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Bibliometric Analysis: Use of Agricultural Waste in the Generation of Electrical Energy

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Abstract: Scientific reports have diversified enormously in the various thematic areas of the scientific world, generating errors and biases in the searches and directing the various investigations. For this reason, this article provides an approach, from the point of view of bibliometric analysis, to reveal the trends of agricultural waste for its potential use as fuel in generating electrical energy. This research has used the programs RStudio, VosViewer, and Excel for the compilation and analysis of data, whose data were extracted from Scopus during the period from 2013 to 15 March 2024, filtering all types of publications that were not original articles and English language. Scientific reports have found that biodigesters are constantly evolving, improving valves, studying and analyzing different types of agricultural waste, and using microorganisms to accelerate the fermentation process of agricultural waste. The terms biogas (330 occurrences), anaerobic digestion (214 occurrences), and agriculture (212 occurrences) were the words with the highest occurrences. At the same time, the author that stood out was Liu Y., who had an H index of 6 and 117 citations in his six articles published in the Scopus database. Moreover, China (1900 citations) was the country with the highest citation numbers, followed by the United States (1060 citations) and India (967 citations). The designs of biogas production increase efficiency and can increase biodigesters' performance. The research also reveals the different types of development and trends that stood out and emerged in the last decade, such as the authors who have had the most impact on this topic that has recently emerged and the countries that have obtained the most significant number of publications on the topic.

Keywords: agricultural waste; electric power generation; biogas; sustainable energy production; bibliometric analysis

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1. Introduction

The agribusiness sector has improved enormously in recent decades due to the increase in the human population [1]. In 1970, the human population was 3.7 billion, while in 2021, it reached 7.9 billion; by 2050, there will be 9 billion human beings and 11 billion by 2100 [2–4]. This increase has caused large companies to invest large amounts of money in the agroindustry sector due to the demand for products for the daily diet [5]. This abrupt increase in agroindustry production has caused the generation of large quantities of agricultural waste, from the harvesting process to consumption, since not only is there a large number of damaged products that are not sold or consumed, but also much waste is generated [6]. For example, it has been reported that 203 MT, 731 MT, 180 MT, and 354 MT of corn straw, rice straw, bagasse, and wheat straw have been generated, which cannot be burned or expelled to the environment because they damage the ecosystem [7,8].

Furthermore, agricultural waste was predicted to increase by 5 to 10% annually, becoming polluting waste, a severe problem worldwide [9]. The large amount of existing

raw materials (agricultural waste) has caused companies, governments, and research centers to look for sustainable ways to use them as by-products with some value [10,11]. The different types of agricultural waste contain 32–65% cellulosic and cellulose, polymeric compounds that play a crucial role in sustainable agriculture [12]. The extraction of cellulose is an example of how agricultural waste can be reused because the extracted cellulose can be easily applicable in medicine, various industries, and food packaging [13]. India and China rank first and second in agricultural waste production, producing 350–900 TN/year of agricultural waste [14]. In recent years, significant advances have been made in the use of agricultural waste (AW) as an energy source, such as AW gasification technologies, AW liquefaction technology (Fischer–Tropsch synthesis, enzymolysis, and hydrolysis), biomass technology, valve explosion pretreatment technology, and biogas electricity generation technology [15,16].

Agricultural waste helps reduce energy dependence on conventional fuels (fossils) [17]. Research centers have reported that AW (such as cow manure or crop straw) is a promising source of future alternative, sustainable, and renewable electrical energy [18]. In 2016, the Chinese government presented its report on the production of biogas generated in 2015, showing a production of 57,000 million m^3, which exceeded the 9000 m^3 of German production and the biogas produced in Sweden by approximately 30% [19]. An analysis of the amount of rice straw waste used for electrical energy mentioned that 6534 tons represent 1011 kWh in China, which would replace 80 million TN of coal; this is presented as an improvement in the global energy structure [20]. Currently, agricultural waste is used for energy generation and bioremediation of water contaminated with heavy metals, decontaminating contaminated soil or sludge, and fueling microbial fuel cells for directly generating electricity and waste treatment. For example, Baseri H. and Farhadi A. (2024) used pistachio hard bark to reduce 0.98, 0.96, 0.95, and 0.95% of the initial concentration of methylene blue, methyl orange, chromate, and cadmium, using contaminated wastewater with the components above [21]. Granado et al. (2024) used Broccoli waste in water contaminated with Pb (II), managing to reduce it by 88.3 $\pm$ 0.8%, operating at a pH of 4 [22]. Tang et al. (2024) used a set of biomass waste in microbial fuel cells as electric current generators and for reduction of heavy metals, achieving an electrical potential and power density of 38 mV and 1.55 $\times$ 10^{-3} mW/m^2, at the same time, reducing the concentration of Pb (II) by 99.6% [23].

As seen in the current literature, there is a large amount of information on the use of agricultural waste. The current trend of the topic is increasing because various research is being carried out in different areas of the topic. This increase in published scientific reports generates the exposure of errors in systematic reviews or published states of the art, which has led to the generation of a bibliometric analysis in order to process all the data to identify, in a precise and quantitative way, the different essential research areas with minor bias [24]. Bibliometric analysis has been characterized as a versatile and powerful technique for the development of metrics in order to obtain information on the intellectual structure that a topic implies, for which scientific publications, studies, and the impact of journals and authors have a more significant impact on the area [25]. A few decades ago, studies stylized a series of methods for measuring scientific productivity. Still, performance analysis uses bibliometric indicators, such as the number of citations, productivity, and H-index [26]. In this sense, the Scopus database (developed by Elsevier) has generated a list of large-scale bibliometric analyses. A free tool for researchers to analyze document sources, authors, countries, and publications [27], Scopus has become the most popular database, using Elsevier as a source and indexing its wide variety of disciplines, such as social sciences, biological sciences, health sciences, engineering, environment, and others [28].

Bibliometric analyses on agriculture or agricultural waste has taken on importance, mainly due to the vast amount of existing documentation; for example, Rejeb et al. (2022) carried out a bibliometric analysis on the use of drones in agriculture, reporting that precision agriculture, machine learning, and remote sensing connected to the Internet are crucial points in agricultural drones [29]. In this sense, the bibliometric analysis on the

efficient use of water in agriculture was also reported, where an increase in the annual production of articles was observed, with Agriculture Water Management being the leading journal to report these types of research and the Academy of Sciences of China having the most significant number of publications [30]. Bertoglio et al. (2021), in their bibliometric analysis of agricultural digitalization, managed to show five trends in this area (remote sensing, intelligent air conditioning, Internet of Things, management of specific sites, and artificial intelligence) [31]. A bibliometric analysis was carried out on the use of technology to improve agricultural productivity, showing that the United States, China, and Brazil have the most publications due to the large amount of economic resources they allocate for this type of research [32].

In this context, the scientific publications on the use of agricultural waste that have been comprehensively analyzed and measured from a global point of view are limited [33]. Evidence shows that agricultural waste is a self-sustaining source, capable of effectively solving the energy difficulties developing countries face [34]. From a global point of view, using this waste for energy generation worldwide is crucial; in agricultural countries, waste is increasing every year. If huge quantities of waste accumulate and are dumped into the environment with proper protocol or procedure, severe environmental and ecological problems will arise [35]. The International Renewable Energy Agency (2019) highlighted the great potential that agricultural waste has and that, shortly, it could easily be a substitute for fossil sources in China, Brazil, and India, which have large populations [36]. However, accurately obtaining information on agricultural waste applied to generating electrical energy is a challenge. Because there is limited availability of bibliometric tools for literature review available in the field, this article will offer a precise and exhaustive overview.

The main objective of this research is to explore and report current research trends in electrical energy generation using agricultural waste as fuel, to give relevance to comparative analyses, and to promote research on the topic. The study of bibliometric analysis allows us to understand the interrelation and correlation of scientific documents published in the Scopus database from 2013 to 2024, for which the research trend was identified due to its vital role in the scientific world. For all this, (a) the distribution of scientific reports was analyzed, (b) the contribution of countries, the primary authors, and research institutions were linked, (c) the terms and research topics were linked with various links of research with the most significant number of citations, (d) the most frequent research terms and topics were identified according to the most influential countries on the topic, and (e) current research trends were identified.

2. Methodology

The Scopus database has excellent coverage of journals that other databases do not have; the main reason is that through its advanced technology, its references and cited articles coincide by 99%. The results of the searches in Scopus allowed us to sort by relevance, dates, sources, authors, titles, and citations (of authors, articles, journals, countries, etc.), applying the limits or exclusions that the researcher wishes. It is an excellent database for collecting information for bibliometric analysis on agricultural waste as a source for generating electrical energy. Due to the above, this research was based on collecting information from the Scopus database as the primary source, considering the typical limitations of a bibliometric analysis. According to Niknejad et al. (2021), citations, H-indices, and numbers of occurrences can represent connections between authors, journals, topics, countries, and institutions to map the trends of the study areas [37]. After several tests using the keyword "agricultural waste" to generate the search string (SS) of Table 1, it was created.

The research reports that the percentage and quantitative distribution of keywords, the production of the number of documents, the production of scientific institutions, and the number with the highest production in the region is more significant than 10 documents. Impact indicators are also reported, for example, citations made in Scopus (H index), quartiles of journals that publish articles according to Journal Citation Reports (by year), sets of articles by citation range, countries, and structures with the highest number of

citations [38]. The presence of the topic of electrical energy generation through agricultural waste is established through its frequency of use and co-occurrence to map the study domain and categorize the topics in a strategic diagram with centrality and density as axes to locate the driving topics of the area, transversally, cutting topics, emerging or disappearing topics, and specialized topics. The analysis performed by VOSviewer software (version 1.6.20) was performed by the method performed by Colares et al. (2020) [39], while for the bibliometric analysis of the R-Studio package (version 4.3.3.), the method described (following their recommendations) by Luo et al. (2018) and Anglada-Tort and Sanfilippo (2019) [40,41].

Table 1. Search strategy for scientific documents.

Criteria	
SS	(TITLE-ABS-KEY (agricultural AND waste) AND TITLE-ABS-KEY (farm AND waste) AND TITLE-ABS-KEY (bioenergy) OR TITLE-ABS-KEY (bioremediation) OR TITLE-ABS-KEY (bioelectricity) OR TITLE-ABS-KEY (electric power generation) OR TITLE-ABS-KEY (biogas) OR TITLE-ABS-KEY (fuel)) AND PUBYEAR > 2012 AND PUBYEAR < 2025
Languages	English
Document types	Article
Period	2013–2024
Database	Scopus
Total documents published	463

3. Results and Discussion

Productivity trend of the amount of literature from 1975 to March 2024: the search chain showed that the total production of published documents on the use of agricultural waste as sources for the generation of electrical energy in the Scopus database can be divided into five large groups, which are articles (65.76%), conference papers (20.08%), book chapters (7.38%), reviews (4.78%), and others (1.97%), Figure 1a. These results are from the production carried out during a more extended period than that established in this research to appreciate, in a more general way, the increase this area has had since 1975 when the first document was recorded. The documents published are not uniform; if an average is made, it would be 20 publications per year, which is the preferred document to report research in article form. The quantity could be more abundant if the search were carried out only for agricultural waste applications (in general); by specifying that it is only for electrical energy generation, a restriction is made on the topic [42]. In Figure 1b, you can see the successive increases in publications on the topic, where the accumulation of articles was 961 in the English language alone, with more than 30 articles per year published in 2013. A maximum of production was observed in 2021 and 2024, with 82 and 79 documents in the form of articles published in English. From 2013 to March 2024, 60.4% of the total production was reported, and fluctuations were observed. However, with a tendency towards an exponential increase, where the large production in 2021 is due to the confinement suffered due to COVID-19, scientists had more time to report their findings [43]. The topic has captured the interest of scientists because the trend is to look for sustainable alternatives to generate electrical energy through low-cost materials so that it is profitable for companies and the government [44]. It is observable that the interest of researchers has increased since 2013, which provides us with a solid basis for the growth of the topic globally. The analysis shows that the appearance of the topics of agriculture or agricultural waste/waste is related to the science topics of biology and bioenergy during this period. The original articles from 2013 to 2024 quadrupled compared to those from 1990 to 2000, giving a growth ratio of 2.36 annual growth.

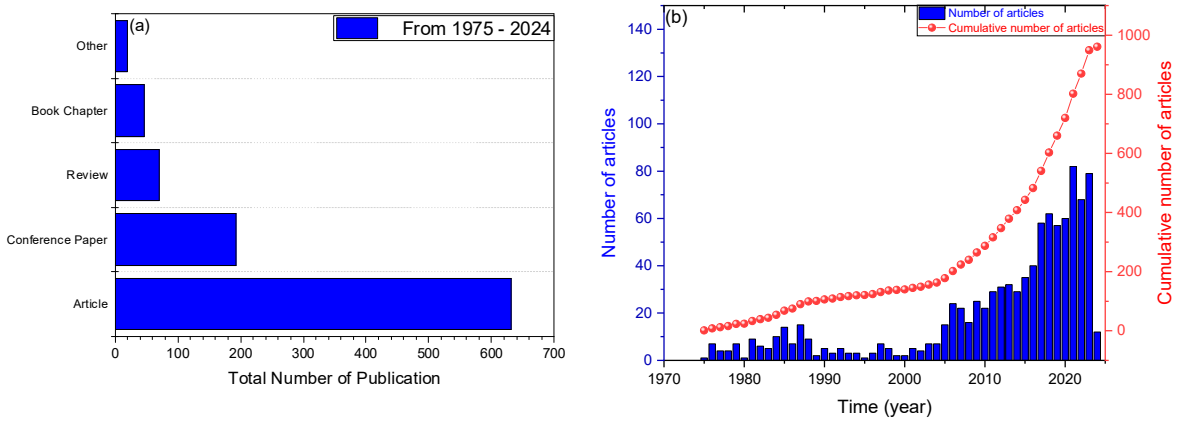

Figure 1. (**a**) Publications of agricultural wastes from 1975 to 2024 and (**b**) publication production performance between 1975 and 2024.

The trend of journals with the highest number of publications: The publication sources with the highest number of articles published in Scopus were carried out by mapping the central journals with their respective publishers; in this way, an analysis of the increase in research in the area was carried out with regard to agricultural waste as a fuel source for the generation of electrical energy [45]. The ten journals with the highest number of publications on the topic from 2013 to March 2024 can be seen in Table 2. The journals Journal of Environmental Management and Science of The Total Environment from the Elsevier publishing house are the preferred sources for researchers to carry out their research reports, with 24 articles each; both journals contain more than 500 citations. Although the journal Science of The Total Environment began publishing on the subject in 2015, it achieved second position in just eight years. It is worth highlighting that seven of the ten journals are from the publisher Elsevier, and five of the journals (Elsevier) have an impact factor greater than 8.5. The use of agricultural waste as a source for the generation of electrical energy is a topic that is still beginning, which is why any research carried out in this regard will be of great interest in scientific articles to be cited when the report is published. For example, the Journal of Environmental Management obtained 782 citations in 24 published articles.

Table 2. Top 10 journals with the highest number of publications between 2013 and 2024 and their citations (excluding self-citations).

N°	Journal	Number of Articles	Publisher	Impact Factor	Citations	Start
1	Journal of Environmental Management	24	Elsevier	8.7	782	2013
2	Science of The Total Environment	24	Elsevier	9.8	567	2015
3	Energies	21	MDPI	3.3	167	2015
4	Bioresource Technology	16	Elsevier	11.4	927	2013
5	Journal of Cleaner Production	14	Elsevier	11.1	567	2015
6	Waste Management	14	Elsevier	12	568	2015
7	Nongye Gongcheng Xuebao/Transactions of The Chinese Society Of Agricultural Engineering	12	Chinese Society of Agricultural Engineering	5	66	2014
8	Biomass and Bioenergy	10	Elsevier	6	261	2013
9	Renewable Energy	10	Elsevier	8.7	311	2013
10	Bioenergy Research	9	Springer New York	7	277	2013

The network of journals preferred by researchers to report progress on agricultural waste as a source of fuel for the generation of electrical energy is found in Figure 2. The spheres with greater intensity of color indicate a more significant number of publications from the journal, which means a more excellent report of articles. However, the prestige of each journal is determined by the impact factor (IF). The IF is the metric that must be considered when selecting a journal because it has a more significant number of citations per publication. Generally, the bibliometric analysis indicates that research centers prefer to publish the progress or results of their research related to the generation of biogas from agricultural waste, applications of agricultural waste, and obtaining bioelectricity from waste, among other issues related to the topic, in the Journal of Elsevier, MDPI (Multidisciplinary Digital Publishing Institute), Chinese Society of Agricultural Engineering, and Springer New York. Figure 2 also clearly shows the formation of four groups: blue (Bioresource Technology), green (Waste Management and Nongye Gongcheng Xuebao/Transactions of The Chinese Society of Agricultural Engineering), yellow (Journal of Environmental Management and Science of The Total Environment), and red (Energies, Journal of Cleaner Production, Renewable Energy, Biomass, and Bioenergy), which are interconnected between the multiple domains of the research reported, which were analyzed by their frequency of citations. The journals with closer circles and similar colors show a closer interaction with greater distance and different colors. The values of Index H of the reviews are directly proportional to the impact factors; these are the impact factors indicating the relevance of the review on the subject, motivated by the fact that some investigators are obliged to publish their scientific reports with the indices of H and impact factors at the same time [34]. The investigation with a large number of citations in the Journal of Environmental Management was carried out by Wang et al. (2021) to analyze the contaminated waters of the aquiculture, which are directly fed to the water bodies without processing, mentioning that the agricultural activity also caused contamination as a result of the eutrophication of more waters, and in extreme cases, reduced concentrations of 83.9 and 82.8% of nitrogen and phosphorus were observed [46]. The Journal of Science of the Total Environment report conducted by Battini et al. (2014) is one of the largest studies, analyzing the impact of a large amount of milk in Italy, estimating that 1.21 Kg of CO_2 is equal to kg^{-1} of fat and protein-corrected milk, and the production of biogas is compensated by 40.6% of the energy used in the farm production process [47].

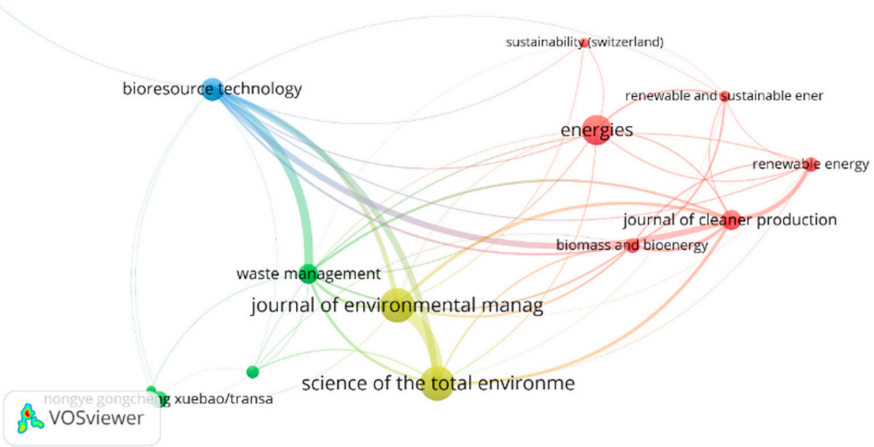

Figure 2. Bibliographic coupling of the main journals focused on publications of agricultural waste as a fuel source for the generation of electrical energy.

The trend of the most representative keywords in the literature: The keywords with the highest occurrence in the Scopus-indexed publications on the use of organic waste as fuel sources for electricity generation are shown in Table 3. It can be seen that the most used keywords are biogas (330 occurrences), anaerobic digestion (214 occurrences), agriculture (212 occurrences), biomass (193 occurrences), manure (177 occurrences), and agricultural

wastes (169 occurrences), which are in the first six positions with more than 160 occurrences. From 2013 to March 2024, the most used term was biogas, along with terms similar to agricultural waste, which indicates that agricultural waste is currently being intensively investigated for the production of biogas, which indicates to us that this is a growing area of research. It can also be seen in Table 3 that waste related to agriculture is also being investigated, precisely because much of the waste related to decomposition produces biomethane. At this point, the research can be divided into three main branches: (1) obtaining gaseous fuel from agricultural waste, (2) obtaining fuel in an aqueous solution from agricultural waste, and (3) obtaining solid fuels from agricultural waste. This is because agricultural waste must be treated using a technology capable of taking advantage of the products generated to generate electrical energy. Su et al. (2024) optimized the grate boiler at 130 t/h, increasing its burning rate by 95.5% and emitting CO at 1917 ppm, much less than the 3178 ppm previously reported [48]. Likewise, Archana et al. (2024) mentioned in their research that the anaerobic digester technology used to produce biogas is the most promising technique to replace the generation of fuel from fossil sources when the biomethane produced from agricultural or cattle waste is the fuel for public transportation, replacing diesel/gasoline [49]. Patel et al. (2024) calculated that 1500 tons/year of agricultural waste can replace the gasoline demand of 2070 kg/year, while decreasing CO_2 production by 41,218.6 tons/year [50]. These reports carried out have the similarity of using agricultural waste as a source for the production of biogas and its subsequent use as a gas-generating source, in addition to mentioning that in order to be able to produce it on larger scales and, thus, supply electricity-generating plants, changes in government policies are needed [51]. With larger scales, thus supplying to electricity-generating plants, changes in government policies are needed [51]. The journals with closer circles and similar colors show a closer interaction with greater distance and different colors.

Table 3. Distribution of the first 30 keywords most frequently reported in publications from the Scopus database.

N°	Words	Occurrences	N°	Words	Occurrences
1	Biogas	330	16	Crops	103
2	Anaerobic Digestion	214	17	Nitrogen	102
3	Agriculture	212	18	Manures	86
4	Biomass	193	19	Animal	82
5	Manure	177	20	Sustainable Development	82
6	Agricultural Wastes	169	21	Biofuel	77
7	Fertilizers	162	22	Carbon Dioxide	71
8	Article	153	23	Greenhouse Gases	71
9	Farms	141	24	Controlled Study	70
10	Methane	137	25	Soil	70
11	Waste Management	122	26	Biofuels	69
12	Animals	118	27	China	66
13	Nonhuman	108	28	Wastewater Treatment	58
14	Agricultural Land	103	29	Pig	57
15	Bioremediation	103	30	Waste Water	57

The interaction network of the keywords is found in Figure 3. A minimum occurrence of 55 times from the Scopus database was used for visualization. For adequate interpretation, the keywords with larger circles obtained a higher frequency, and the correlation of the circles was determined by the position in which each keyword was located in the article. The data obtained from VOSViewer identified nine clusters of red color (Group A), three clusters of light blue color (Group B), seven clusters of blue color (Group C), six clusters of yellow color (Group D), five purple color clusters (Group E), and nine green groupings (Group F), where the keywords biogas production, source, development, process, and perspective are the ones that have the most significant interactions with the other closest keywords. In addition, keywords about dairy farms and performance are observed, as well as the interaction of the keyword biochar with conversions, products, and challenges. This indicates a trend in the use of dairy farms, wastewater, and livestock waste as a source for biogas production, trends that are just being reported in scientific research. The generation of biodiesel through agricultural waste is the reason for the scientific community's attention, so we use it as the primary material of vegetable and fruit waste, which has a rapid fermentation that produces natural minerals [46]. The use of agricultural waste also requires attention to the application of the circular economy and also "cero residue," which is another point of interest to scientists who are interested in the fact that the waste is used in manufacturing other products [39].

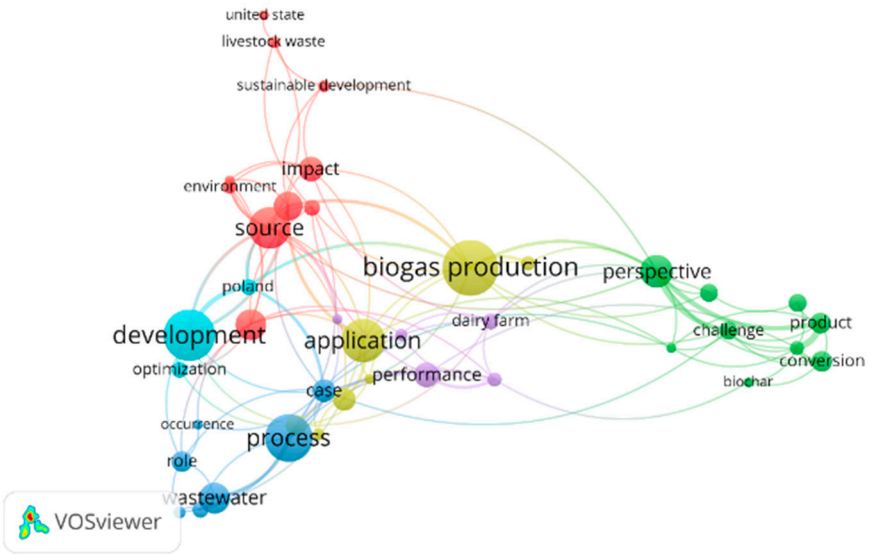

Figure 3. Realization of the Search Network, showing the co-occurrence of keywords from the Scopus database for the period 2013–2024.

Table 4. Authors with the highest H index on the topic obtained from the Scopus database (2013–2024).

N°	Authors	H-Index	Citations	Most Cited Article	Number of Articles	Ref.
1	Liu Z.	6	117	Effect of the carbonization temperature on the properties of biochar produced from the pyrolysis of crop residues	6	[52]
2	Koutinas A.A	6	269	Whole-crop biorefinery	7	[53]
3	Wang Y	5	183	Performance evaluation of a large-scale swine manure mesophilic biogas plant in China	9	[54]
4	Xu J	5	168	Performance evaluation of a full-scale innovative swine waste-to-energy system	2	[55]

Table 4. *Cont.*

N°	Authors	H-Index	Citations	Most Cited Article	Number of Articles	Ref.
5	Angenent L.T.	4	131	Integrating electrochemical, biological, physical, and thermochemical process units to expand the applicability of anaerobic digestion	3	[56]
6	Rodríguez-Rodríguez C.E.	4	124	On-farm biopurification systems: role of white rot fungi in depuration of pesticide-containing wastewaters	3	[57]
7	Tester JW	4	131	Cost analysis of oil, gas, and geothermal well drilling	4	[58]
8	Wang F	4	56	Effects of outdoor dry bale storage conditions on corn stover and the subsequent biogas production from anaerobic digestion.	4	[59]
9	Wang J	4	160	Decentralized biogas technology of anaerobic digestion and farm ecosystem: opportunities and challenges.	6	[60]
10	Zhang Y	4	99	Pretreatment of lignocellulosic biomass for enhanced biogas production	4	[61]

Trend of authors with greatest impact: Table 4 shows the top 10 authors with the most significant impact on the topic, with little production of articles observed from 2013 to March 2024. However, this information reveals the trend of using agricultural waste as raw material for generating electrical energy, which is being carried out by different research groups dealing with a specific problem. It is observed that the most cited articles have terms similar to agricultural waste or biogas generation; for example, Liu Z. has an H index of 6 with 117 citations in his six published articles, his most cited article being the one in which he studied the effect of temperature on crop residues for the production of biocarbon, achieving improved values of electrical conductivity through pyrolysis at temperatures between 300 and 700 °C, obtaining a solid source for energy generation [52]. It is worth highlighting the work carried out by Tester JW and his team, entitled "Cost analysis of oil, gas, and geothermal good drilling", where he carried out an economic analysis of the cost of production from oil and onshore gas wells in the United States with accurate data [58]. Analyzing Figure 1b and Table 4, the increase in citations and articles shows the relevance of scientific reports to improve research using agricultural waste with energy applications. It is important to note that the first four articles in Table 4 are original research that can collaborate with new researchers to generate new materials with applications in generating electricity using agricultural waste as a source. Furthermore, the journals that publish these research reports have their objective and scope topics of environmental bioengineering, biomass conversion, bioenergy (optimization), biocatalysts, and biofuels.

Furthermore, it is observed that the values reveal a connection between the citations of several researchers from various geographical points. Research on the use of agricultural waste for its potential use in energy generation reveals that the pilot-scale demonstration has been optimized in such a way that it is investing in a model at industrial scales, and all this has been possible because the researchers and their institutions promote research in this area [62,63]. The observation of cluster accumulation can be noted by color, where the point is derived by averaging the shades of the closest clusters, Figure 4 [64]. The assignment of the group color is because closer elements of the same group are given a greater weight. Therefore, the relationship between the number of citations received and the article identifies the scientific report with the most impact. Due to this, scientific reports that have a high number of citations indicate important milestones for technological development. Furthermore, the conglomerate of groups of leading investigators of the investigative centers has obtained an investigative direction with greater importance in viability and logistics to obtain a world-class standard technology that presents itself as a

primary material for agricultural purposes, to maintain the global acceptance of obtaining energy from biogas [35]. Also, obtaining biohydrogen is another crucial point for the authors who mark the tendency in this area thematic, which is vital in the use of waste vegetables and waste food. However, removing important optimization points of the devices used in biodigesters is necessary [44]. One of the articles recently published by Liu et al. (2023) is the study of antibiotics in a large porcine sample, including the presence of 12 antibiotics in the waste of the pigs where the method of stabilizing anoxia eliminated 43% of antibiotic load from the environment and the compost used for the single biogas production contained 8% in the final antibiotic load after passing a series of vehicles for an integrated treatment [65].

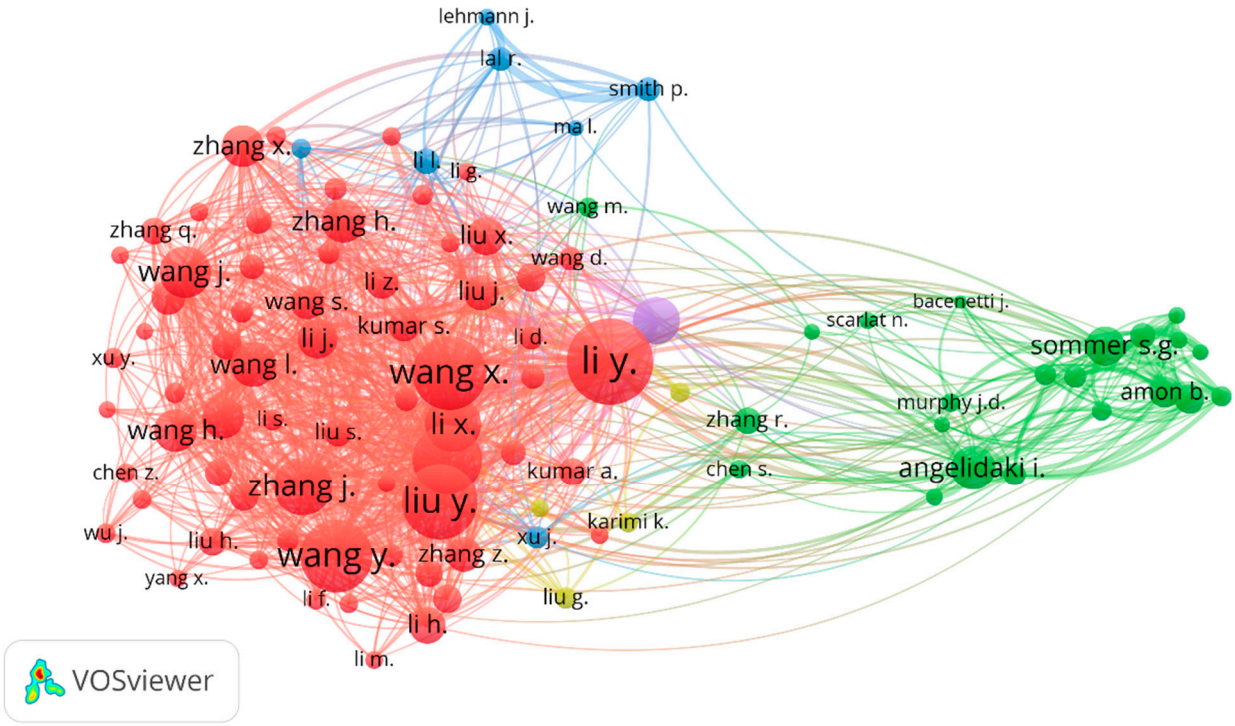

Figure 4. Contributions made between the authors' networks.

Trend of the countries with the highest number of citations: Table 5 shows the countries with the most citations promoting research on agricultural waste used to generate electrical energy. Noting that all continents are promoting this area of research, except Africa, the countries show heterogeneity in economic development, population size, and climate. China is the country that shows the most significant proliferation of documents published in the Scopus database, with a total of 1900 citations; the documents published by this country represent 48.8% of the total during the period from 2013 to March 2024. The United States of America is in second position, with 296 published documents, representing 30.80% of the total, and 1060 citations. In the same way, India, with 185 (19.25%) documents with 967 citations; Italy, with 216 (22.48%) documents with 906 citations; and Germany, with 95 (9.89%) documents with 587 citations, represent the five countries with the highest number of citations received. The China Agricultural University is the institution that contributed the most to China, with 34 published articles. In contrast, Cornell University and the University of Agriculture contributed 13 and 12 published documents to the USA and India, respectively. In Italy and Germany, the institutions that contributed the most published documents were Università Degli Studi Di Milano (12 documents) and Harper Adams University (10 documents). The large amount of financial support for the generation of projects that these countries have invested in the research groups of each institute is one factor that shows the relevance of the publication documents [66]. Government policies for creating research facilities, such as laboratories, and improving educational quality

have promoted international relations of research groups for the creation of networks, thereby improving the quality of published results and reports [67]. The search chain on agricultural waste as a potential source for generating electrical energy reveals that four countries exceeded 900 citations and 180 published articles, Figure 5. The formation of six groups is mainly shown, led by China (red), USA (purple), India (light blue), Italy (green), United Kingdom (lime green), and Germany (orange). China has a strong interaction with Japan, Malaysia, Pakistan, Australia, and South Korea, while the USA mainly has interactions with Chile, Japan, South Korea, Canada, and Costa Rica. The data shown in Figure 5 were created from the bibliometric coupling of the published scientific reports with their respective citations, considering the relevant research and countries for each of them. China and the USA are the pioneers on the subject, where connections with other scientists from other regions expand and improve advances in the use of biogas production from agricultural waste, improving the method for reducing pollutants gases (carbon monoxide, carbon dioxide, nitrogen oxides among others) in the biogas generation process [68].

Table 5. Countries with at least 50 publications on the topic of electricity generation through agricultural waste.

N°	Country	Citations	Documents	Average Citations	Institution
1	China	1900	469	24.10	China Agricultural University
2	USA	1060	296	24.70	Cornell University
3	India	967	185	8.10	University Of Agriculture
4	Italy	906	216	26.60	Università Degli Studi Di Milano
5	Germany	587	95	34.50	Harper Adams University
6	United Kingdom	549	111	27.40	Newcastle University
7	Australia	432	31	48.00	Universidad De Melbourne
8	Denmark	399	49	39.90	Aarhus University
9	Poland	355	48	14.20	Poznań University Of Life Sciences
10	Canada	289	51	36.10	University Of Toronto

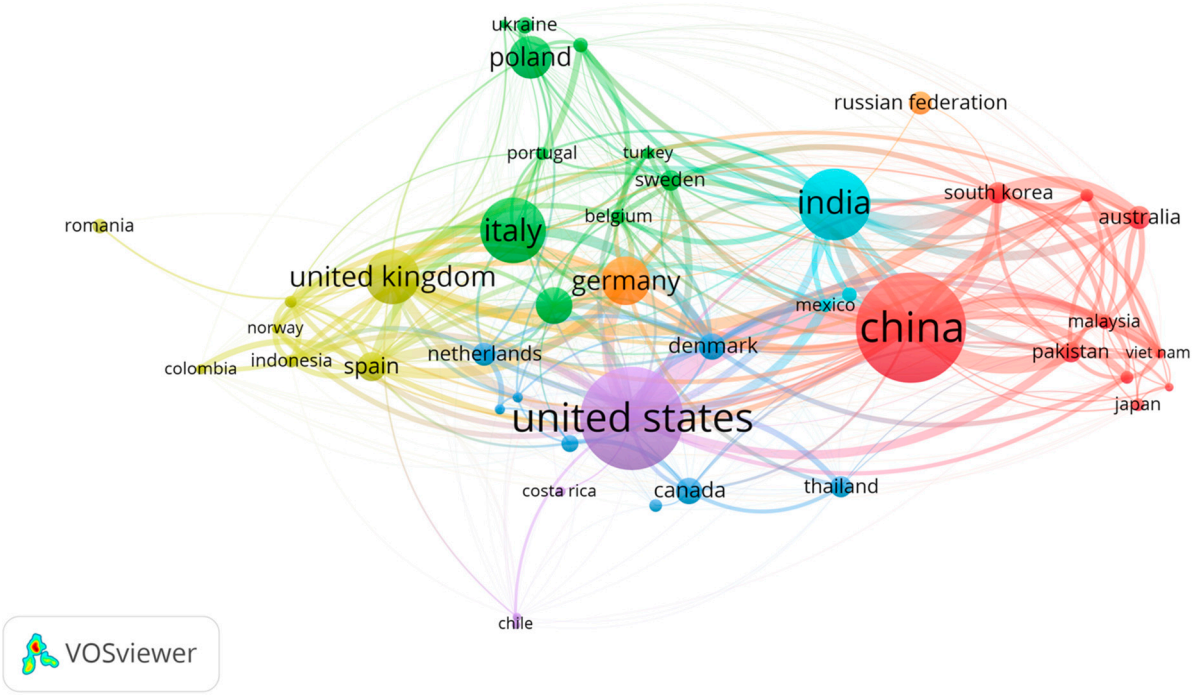

Figure 5. Report of countries with a minimum of 5 publications with their respective citation correlation.

The use of agricultural waste as fuel sources for the generation of electrical energy: The use of agricultural waste as fuel sources for the generation of electrical energy has been intensively investigated in the last decade, with waste from vegetables, fruits, and tubers being the ones usually used. The design of different types of biodigesters has also been reported to optimize and improve the process of generating electrical energy. The themes have evolved since 2013, with the most notable terms being performance, biomethane, production, waste, biomass, sustainable, and others; so currently, in the year 2024, they will be consolidated into four terms (biogas, anaerobic, farms, and soil), Figure 6. In addition, it is observed that the terminology of agricultural waste or agricultural waste has begun to be present in scientific reports, Figure 7. To date, scientific reports have been oriented toward the biorefinery, lignocellulosic biomes, circular economy, bioremediation, and crop residue, so it is encouraged that new research is directed toward these specific points in the use of agricultural waste for the generation of electrical energy. The use of microorganisms to accelerate the degradation of organic matter is beginning to be reported; for example, Ye et al. (2024) used microorganisms (*Thiobacillus*, *Auicella*, *Sphingomonas*, and *Rhodobacter*) as biocatalysts in agricultural waste for the generation of biogas [69]. Likewise, Oliveira et al. (2024) reported the generation of biomethane, bioelectricity, and biofertilizer from the use of sugarcane waste, a highly produced product in Brazil, generating between 0.6 to 1.3 billion Nm^3 $year^{-1}$, which would represent 1.768–3.961 GWh $year^{-1}$ of electrical energy and 1.6 to 3.3 million Mg $year^{-1}$ of biofertilizer [70].

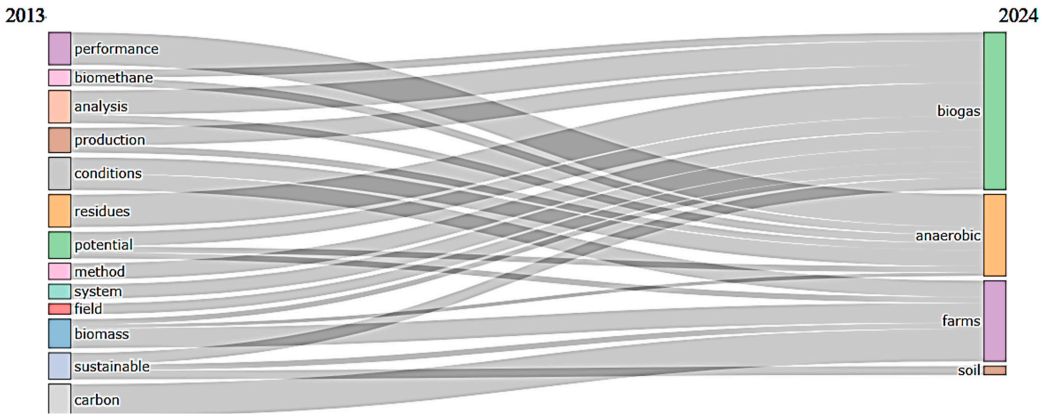

Figure 6. Evolution of the trend of keywords to date.

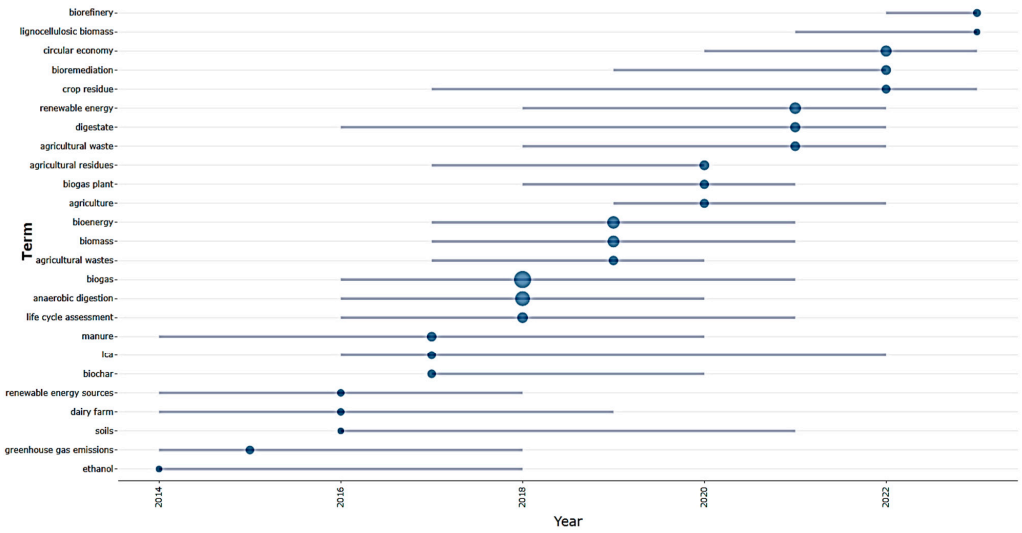

Figure 7. Trend of new keywords from 2013 to 2024.

4. Conclusions

The article presents a bibliometric analysis using the Scopus database's reports from 2013 to 15 March 2024. The selected articles were oriented to using agricultural waste to generate electrical energy. It has been shown that the existence of links initiated between researchers serves as support among themselves to increase the number of citations, as well as the creation of collaborative projects in order to improve essential points of the topic; this makes companies, governments, or institutions that finance research bet on these projects. Furthermore, the area of electrical energy generation from waste has evolved immensely in recent years, but the use of agricultural waste as a source of electrical energy generation began in 2020, which makes this area of study a new and promising topic due to the large number of existing questions for the improvement of current technology. The most outstanding findings found are:

- The scientific journals most selected by the authors on this topic are the Journal of Environmental Management, Science of The Total Environment, Energies and Bioresource Technology, from Elsevier, and MDPI.
- The keywords with the highest occurrence reported by researchers in their papers are biogas and anaerobic digestion, but starting in 2020, agricultural waste has begun to appear and gain importance.
- The most significant number of scientific documents were published in China, the USA, and India, whose analysis connects the laboratories of these countries with different geographical areas.
- The authors with the highest number of citations during the analyzed period are Liu Y., Wang X., and Wang Y., with an interaction of research works carried out between them or other researchers with a large number of citations.

In the publication of articles, the investigators have carried out studies in Earth Sciences, Environmental Sciences, Genetics, and Molecular Engineering with applications in agriculture. However, the more critical points are water (water pollution), irrigation and waste (from the point of view of making decisions and management), and production of crops (from the point of view of agricultural yield), but all these points are directed to the production of biogas as the final stage. The differences observed show a need for multidiscipline training integration. The existing limitations are related to adequate agricultural waste collection, the biodigesters' performance (cost/benefit) for their profitability, and raising awareness among companies and governments for investment in these projects.

For future work, strategic plans are recommended so that small urban groups or agro-industrial companies have a minimum flow to ensure a minimum flow for the viability of the facilities. These plans must be based on choosing solutions from centers of adequate supplies. In addition, raising awareness among business people and state policies for investment in the issue of recycling, where they can observe the great benefits that the application of this method will bring to society.

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