cluster, led by China and the USA, includes Asian and Middle Eastern partners (e.g., Malaysia, Saudi Arabia, Pakistan), highlighting rapidly growing collaborations in emerging economies. The blue cluster is dominated by Australia and European mid-size economies such as the Netherlands and Belgium, which act as connectors between regions. The yellow cluster groups countries from Africa and the UK, pointing to region-specific challenges in biomass energy and bioeconomy transitions. Finally, the purple cluster (India, Canada, Russia, Chile, Argentina) brings together large nations with expanding but heterogeneous research capacities.

3.2. Research impact of key publications

The following sections will analyse publications that stand out, either in terms of the number of citations or their thematic relevance. The sections cover the productivity ranking and the papers with the highest number of citations. The analysis of the most significant studies highlights the critical role of agricultural residues in advancing sustainable energy solutions and mitigating environmental impacts. Beyond the productivity rankings, it is essential to delve deeper into the socio-economic and technological factors driving research in leading countries.

3.2.1. Most influential publications by topic

Analysing the development of a research topic provides valuable insights, particularly when examining productivity rankings by country, research area, key sources, and leading authors within the field. This way, it is possible to generate ideas and identify the reasons behind the development of certain types of research in the context in which countries find themselves. The type of research carried out tends to vary with a country's economy and its primary activities.

The top 10 countries account for 80% of total publications (Table 1), indicating that the research field is concentrated in these countries. As previously mentioned, China, India, and the USA lead the ranking. These three countries have strong agricultural sectors, with China being the largest global producer of wheat, the USA the largest producer of corn, and India the largest producer of rice [40], which explains their interest in developing studies in this area. The primary research areas identified were Environmental Sciences and Ecology, followed by Energy Fuels, Engineering, and Agriculture. These areas are closely interconnected, and the studies conducted account for multiple fields of research. For example, anaerobic digestion enables energy and biogas production from agricultural materials and supports environmental applications. In parallel, Biotechnology is a rapidly growing field; however, scientific publications in this area are still more strongly associated with basic research at laboratory and pilot scales rather than with full-scale commercial applications. In parallel, Biotechnology represents a rapidly expanding field that continuously drives innovative applications for biomass valorization and the optimization of sustainable bioenergy systems.

Among the most productive authors regarding the number of publications (Table 1), 5 are affiliated with institutions in India (Kumar V., Kumar R., Singh P., Kalamdhad A.S., Kumar S.), 2 from China (Awasthi M.K. and Li Y.), 2 from Greece (Kornaros M. and Papadakis P.G.), and 1 from Spain (Jurado F.). The authors' origins are linked to the most productive countries, primarily China, India, and Spain, which rank 7th. Regarding journals ranked among the top 10 for publishing scientific papers, Energies and Sustainability from MDPI; Bioresource Technology and Science of the Total Environment from Elsevier; and Biomass Conversion and Biorefinery are from Springer concentrate the most significant number of papers related to the research topic (209), other journals, such as Journal of Cleaner Production, Renewable Sustainable Energy Reviews, Journal of Environmental Management, Biomass Bioenergy, and Fuel also concentrate a considerable number of publications (108).

3.2.2. Research impact of reviews

The 10 most-cited review articles in the WoS database are presented in Table 2. The most recurrent theme is the use of residual biomass to obtain clean energy and mitigate greenhouse gas emissions. The most cited article presents various routes for valorizing biomass, including direct combustion, gasification, pyrolysis, anaerobic digestion, and transesterification. It also provides an overview of the availability of agricultural waste (such as wheat straw, rice straw, corn straw, and sugar cane bagasse), addressing the benefits linked to their use in bioenergy production routes and promoting a discussion on the possible impacts that the use of this waste can have, such as reducing soil quality and negative effects on its microbiota [41].

The articles that occupy the third, fourth, sixth, eighth, ninth, and tenth positions in the ranking also discuss bioenergy, highlighting the importance of research into the use of biomass for energy conversion and the migration towards a cleaner global matrix with lower

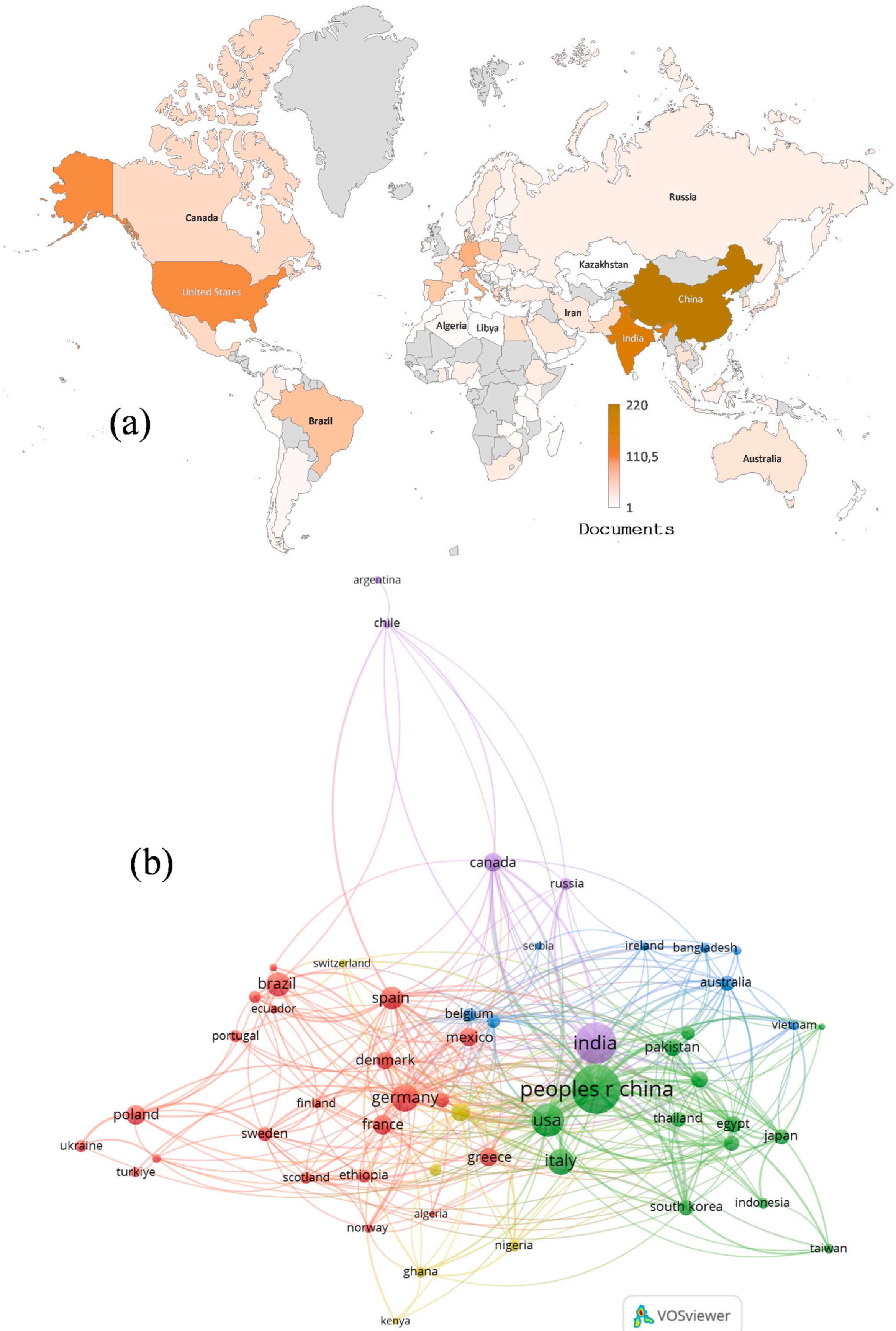

Fig. 3. (a) Graphical map of publication countries and (b) collaboration network by cluster across different countries.

Table 1
Ranking of the top 10 countries, areas, journals, and authors by publications from the last 5 years.

Criteria	Ranking	-	Number	%
Countries/ Regions	1st	China	220	21.91
	2nd	India	153	15.24
	3rd	Usa	100	9.96
	4th	Germany	69	6.87
	5th	Italy	63	6.28
	6th	Brazil	52	5.18
	7th	Spain	47	4.68
	8th	Poland	37	3.69
	9th	France	34	3.39
	10th	England	33	3.29
Research Areas	1st	Environmental Sciences Ecology	343	34.16
	2nd	Energy Fuels	329	32.77
	3rd	Engineering	221	22.01
	4th	Agriculture	213	21.22
	5th	Science Technology Other Topics	194	19.32
	6th	Biotechnology Applied Microbiology	129	12.85
	7th	Chemistry	67	6.67
	8th	Meteorology Atmospheric Sciences	27	2.69
	9th	Food Science Technology	25	2.49
	10th	Plant Sciences	23	2.29
Journals	1st	Energies	47	4.68
	2nd	Sustainability	47	4.68
	3rd	Bioresource Technology	42	4.18
	4th	Science Of The Total Environment	38	3.79
	5th	Biomass Conversion And Biorefinery	35	3.49
	6th	Journal Of Cleaner Production	33	3.29
	7th	Renewable Sustainable Energy Reviews	24	2.39
	8th	Journal Of Environmental Management	19	1.89
	9th	Biomass Bioenergy	16	1.59
	10th	Fuel	16	1.59
Authors	1st	Kumar V	11	1.10
	2nd	Awasthi MK	10	1.00
	3rd	Kornaros M	7	0.70
	4th	Kumar R	7	0.70
	5th	Singh P	7	0.70
	6th	Jurado F	6	0.60
	7th	Kalamdhad AS	6	0.60
	8th	Kumar S	6	0.60
	9th	Li Y	6	0.60
	10th	Papadakis VG	6	0.60

* Percentage of 1004 documents (automatically calculated in WoS).

environmental impacts. The third-most-cited article examines the environmental impacts of burning rice straw in open fields, a common practice in countries with high rice production, such as India, China, Vietnam, and Indonesia. More sustainable alternatives to this practice are presented and discussed, including the production of biogas and electricity, furniture, use as ground cover, and animal feed [43]. The subject most often covered in the review articles is the use of different routes, such as thermal conversion (pyrolysis gasification), biological conversion, including ethanol production and anaerobic digestion, to valorize residual biomass, as well as the discussion of various methods for pre-treating lignocellulosic biomass to improve energy conversion yields [44,46,48,50]. The main challenges addressed in these articles pertain to the recalcitrance of lignocellulosic biomass, which hinders efficient conversion; economic barriers to implementing projects; and the need for further studies into the use of digestate due to ammonia and nitrate emissions associated with the practice.

The second most cited article evaluates the environmental impacts of conventional plastics compared to bioplastics derived from renewable resources, detailing different types of bioplastics and their characteristics, including anaerobic digestion as an option for producing biogas from bioplastics. Despite being renewable, bioplastics have some disadvantages, including a greater impact on eutrophication and toxicity, as well as limitations in biodegradation. The main research opportunities are in optimizing the production, use, and biodegradation of these materials [42]. The articles in positions 7 and 9 also relate to energy. The seventh discusses the methods currently used in Ethiopia to obtain energy from waste biomass. However, the current practice involves rudimentary burning for cooking, with low efficiency and health risks, highlighting the challenges faced by the country. In this article, the possibilities of using agricultural residues to generate electricity from biogas via engine facilities [47] are also discussed. The ninth article discusses methane production in microbial electrolysis cells (MECs), explaining the mechanisms involved, the process's components, advantages, and challenges, particularly the high cost and the challenges of scaling up to commercial levels. MECs are a capable technology for producing fuel and energy from organic matter, including agricultural waste, and the oxidation in MECs provides a high methane content in biogas [49]. The most highly studied focus on the use of residual biomass for clean energy production and greenhouse gas mitigation. Key themes include biomass valorization through methods such as anaerobic digestion, pyrolysis, and gasification, as well as the environmental impacts of practices like rice straw burning and bioplastic production. Challenges highlighted include the recalcitrance of lignocellulosic biomass, economic barriers, and the need for improved digestate management. Future prospects emphasize combining pre-treatment processes to enhance energy conversion efficiency and expanding biomass use in biorefineries to support global climate goals and the circular economy. These reviews underline the importance of sustainable waste management and innovative technologies in achieving environmental and energy targets.

3.2.3. Research impact of original research articles

Table 3 was obtained by filtering the documents by type and selecting only “articles”, then the most cited were selected and presented.

The article at the top of the ranking addresses waste management (leaves, straw, husks, manure, pomace/fruit peels, among others) to promote sustainability. It discusses the impacts of inadequate management of this waste on air and water pollution and proposes strategies for reusing it within a circular economy. The waste is compatible with the production of biocombustibles, biofertilizers, biochar, bioplastics, and other materials of industrial interest [51], as proposed in the article in sixth position [56]. Second place goes to a study on the development of biorefineries, which explains different conversion technologies (anaerobic digestion, fermentation, pyrolysis, and gasification) through which value-added products can be obtained from agricultural waste [52]. Following the same line of studies, the third position in the ranking is occupied by an article on the valorization of agro-industrial food by-products, highlighting their importance for environmental, social, and economic sustainability and the opportunity to develop new food ingredients, functional products and biomolecules with benefits for human health from these materials [53]. The main challenges reported refer to technical and economic difficulties in scaling up the processes studied. The greatest opportunities for study include combining different methods and pretreatment, as well as conversion to the products of interest, so that process integration improves overall conversion efficiency and increases its economic viability.

The articles in positions 4 and 5 assess the biogas production capacity in Greece and China [54], and the contribution to carbon neutrality in China [55]. Current agricultural and livestock waste management practices in the countries are discussed, along with their impacts, and a biogas production route is suggested, with the potential for energy generation assessed in each case [54]. The article in fifth place focuses on biomethane production as a means of reducing GHG emissions and discusses its contribution to China's achievement of

Table 2
Top 10 most cited reviews in the last 5 years on research topics.

Ranking	Review Title	Journal	Times Cited, WoS Core	Publication Year	Reference
1st	Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source	Heliyon	155	2022	[41]
2nd	Bioplastic production in terms of life cycle assessment: A state-of-the- art review	Environmental Science And Ecotechnology	113	2023	[42]
3rd	Rice straw burning: a review on its global prevalence and the sustainable alternatives for its effective mitigation	Environmental Science And Pollution Research	104	2021	[43]
4th	Critical review of biochemical pathways to transformation of waste and biomass into bioenergy	Bioresource Technology	103	2023	[44]
5th	Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: A review	Science Of The Total Environment	93	2021	[45]
6th	Optimization of biogas yield from lignocellulosic materials with different pretreatment methods: a review	Biotechnology For Biofuels	93	2021	[46]
7th	The current status, challenges and prospects of using biomass energy in Ethiopia	Biotechnology For Biofuels	87	2021	[47]
8th	Advances in Valorization of Lignocellulosic Biomass towards Energy Generation	Catalysts	81	2021	[48]
9th	Microbial electrolysis cells for electromethanogenesis: Materials, configurations and operations	Environmental Engineering Research	79	2022	[49]
10th	A review about pretreatment of lignocellulosic biomass in anaerobic digestion: Achievement and challenge in Germany and China	Journal Of Cleaner Production	74	2021	[50]

Table 3
Top 10 most cited articles in the last 5 years on research topics.

Ranking	Article Title	Journal	Times Cited, WoS Core	Publication Year	Reference
1st	Agricultural waste management strategies for environmental sustainability	Environmental Research	405	2022	[51]
2nd	Agricultural waste biorefinery development towards circular bioeconomy	Renewable & Sustainable Energy Reviews	125	2022	[52]
3rd	Valorization of food agro-industrial by-products: From the past to the present and perspectives	Journal Of Environmental Management	105	2021	[53]
4th	Agricultural and livestock sector's residues in Greece & China: Comparative qualitative and quantitative characterization for assessing their potential for biogas production	Renewable & Sustainable Energy Reviews	85	2022	[54]
5th	Potential biomethane production from crop residues in China: Contributions to carbon neutrality	Renewable & Sustainable Energy Reviews	81	2021	[55]
6th	Valorization of agricultural residues: Different biorefinery routes	Journal Of Environmental Chemical Engineering	79	2021	[56]
7th	Biochar for environmental sustainability in the energy-water-agroecosystem nexus	Renewable & Sustainable Energy Reviews	78	2021	[57]
8th	Biohydrogen from organic wastes as a clean and environment-friendly energy source: Production pathways, feedstock types, and future prospects	Bioresource Technology	74	2021	[58]
9th	Biomethanation of agricultural residues: Potential, limitations, and possible solutions	Renewable & Sustainable Energy Reviews	70	2021	[59]
10th	Agricultural waste biomass for sustainable bioenergy production: Feedstock, characterization, and pre-treatment methodologies	Chemosphere	68	2023	[60]

carbon neutrality by 2060 [55]. The main difficulties reported concern issues specific to each country and region, such as transport efficiency, the influence of climatic factors on microbiological routes, and the lack of public policies that encourage research and the development of technologies to optimize the energy use of biomass. The importance of evaluating each case specifically to solve these problems is highlighted.

The seventh most cited article discusses the use of biochar in various applications, such as bioenergy production by improving biogas and hydrogen production in AD, its use in GHG mitigation through its use in agricultural soils, in the remediation of water contaminated with pesticides, heavy metals, antibiotics and dyes, as well as its ability to promote improved soil quality by increasing water retention and microbial diversity [57]. The articles in positions 8, 9, and 10 discuss the use of residual biomass in biorefinery routes to obtain bioenergy. The main residues are presented, along with the conversion routes that can be used, pre-treatments to increase efficiency, and key parameters to improve processes. The articles highlight the need for well-planned policies to boost sustainable waste recovery routes and identify the development of economic analyses of processes, evaluating installation and operating costs, as well as return on investment, to enable the implementation of large-scale projects [58–60].

The most highly studied focus on strategies for agricultural waste management and its valorization to promote sustainability and the circular bioeconomy. Key topics include biorefinery development, biogas production, and the use of agricultural residues for bioenergy, biofertilizers, and bioplastics. Challenges such as scaling up processes, economic barriers, and the need for tailored policies are frequently discussed. Opportunities lie in integrating pre-treatment methods to improve efficiency and economic viability. Articles also highlight biochar's role in enhancing biogas production, mitigating greenhouse gas emissions, and improving soil quality. These studies emphasize the importance of innovative technologies and policies to optimize the utilization of agricultural waste and advance global climate goals.

Furthermore, the literature highlights a wide variety of biomass types and advancements in their processing. The most frequently studied feedstocks include lignocellulosic agricultural residues (such as wheat straw, rice straw, and corn stover) and high-moisture agro-industrial wastes (e.g., sugarcane bagasse and cheese whey). Regarding biomass processing and pretreatment, there is a clear trend toward optimizing physical, chemical, and hydrothermal methods to disrupt the recalcitrant lignin structure and maximize methane yields. For instance, recent advances demonstrate the effectiveness of ozone pre-treatment on sugarcane bagasse, which facilitates the integrated production of second-generation ethanol and biogas [61]. Similarly, the literature extensively discusses the achievements and ongoing challenges of scaling up these lignocellulosic pre-treatments to reduce hydraulic retention times and improve overall energy recovery efficiency [46,50].

Furthermore, the "innovative technologies" frequently emphasized in this field transcend conventional single-substrate anaerobic digestion, shifting towards integrated biorefinery approaches and process enhancements. A major technological trend is the integration of biochar—derived from various feedstocks or digestate—into anaerobic digestion systems to improve process stability, buffer capacity, and biogas production [62,63]. Additionally, other cutting-edge advances include two-stage anaerobic digestion for the production of biohythane (a hydrogen and methane blend) from agro-industrial solid waste [64], and the application of microbial electrolysis cells (MECs) for electromethanogenesis. Although MECs currently face scalability barriers, they are highlighted as a highly efficient technology for maximizing energy recovery from organic matter [49].

3.3. Key features of the publications

3.3.1. Journal and reference analyses

Fig. 4a shows the journal clusters' configuration, which includes the most frequently published research on the use of agricultural and agro-industrial residues for biogas and methane production via anaerobic digestion. Among them, Energies, Sustainability, Renewable & Sustainable Energy Reviews, and Waste and Biomass Valorization stand out as the main publication hubs (Table S2). These journals are broad in scope and mostly open access, reflecting the growing trend toward more inclusive and accessible dissemination of scientific knowledge in renewable energy and bioresource valorization.

The most active journals can be grouped into several thematic clusters (Fig. 4a). The red cluster brings together titles such as Energies, Bioresource Technology, Journal of Cleaner Production, Industrial Crops and Products, and Biomass Conversion and Biorefinery, which

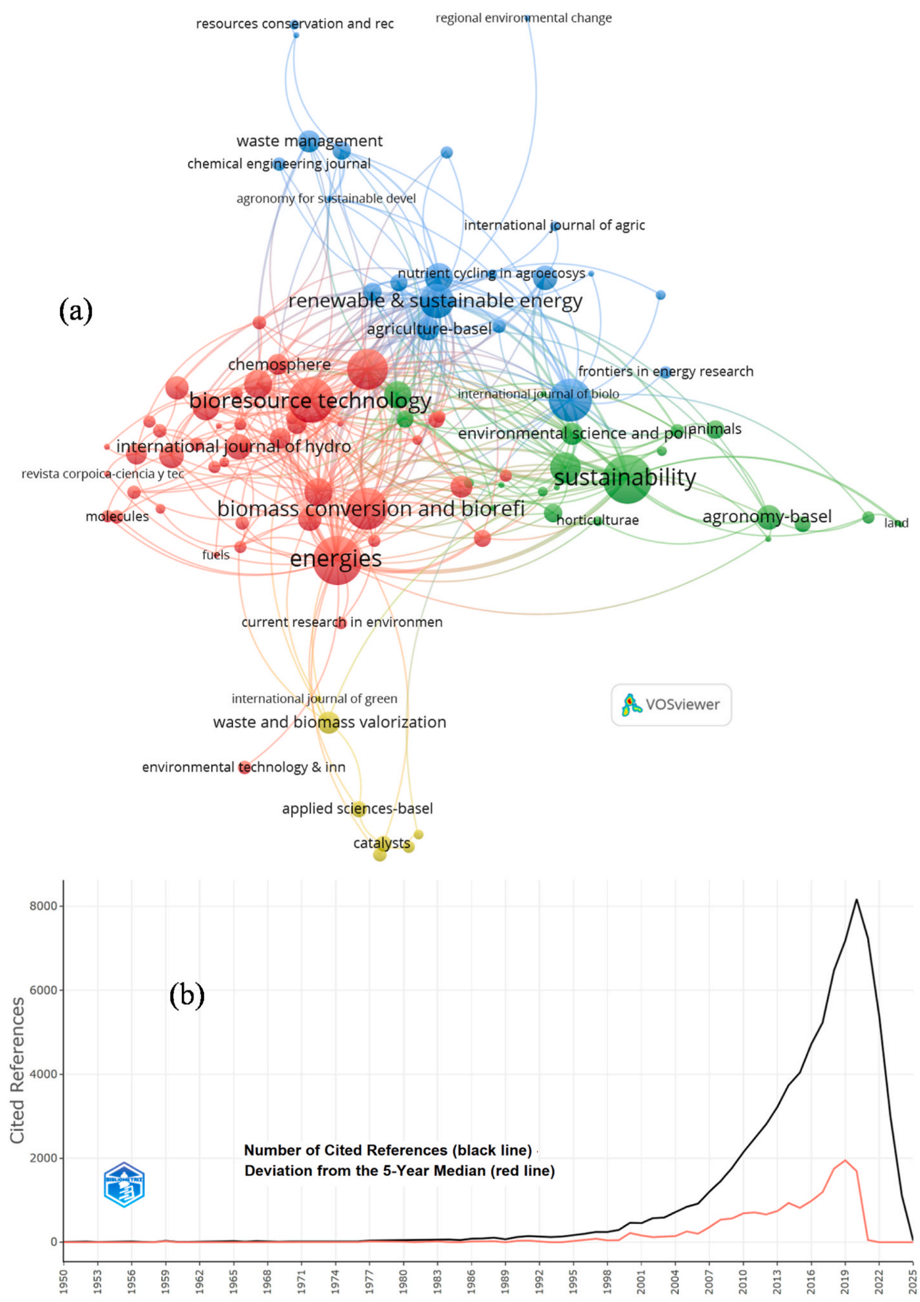

Fig. 4. Scientific publications 1: (a) the most influential journals by cluster and (b) reference spectroscopy.

focus on applied research, process improvement, and industrial biotechnology. The green cluster includes Sustainability, Processes, Environmental Research, Environmental Science and Pollution Research, and Biocatalysis and Agricultural Biotechnology, reflecting the intersection between environmental management, engineering, and biotechnology. The blue cluster comprises Renewable & Sustainable Energy Reviews, Biomass & Bioenergy, Science of the Total Environment, Agriculture-Basel, Energy, Global Change Biology Bioenergy, Applied Energy, and Agronomy for Sustainable Development—journals that approach the topic from broader perspectives on renewable energy and sustainability. Finally, the yellow cluster includes Waste and Biomass Valorization, Catalysts, Applied Sciences-Basel, and the International Journal of Green Energy, with a focus on resource recovery and catalytic conversion in energy systems.

Overall, the distribution of publications across these outlets suggests a mature yet diverse research landscape. Knowledge generation in this field is not concentrated in a few journals but spread across different disciplines, reflecting its multidisciplinary character. This pattern reinforces the view that anaerobic digestion has evolved from a waste treatment technology into a key component of circular bioeconomy strategies.

Fig. 4b presents the reference-spectroscopy analysis, which examines the temporal distribution of the cited literature across the 1004 papers analyzed. The black line shows the total number of references cited each year. In contrast, the red line represents deviations from the five-year median, which is calculated by taking the median number of citations

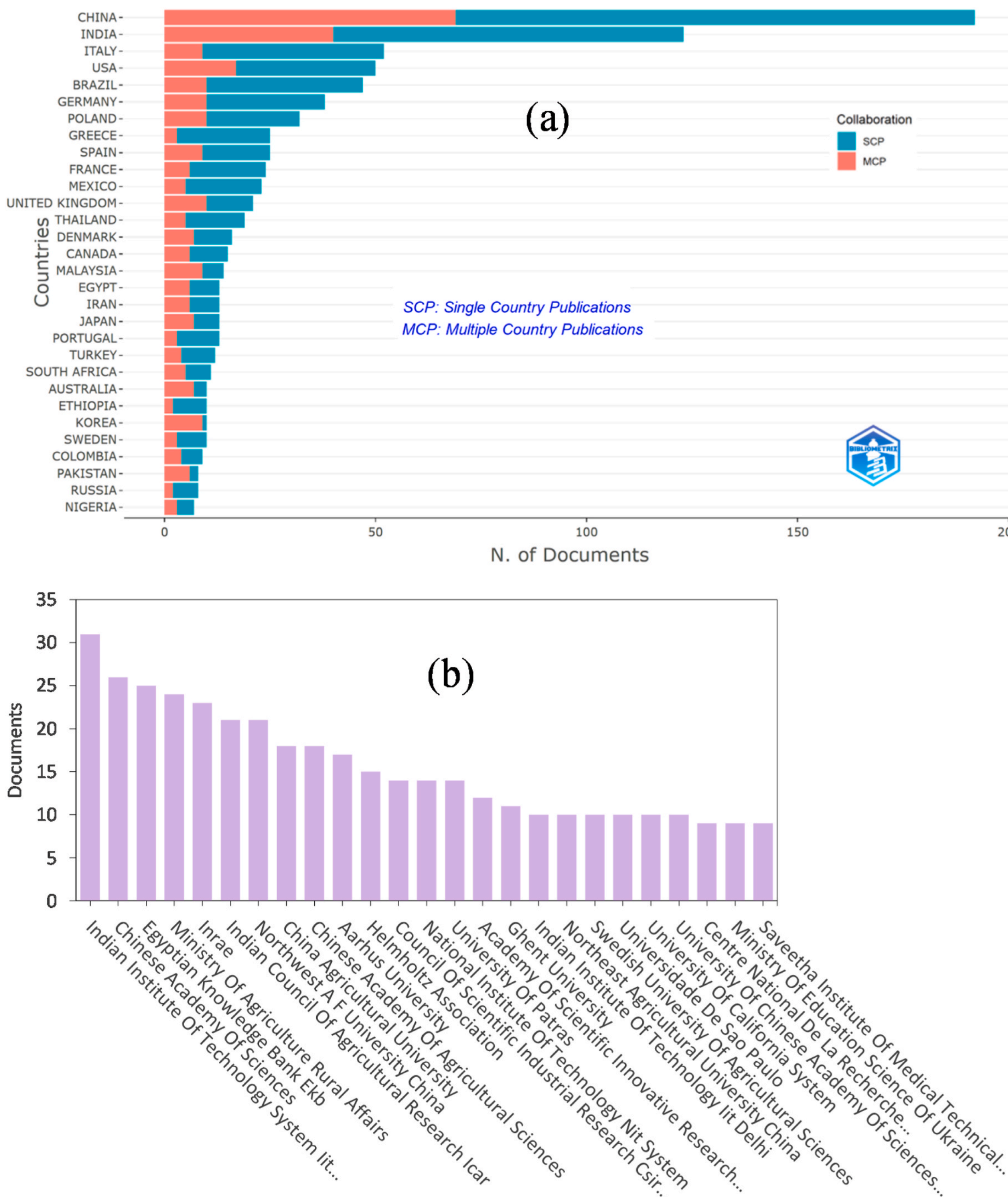

Fig. 5. Scientific publications 2: (a) corresponding authors countries and (b) the most relevant affiliation.

across a rolling five-year window (two years prior, the current year, and two years after). The deviations are obtained by subtracting this rolling median from the actual citation count of the specific year [65], highlighting peaks in scientific activity and influence over time.

Most cited works date from 2010 to 2025, indicating that current research on agricultural and agro-industrial residues for biogas production relies mainly on recent advances. Before 2000, fewer than 300 references per year were cited, suggesting that anaerobic digestion and waste-to-energy research were still in their early stages. After 2005, citations grew steadily, coinciding with the expansion of studies on renewable energy, biomass valorization, and circular economy concepts.

A sharp increase occurred after 2010, peaking around 2020 when the number of cited references exceeded 8000. This period reflects a phase of consolidation and diversification in the field, influenced by global policies promoting biomethane and renewable gases, the European Green Deal, and a stronger focus on carbon-neutral energy systems [66]. After 2021, the curve shows a moderate decline, which is common since recent papers have not yet reached their full citation potential. Still, over 80% of the citations correspond to the last 15 years, confirming the dynamic and evolving nature of this research domain. The citation spectrum reveals a young yet rapidly advancing scientific foundation, closely aligned with global sustainability goals. The surge in citations around 2020 marks a turning point, as studies on residual biomass utilization, biogas upgrading, and anaerobic digestion optimization became central to the broader discussion of the energy transition and the circular bioeconomy. This last point may also stem from the fact that the most recent publications are still relatively young and require consolidation.

3.3.2. Authors and affiliation

The bibliometric analysis of authors and affiliations provides insight into how research on the use of agricultural and agro-industrial residues for biogas and methane production is distributed across countries and institutions. Fig. 5a illustrates the number of corresponding authors by country and their collaboration patterns, distinguishing between Single-Country Publications (SCP) and Multiple-Country Publications (MCP). Fig. 5b highlights the institutions working hard to use crop residues for biogas production, offering a clearer picture of global participation and academic leadership in this area.

The results, as previously mentioned, reveal a strong concentration of research activity in China, India, Italy, and USA. However, regarding collaboration with other countries, there seems to be resistance to international cooperation, as evidenced by the high number of single-country publications: China 64.1%, India 67.5%, Italy 82.7%, and the USA 66.0%. This, in a way, limits joint work with countries from other regions. This situation can be explained, for example, by the fact that geography plays an essential role in the types of residues generated, which later become feedstock for biogas production. The residues produced in Europe do not have the same characteristics as those generated in Latin America. On the other hand, countries such as Malaysia, Korea, Australia, and Pakistan have focused their efforts on making research projects more collaborative at the international level.

As shown in Fig. 5b, the Chinese Academy of Sciences leads with over 30 publications, followed by the China Agricultural University, the Ministry of Education of China, and the Indian Institute of Technology System. European institutions such as the National Research Council of Italy, the Helmholtz Association (Germany), the Polish Academy of Sciences, and Swedish University of Agricultural Science are also among the top contributors. This pattern is consistent with broader developments in China's renewable energy landscape, where policies like the Renewable Energy Law and the Biogas Development Program have significantly boosted research on anaerobic digestion [67].

India follows in second place, supported by universities such as the Indian Institute of Technology System, the Indian Agricultural Research Institute, and the Ministry of Agriculture and Farmers Welfare. The predominance of SCP records points to strong domestic collaboration networks centered on agricultural residues and rural energy systems. Research from India often focuses on valorizing resources such as sugarcane bagasse (with 26,6 million metric tonnes being the second largest producer), rice husk (producing 22% of the rice in the world), and manure for biogas generation, emphasizing affordable technologies tailored to rural needs [68]. Beyond mere technological feasibility, the developmental relevance of the high publication output from China and India must be critically assessed regarding its actual impact on rural poverty and smallholder resilience. For example, the valorization of crop-specific systems, such as cashew processing residues, directly intersects with smallholder livelihoods by offering new avenues for income diversification and economic stability [69,70]. Integrating these decentralized systems ensures that the bioeconomy directly benefits local farming communities rather than remaining purely industry-centric.

Italy and Germany also make significant contributions, particularly through international collaborations, reflecting their participation in European research consortia. Italian institutions, including the University of Bologna, University of Milan, and the National Research Council (CNR), maintain close partnerships with European and Latin American researchers, especially on topics such as anaerobic co-digestion and digestate management. These efforts align with EU initiatives like the REPowerEU Plan [36] and the work of the European Biogas Association (EBA), which promote biomethane as a key renewable energy vector.

The United States and Brazil follow, each with distinct research profiles. In the U.S., universities such as Iowa State University, the University of California, and the University of Florida have produced numerous studies focused on life-cycle assessment (LCA), bioenergy policy, and the treatment of agro-industrial waste streams. In Brazil, institutions like the University of São Paulo (USP) and the Federal University of Viçosa (UFV) stand out for their research on the valorization of residues from sugarcane industries, particularly vinasse and filter cake [71,72].

3.4. Keyword mapping and three-field network analysis

3.4.1. Keyword analysis

Fig. 6 visualizes the cluster of keywords weighted by frequency of occurrence and organized by frequency of co-occurrence with other keywords. Fig. 6a shows the network relationships, with each node coloured according to the keyword with which it co-occurs most frequently. The green network ties methane to biochar and related char-producing conversion processes such as pyrolysis and gasification, as well as to life cycle assessment (LCA) and related environmental impact keywords, e.g., global warming potential and greenhouse gas emission (s), along with nitrous oxide and hydrogen. The ties of methane with biochar, from pyrolysis or gasification, may be because biochar can be obtained from digestate resulting from anaerobic digestion [73], or also used as an input to increase the production of biogas and methane in anaerobic digestion systems [62,63]. While the connection between methane and LCA is perhaps due to an overlap between interest in methane as a primary AD product and its role as a powerful greenhouse gas. However, the networking of biochar with LCA and climate change keywords may reflect interest in biochar derived from crop residues or digestate from anaerobic digestion as a tool for carbon sequestration [74,75].

The red network ties anaerobic digestion and biomass to nutrients, such as phosphorus and nitrogen, and to feedstocks, both specific (e.g., sugarcane or cow manure) and categories (e.g., energy crops and cover crops). This network also includes process keywords, such as anaerobic co-digestion and biohydrogen, because these have recently been explored as byproducts of anaerobic digestion [64,76]. Lastly, this network includes spatial modelling keywords and yield, representing research into the spatial potential for feedstock production, methane yield, and nutrient cycling [77]. In this regard, some studies have shown

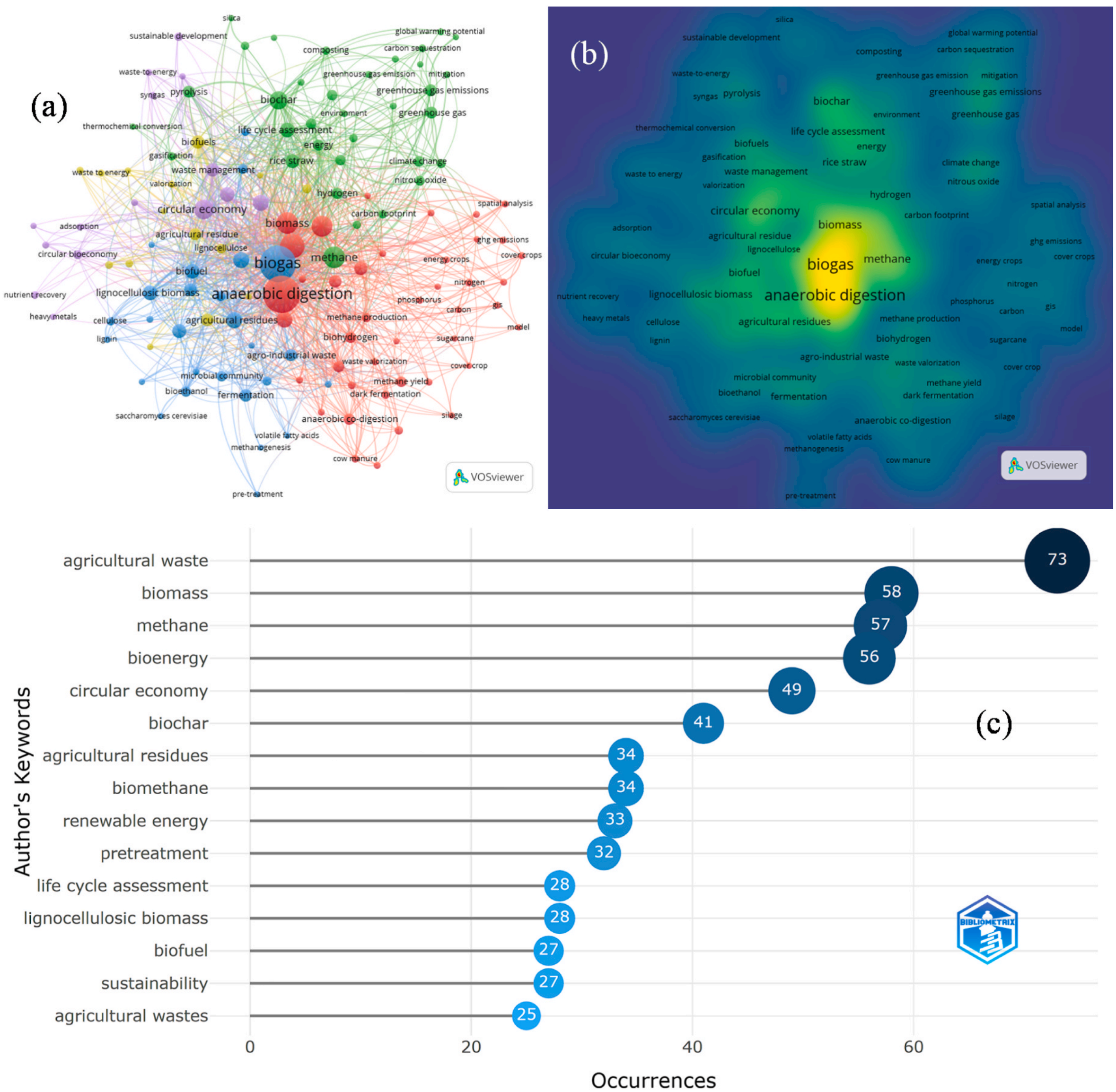

Fig. 6. The most frequent author keywords: (a) cluster-based map; (b) density map visualization from VOS viewer, and (c) most frequent author keyword from Bibliometrix.

the geospatial potential of available agricultural residues [78], which could eventually be used for biogas production.

The purple network ties circular economy to waste management, sustainable development, along with heavy metals and nutrient recovery. The inclusion of waste-to-energy along with syngas and nutrient recovery indicates prominent pathways for circular bioeconomy strategies, specifically for energy recovery, providing an alternative to fossil fuels, and nutrient recycling. The blue network is biogas-linked to biofuel and bioethanol, as well as to specific feedstock category keywords, such as lignocellulosic biomass, agricultural residues, agro-industrial waste, and associated lignocellulosic fiber (LCF) constituent terms, along with process and microbial terms. The networking of LCF to microbial process terms and alternative product keywords, as well as pretreatment, may indicate the prevalence of research on converting recalcitrant feedstocks, i.e., those rich in LCF, or an interest in exploring alternative production pathways/products that are better suited to these types of feedstocks. The network of various feedstock terms may indicate overlapping and often interchangeable use of these terms. Details of the conformation of all clusters are shown in Table S3.

Fig. 6b overlays the network with a heatmap illustrating the most commonly occurring keywords and keyword clusters. The core of the heatmap network is around biogas, biomass, methane, and anaerobic digestion, with peripheral ties to biofuels, agricultural residues, and lignocellulosic biomass. The secondary clusters form around circular economy (including agricultural residues, waste management, and valorization) and life cycle assessment (including energy, biochar, environment, and rice straw). The latter likely indicates the most common products studied by LCA, namely biochar and energy, and a common feedstock, rice straw. There are less prominent heat zones around various environmental impact keywords, such as climate change (containing nitrous oxide) and greenhouse gas emission clusters (containing mitigation, carbon sequestration and global warming potential) as well as particularly common process keywords such as pyrolysis and fermentation.

Fig. 6c indicates the next 15 most frequently used author keywords captured by the Bibliometrix search after excluding the two most frequently used keywords, anaerobic digestion and biogas. Unsurprisingly, these two keywords are used 172 and 161 times, respectively, both with usage rates more than double that of the next most frequently occurring keyword, agricultural waste, at 73 uses. Biomass, methane, and bioenergy are the following most frequently used keywords, with 58, 57, and 56 uses, respectively. Circular economy (with 49 occurrences) is almost twice as common as sustainability or life cycle assessment, perhaps indicating a shift in interest in this research area towards nutrient cycling and circularity aspects rather than a more traditional focus on sustainability and linear systems. After biogas and methane, biochar at 41 uses is the leading by-product keyword, suggesting that current research interest has shifted from nitrogen cycling via biofertilizer and digestate to carbon cycling and sequestration. Alternatively, the value of digestate is more established, whereas biochar remains an emerging and exciting topic. Within the "feedstock" keywords, agricultural waste is used most frequently, followed by biomass, agricultural residues, and, lastly, lignocellulosic biomass (agricultural waste is used least, but this is a form of agricultural waste). Within feedstock keywords, none of the terms are mutually exclusive, with some agricultural waste(s) and residues being considered lignocellulosic biomass, most notably straws.

3.4.2. Three-fields plot analyses

Fig. 7 shows a 3-field plot of keywords, publication country, and journal, organized in a Sankey diagram. For the two top-leading keywords and countries, the correlation is proportional to the frequency of both, i.e., AD and biogas are relatively highly correlated with China and India. Agricultural waste, the 3rd most frequent keyword, is, however, more strongly correlated with China, whereas lignocellulosic biomass shows a higher correlation with India than with agricultural waste. As noted above, this may be due to differences in keyword use conventions rather than real differences in the types of agricultural biomass studied. Biochar, despite a lower occurrence, is highly correlated with both China and India, disproportionate to the relatively lower occurrence, 8th position, indicating a particular high interest in biochar relative to other countries. This is particularly the case for India, where biochar has a higher correlation than any other product keywords, e.g., biogas, methane, etc. However, for China, both biogas and methane show a similar correlation to biochar. As to whether sustainability or circularity aspects explain the interest in biochar, it is unclear. However, correlation of circular economy, 7th position, or life cycle assessment, 13th position, is not disproportionately high to either country. The circular economy is notably more highly correlated with Italy (the 3rd most frequent country), suggesting potentially greater interest in the concept of CE in Europe. The other European countries generally have relatively high correlations with anaerobic digestion and biogas, as expected; however, in the UK and Spain, biogas is more highly correlated than anaerobic digestion. USA is highly correlated with anaerobic digestion, biogas, methane, and bioenergy, whereas feedstock, sustainability, and other product keywords are not, indicating a particular interest in energy and gas products.

In regard to correlation with publication journals, China is most highly correlated with Bioresource Technology, followed by Science of the Total Environment (STOTEN), Journal of Cleaner Production (JCP), Journal of Environmental Management (JEM), Sustainability, and Industrial Crops and Products. This potentially indicates that, despite extensive technical research into process, products, and feedstocks, there is also an environmental sustainability focus. The major environmental journals, STOTEN, JCP, JEM, and Sustainability, all have the highest correlation to China. Even considering China's high volume of publishing, this correlation is disproportionately high. While India is also highly correlated with the two most frequent journals, Bioresource Technology and STOTEN, it is also notably correlated with a broad selection of journals covering reviews, environment, and technical research, such as Fuel and Industrial Crops and Products. The USA is most strongly correlated with STOTEN, followed by JCP and Bioresource Technology, suggesting that, despite strong correlation with gas keywords, there is an environmental aspect to the research. Italy is most strongly correlated with Sustainability, indicating, along with the high correlation with the circular economy keyword, a strong interest in the sustainable bioeconomy.

3.5. Trends and emerging interest in research topics over time

Fig. 8 provides a picture of how research interest in biogas has evolved over the past five years. Biogas derived from agricultural and agro-industrial residues has undoubtedly become a key vector in the global energy transition. Over this period, the research landscape has shifted markedly, reflecting changing global priorities and external pressures.

Before the COVID-19 pandemic and the onset of the war in Ukraine (2020–2021), interest in biogas production from agricultural residues was primarily driven by its potential to be integrated into the energy mix as a renewable technology capable of contributing to both decarbonization and energy diversification (Fig. 8a). The focus during this time was clear: biogas as a tool for reducing carbon dioxide emissions through the proper treatment and valorization of organic residues. Lignocellulosic biomass studies emphasized the use of lignocellulosic

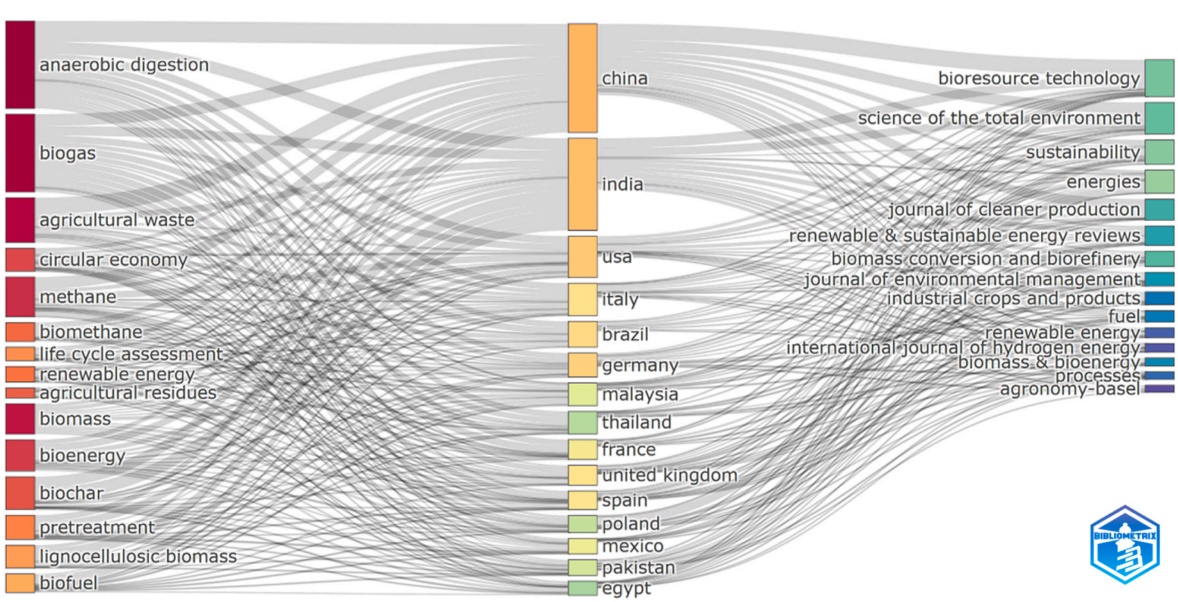

Fig. 7. Three-fields plot: (a) correlation between author-keywords, countries, and journals.

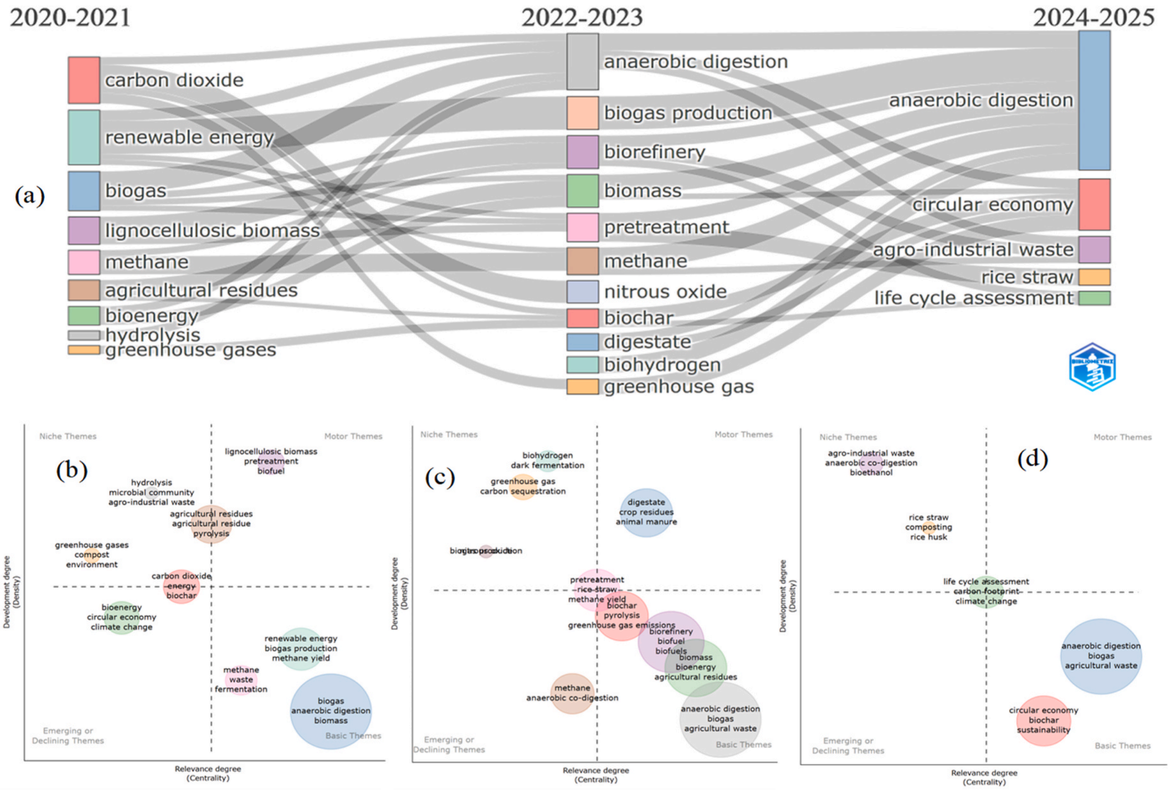

Fig. 8. Changes in the research interest: (a) thematic evolution map; (b) thematic map with cluster from 2020 to 2021 (c) thematic map with cluster from 2022 to 2023, and (d) thematic map with cluster from 2024 to 2025.

residues, such as straw, husks, and forestry residues, especially in regions where these materials accumulated in large volumes [79]. These efforts sought efficient pathways to convert these waste streams into bioenergy, reinforcing the role of biogas in circular, low-carbon systems. It was also during this phase that the concept of the *circular economy* began to gain traction, emerging as a key thematic link between waste management, renewable energy, and resource efficiency.

Between 2022 and 2023, Fig. 8b, research attention increasingly turned toward *biorefinery concepts*. The idea was to integrate agricultural and agro-industrial residues into multi-output systems capable of producing not only biogas but also biofertilizers, bio-based chemicals, and other value-added products [80]. This approach reflects the growing recognition that sustainable waste valorization requires technological integration and systems thinking. However, a critical perspective in this thematic evolution is assessing whether these emerging models—such as biorefineries, biochar applications, and LCA methodologies—reflect a genuine shift toward farmer-inclusive sustainability. For these advanced technologies to succeed, they must transition from industry-centric models to decentralized frameworks that actively involve rural populations.

During this period, the *pretreatment* of lignocellulosic residues remained a central theme. For example, sugarcane bagasse, traditionally used for cogeneration in ethanol mills, began to be studied as a potential substrate for both second-generation ethanol and biogas production [61,81]. Similarly, efforts to extract and utilize *phenolic compounds* and other bioactive substances from agro-industrial by-products have increased, with biogas production emerging as a complementary process for managing the residual biomass generated after biochemical extraction [82,83]. On the other hand, numerous studies investigated *digestate management* and fertilizer recovery strategies aimed at mitigating emissions of *nitrous oxide* and other nitrogen-based gases from agricultural systems [84,85]. These topics gained importance as researchers and policymakers sought integrated solutions for nutrient recycling and emission control within sustainable farming frameworks.

In the period 2024 - 2025, anaerobic digestion continues to stand as a cornerstone technology for managing agricultural and agro-industrial residues (Fig. 8c). However, *circular economy principles* have become increasingly influential [86,87], driving research toward minimizing waste generation and linking digestion processes to broader biorefinery strategies. A particularly notable trend is the emerging global interest in *rice straw* utilization for energy and biogas production [88–90], as a response to the ongoing challenge of improper disposal and open-field burning of this residue in rice-producing countries. This shift underscores a growing commitment to addressing both energy recovery and air quality issues simultaneously. On the other hand, the environmental dimension of biogas research has deepened significantly. There is now a clear emphasis on *Life Cycle Assessment (LCA)* as a tool for quantifying the environmental impacts of biogas systems based on agricultural and agro-industrial residues. Recent studies have highlighted the importance of evaluating key indicators, including greenhouse gas emissions, land-use change, eutrophication potential, and acidification [91,92]. This analytical approach not only supports policy and investment decisions but also strengthens the scientific foundation for sustainable bioenergy development.

Looking ahead, research on biogas and biomethane is expected to continue along these trajectories, with themes such as the circular bioeconomy, residue valorization, and integrated biorefineries serving as fundamental pillars. However, the field's evolution will likely depend on interdisciplinary engagement that bridges the energy, agricultural, industrial, and environmental domains.

3.6. Perspective of crop residues and intermediate crops to achieve the SDGs

Biogas production from different sources has evolved significantly over time. Initially, the main motivation behind biogas generation was environmental sanitation, the need to control and properly manage organic waste. Later, attention shifted toward the efficient handling of animal manure. As energy issues gained prominence, biogas emerged as a renewable energy alternative, and the use of dedicated energy crops became increasingly evident in efforts to maximize renewable energy production. Over time, however, new global concerns began to shape the sector. Issues such as food security, the responsible use of raw materials for energy generation, and the sustainable management of residues from multiple sources gave biogas production a more sustainable and integrated character. The focus expanded from heat and electricity generation to include the strategic production of biomethane, which has become a key element for enhancing energy security. Today, biomethane is increasingly seen as a crucial energy vector that promotes the circular use of resources and contributes to achieving global decarbonization and net-zero emission targets [93].

In this context, crop residues are no longer seen as mere waste to be disposed of, but as strategic secondary raw materials that can drive the circular bioeconomy and enhance rural livelihoods, e.g., open-field burning of rice straw—a practice causing severe environmental degradation—can be valorized in decentralized biogas plants to generate clean energy [94]. Furthermore, the integration of intermediate or cover crops exemplifies this shift, as these crops simultaneously protect soil health, prevent erosion, and provide sustainable biomass for biomethane production without competing with food crops. [28]. Beyond environmental benefits, adopting this perspective highlights the vital socio-economic dimension of agricultural sustainability. For instance, recent empirical studies demonstrate that the efficient utilization of integrated agricultural systems—such as residue valorization and intercropping in cashew-producing communities—can significantly diversify farmer income, reduce market vulnerability, and foster long-term livelihood resilience [69].

Thus, the United Nations Sustainable Development Goals (SDGs) have deeply influenced research and policy directions regarding the use of agricultural and agro-industrial residues for biogas and biomethane production [95]. As illustrated in Fig. 9, there is a clear connection between the SDGs and the current research focus areas in this field. The strongest research emphasis is on SDG 7 (Affordable and Clean Energy, 22.83%), reflecting the high relevance of biogas and biomethane as renewable energy carriers in the global energy transition. Following closely, SDG 12 (Responsible Consumption and Production, 22.31%) highlights the importance of sustainable waste management and circular economy principles, particularly within agro-industrial systems that seek to reduce environmental impacts and optimize resource efficiency. Traditionally, this has been framed around material and energy flows; however, there is a pressing need to expand this paradigm to include "social circularity," ensuring that residue valorization generates rural employment, income stability, and social inclusion. Another strong connection is with SDG 6 (Clean Water and Sanitation, 19.10%), underscoring the vital role of sustainable agro-industrial practices, including proper handling of both solid and liquid residues, in reducing water contamination and protecting aquatic ecosystems.

Interestingly, SDG 13 (Climate Action, 11.7%) ranks fourth in research attention. While there is growing interest in mitigating climate change by reducing greenhouse gas emissions, such as methane and nitrous oxide, from agricultural systems [85], research still primarily focuses on energy generation and the optimization of residue management technologies. This suggests that while climate mitigation is a key driver, it often appears as a complementary outcome rather than the central research goal.

Socially oriented objectives, such as SDG 2 (Zero Hunger, 7.21%), emerge as indirect benefits of progress in other areas. Furthermore, literature must explicitly incorporate SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) to fully capture the socio-economic dimension of residue valorization for smallholder farmers. On the other hand, the sustainable production of biogas and biomethane from agricultural residues helps reduce pressure on land use, particularly by minimizing the need for dedicated energy crops. In turn, this contributes to food security by ensuring that arable land remains available for food production rather than being diverted to energy purposes. The biofertilizer production from anaerobic digestion indirectly supports sustainable food production.

Furthermore, within the agricultural sector, strategies aimed at soil preservation and ecosystem restoration, such as the use of intermediate crops or cover crops, are gaining increasing relevance primarily in countries with specific agri-environmental regulations. These crops not only prevent soil erosion, improve fertility, and enhance biodiversity, but can also serve as valuable feedstock for biogas production. Their use provides dual benefits: promoting sustainable soil management and providing additional biomass for renewable energy generation. Such integration reinforces the circularity of agricultural systems, reduces pressure on primary crops, and supports achieving both SDG 2 (Zero Hunger) and SDG 15 (Life on Land) through improved land-use efficiency and enhanced ecosystem resilience. Overall, the convergence between biogas production, residue valorization, and sustainable cropping systems represents a tangible pathway toward achieving multiple SDGs simultaneously. By integrating circular bioeconomy principles with renewable energy technologies, the biogas sector not only contributes to climate mitigation and clean energy access but also strengthens food security, soil health, and rural livelihoods — embodying the multidimensional spirit of sustainable development.

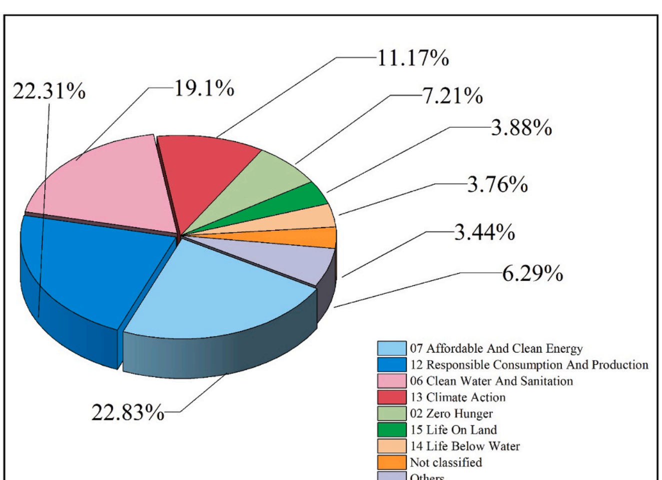

Fig. 9. Relationship between SDGs and the interest of scientific publications in the researched topic.

4. Conclusions

This bibliometric analysis of the literature from the past five years (2021–2025) highlights a significant expansion and thematic maturation in the field of biogas production. The findings reveal a clear conceptual evolution from a singular focus on anaerobic digestion for energy generation toward an integrated circular bioeconomy paradigm. Based on the comprehensive mapping of 1004 documents, the main conclusions are synthesized as follows:

- Research leadership is highly concentrated in China and India, closely linked to the availability of massive agricultural resources. Consequently, the literature increasingly targets specific, high-potential feedstocks—such as wheat straw, rice straw, corn straw, and sugarcane bagasse—rather than generic biomass categories. Emerging research hotspots are strongly centered on multi-output biorefinery concepts, biochar applications, and Life Cycle Assessment. However, a critical technological frontier remains the optimization of pre-treatments to overcome lignocellulosic recalcitrance and improve overall energy conversion yields.

- The integration of biogas systems demonstrates a strong alignment with SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). Beyond mere energy recovery, transitioning toward sustainable agricultural practices—such as using intermediate and cover crops or shifting away from open-field burning of rice straw—demonstrates that residue valorization can simultaneously protect soil health, mitigate greenhouse gas emissions, and support food security without competing for arable land.
- The scope of this study is inherently limited by the search parameters and the coverage of the Web of Science database. Future research must prioritize bridging the gap between lab-scale biotechnological advances and commercial applications, focusing on integrated socio-economic and environmental assessments to ensure that residue valorization effectively advances global energy security and circular economy objectives.

CRediT authorship contribution statement

Jean Agustin Velasquez-Pinas: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cristian Wedgwood:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Diego M. Yepes Maya:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Larissa Ampese:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Tania Forster-Carneiro:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Thomas Prade:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2026.102864.

Data availability

Data will be made available on request.

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