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Review

Research Progress on Anaerobic Digestion of Cellulose Waste Based on Bibliometric Analysis

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Abstract: The bibliometric method was used in this study to analyze current advances in the anaerobic digestion (AD) of cellulose waste. The result shows that the number of articles increased rapidly after 2010, suggesting a growing interest in this field. The USA and China were the top two countries with the highest number of published articles. AD of cellulose waste is being actively explored in many countries, and partnerships between countries are being actively formed. The top three subject categories were Environmental Sciences & Ecology, Engineering, Energy & Fuels. The most widely published and influential journals were Bioresource Technology, Water Science and Technology, and Waste Management. The co-occurrence and trend analysis of author keywords indicates that current research is primarily focused on pretreatment and co-digestion. Microbial community analysis plays a crucial role in elucidating the mechanisms, and life cycle analysis (LCA) could evaluate the impact on the environment at different stages. Microbial community analysis and LCA will be the hotspots in the future. To some extent, this study helps to understand the current global status and trends of the related research.

Keywords: cellulose waste; anaerobic digestion; pretreatment; microbial community; life cycle assessment; bibliometric analysis

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1. Introduction

Cellulose waste, which is a significant component of organic waste, is both abundant and challenging to manage. Large quantities of cellulose waste are generated annually from agriculture, forestry, and municipal activities. The production of cellulose wastes, such as waste paper, crop residues, and garden waste, is increasing year by year. For example, China is the world's largest producer and consumer of paper [1], resulting in tremendous production of waste paper annually. Agricultural waste is an important source of cellulose biomass. According to the International Rice Research Institute, an average of 0.7–1.4 kg of rice straw waste is generated for every 1 kg of rice produced [2]. Average annual production of agricultural straw reaches 1.14 billion tons [3]. Cellulose waste is a huge biomass resource when disposed of rationally [4].

Relying on incineration and landfill for waste disposal can create secondary pollution and is not economically viable [5]. The dioxins from the incineration process may be hazardous to human health [6]. Recycling and reproduction for new products is considered an environmentally friendly way to dispose of waste paper. But changes in paper quality and contamination during the recycling process have led to the limited recovery of waste paper [7]. The large amount of straw produced each year is also difficult to fully absorb by returning it to the fields. Studies have demonstrated that cellulose biomass has a significant potential for biomass fuel production [8]. Circular economy (CE) and sustainable development goals (SDG) have a significant impact on national policy and how trash is managed [9]. Anaerobic digestion (AD) of organic waste can produce energy and other organic products while efficiently degrading organic waste and reducing human dependence on fossil energy. The by-products of anaerobic digestion continue to be utilized, which can create economic benefits, with environmental, economic, and social benefits [10]. AD has gained widespread attention.

However, the crystalline and reticulate structure formed by the lignin, cellulose, and hemicellulose increases the difficulty of AD [11]. Therefore, the hydrolysis rate of cellulose waste is slow, and the methane yield is low [12]. Scholars have conducted extensive research to improve the methane yield of cellulose waste. The bibliometric approach examines the growth and distribution of articles by analyzing the characteristics of articles in related fields, which in turn allows for the analysis of current and future research directions [13]. Thus, we conducted a literature search and bibliometric analysis based on the Web of Science database. Based on bibliometric analysis, this article provides a review of the current state of research and future trends in the AD of cellulose waste, with a focus on pretreatment, co-digestion, microbial communities, and LCA.

2. Materials and Methods

The Web of Science of the Institute for Scientific Information (ISI) is internationally recognized as the leading search tool for science statistics and scientific assessment and is a major platform for international exchange among scholars [14]. The document data were retrieved from the Web of Science database using the keywords (cellulos* waste* or fiber* waste* or fibre* waste* or garden waste* or paper* waste* or straw* waste* or agricultur* residue* or yard* waste* or lignocellulosic biomass or forests waste or grass) and (anaerob* digest* or biogas or methane). The data source is the Web of Science core collection. The literature from 1 January 2002 to 31 December 2021 was downloaded on 10 July 2022. The bibliometric analysis method described by Mao [15] and Microsoft 2019 were used to analyze the trend of publications. Bibliometrix (in R) and VOS viewer were used to visualize the data. Author keywords, instead of 'Keywords Plus' provided by Web of Science, were used for keyword analysis. The articles were divided into four parts according to their year of publication (2002–2006, 2007–2011, 2012–2016, and 2017–2021) for further statistical analysis.

3. Results of Bibliometrics Analysis

3.1. Article Output Trend Analysis

Figure 1 displays the overall publications as well as the number of articles from the top five countries for the period 2002–2021. In terms of periods, the total numbers of articles published in 2002–2006, 2007–2011, 2012–2016, and 2017–2021 were 973, 1475, 2973, and 5006, respectively, with an increase rate of 51.6%, 101.5%, and 68.4%, respectively. Research on the AD of cellulose waste has developed rapidly since 2010, which may be related to the emphasis placed by the Food and Agriculture Organization of the United Nations (UN) on bioenergy, agroenergy, and wood energy [16]. As shown in Figure 1, the number of publications in China has increased since 2009. This may be related to the fact that China is a large agricultural country and the policies that have been introduced in China since the 12th Five-Year Plan (2011–2015) [17–19].

The results of a bibliometric analysis of articles published between 2002 and 2021 by countries and institutions are shown in Figure 2, which shows that AD of cellulose waste has been actively explored and studied in many countries around the world. Over 50 countries worldwide are implementing strategies related to sustainable energy, economy, and other initiatives that exert the AD of cellulose waste.

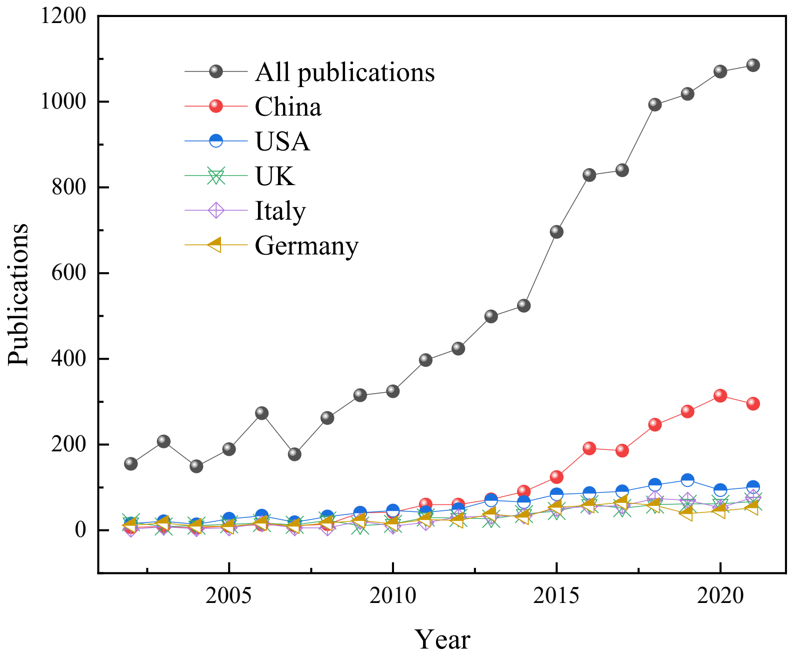

Figure 1. Number of SCI publications on related research and trends in the top 5 most productive countries in 2002–2021.

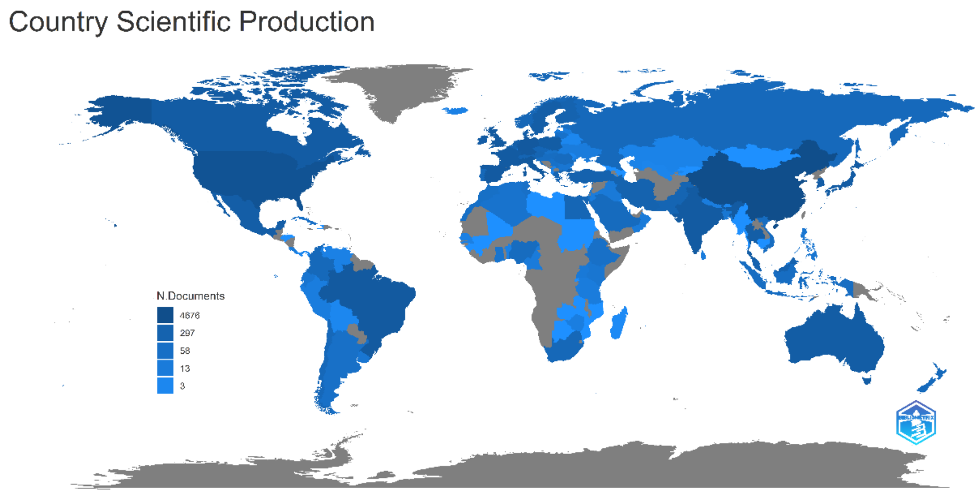

Figure 2. Map representation of the number of publications per country on the related research; N.Documents: number of documents.

3.2. Authors with the Highest Number of Articles

The analysis of the authors helps us to learn the leading researchers and current research trends in this field. Figure 3 shows the relationship between the number of articles published by the top 10 authors in terms of the total number of articles published over time. The size of the circles indicates the number of publications, while the color of the circles represents the total number of times that author has been cited. Since 2010, the number of publications and cited times of the authors have increased rapidly, indicating that the research system related to AD is gradually improving, and the authenticity and stability of the conclusions of the articles have been widely recognized. The faster growth of author output and cited times from 2010 onwards compared to the pre-2010 period indicates that AD of cellulose waste is gaining increasing attention. This is consistent with the conclusion that the number of publications has been rapidly increasing since 2010. Since 2018, Li YY, Li Y, and Yuan HR have issued more articles and been cited more frequently, which can provide more theoretical bases and prospective proposals for future research.

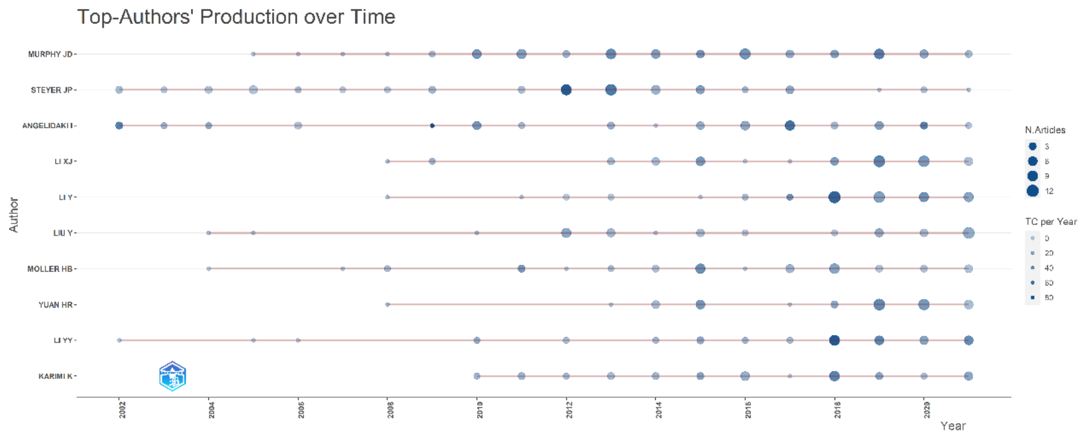

Figure 3. Changes in the number of publications and cited times of the top 10 authors during 2002–2021; N.Articles: Number of articles; TC per year: total cited times per year.

3.3. Distribution of Journals and Subject Categories

According to the discipline classification in Journal Citation Reports (JCR), the retrieved articles are distributed among 66 subject categories. The top 5 subject categories are listed in descending order as follows: Environmental Sciences & Ecology (3877), Engineering (3685), Energy & Fuels (3073), Agriculture (2390), Biotechnology & Applied Microbiology (1899). The first three subject categories have large proportions perhaps because the AD of cellulose waste satisfies the needs of treating organic waste and developing environmentally friendly energy. The AD process depends on microorganisms. Agricultural waste, such as corn straw and wheat straw, has a high methanogenic potential, so the numbers of articles in the biotechnology and applied microbiology and agriculture categories are also large.

Table 1 shows the characteristics of the top 10 journals with the largest number of publications. Bioresource Technology published the most articles, followed by Waste Management and the Journal of Cleaner Production. Bioresource Technology published the most articles with 946 and the highest H-index, which indicates that Bioresource Technology is the most influential journal in this field. It should be noted that the H-index is influenced by the number of published articles and the times it is cited. As the citation frequency of papers may change over time, the H-index calculated in the article is based on data up to 10 July 2022.

Table 1. The top 10 journals with the highest number of articles.

Journal	TP	H-Index	IF2022
Bioresource Technology	946	92	11.89
Water Science and Technology	596	57	2.43
Waste Management	459	66	8.82
Journal of Cleaner Production	316	46	11.07
International Journal of Hydrogen Energy	299	52	7.14
Biomass and Bioenergy	209	42	5.77
Renewable Energy	204	43	8.63
Science of The Total Environment	165	34	10.75
Energies	160	21	3.25
Waste and Biomass Valorization	157	21	3.45

TP: total number of publications, IF: impact factor.

3.4. Research Trends and Hotspots Analysis

Keyword analysis is conducted to comprehend research trends and frontiers [20]. Keywords with the same meaning need to be combined before processing. Figure 4 shows the clustering analysis of the keywords that appeared more than 40 times in this study. The results show that there are 119 keywords with more than 40 occurrences. Among them, the most frequently used keywords in the literature include anaerobic digestion (2119), biogas (1369), methane (1225), co-digestion (443), pretreatment (346), food waste (304), biomass (297), lignocellulosic biomass (274), microbial community (273) and life cycle assessment (LCA) (270). This result indicates that pretreatment and co-digestion are crucial for improving the efficiency of AD of cellulose waste. Microbial community analysis is becoming more significant as an internal justification for changes in AD efficiency. LCA is becoming more and more significant as a tool for investigating the potential environmental impact of the waste life cycle and for the integrated assessment of waste treatment, resource utilization, and environmental impact.

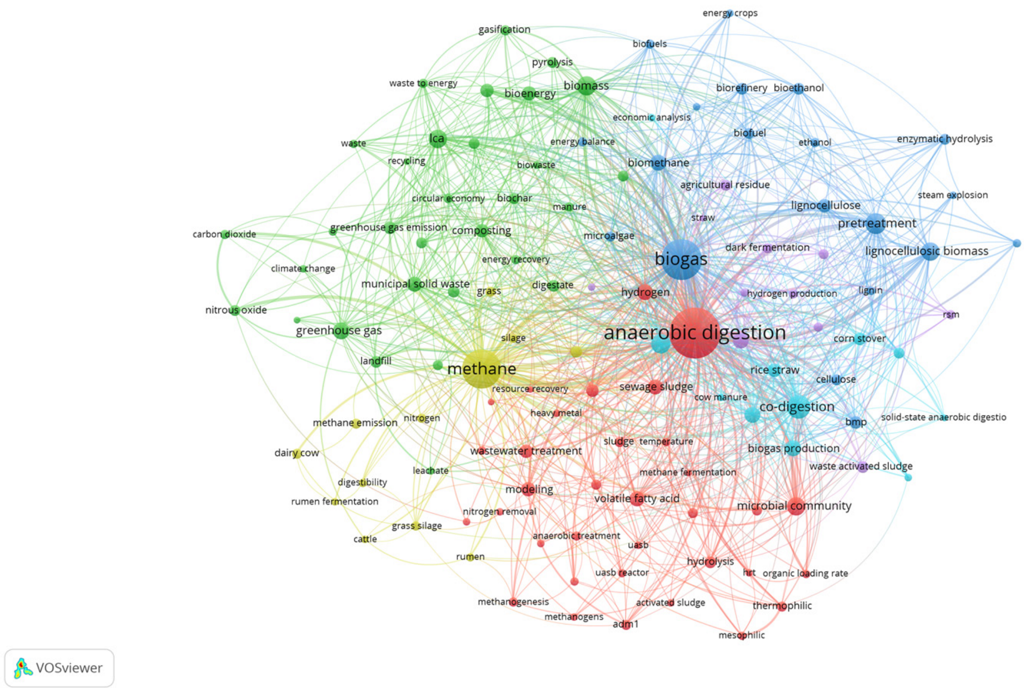

Figure 4. Clustering analysis of keywords occurring more than 40 times.

Figure 5 displays the research trends according to the quadrants. AD, biogas, and biomass are in the first quadrant, indicating that they are more significant and better developed. LCA is in the second quadrant, which proves that the study is developing. The presence of greenhouse gas (GHG) at the junction of the 2 and 3 quadrants indicates that GHG analysis is becoming more and more important, probably because AD of organic waste results in energy production, lower greenhouse gas emissions, and support for sustainable energy [10]. Gas fuels can provide higher GHG reductions compared to liquid fuels, strengthening the connection between AD and GHG. Based on the research presented above, this paper reviews the fundamental situation of the AD of cellulose waste from four aspects: pretreatment, anaerobic co-digestion, microbial community, and LCA analysis.

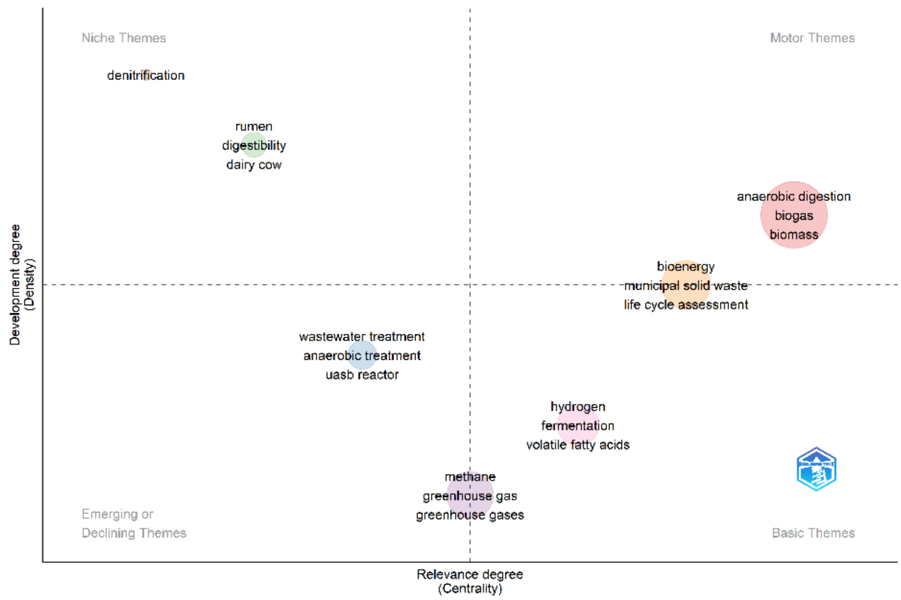

Figure 5. Research trend thematic map based on keyword analysis.

4. Treatment to Improve the Efficiency of AD of Cellulose Waste

4.1. Pretreatment

Hydrolysis of cellulose waste is the rate-limiting step in AD [21]. Pretreatment has gained significant interest as the foremost and most efficient approach for enhancing anaerobic digestion efficiency. The improper selection of conditions may not promote methane production. The common pretreatment methods and their effects are shown in Table 2.

According to the table, the pretreatment methods can be classified into physical pretreatment, chemical pretreatment, and biological pretreatment. The mechanism of physical pretreatment to enhance the methanogenic capacity of cellulose waste varies. Crushing destroys the cell wall of the plant and increases the specific surface area to enhance biodegradability [22]. Microwave, ultrasound, electron beam, and γ-ray can destroy the structure of cellulose. Physical pretreatment stands out for its convenient and straightforward nature. However, physical pretreatment may lead to the loss of components. Microwave and thermal pretreatments may produce furfural, melanoid, and other substances due to the temperature rise, which may inhibit methane production [10,23]. Chemical pretreatment proves to be highly effective. Chemical pretreatment can improve the biodegradability of the waste by breaking chemical bonds or glucoside side chains [11]. Substances from the chemical pretreatment process can also act as catalysts to promote anaerobic digestion [24]. Acids and alkalis are commonly used due to their convenience and ready availability. But they may cause pollution because acid or alkali cannot be recovered [25]. And substrates must be washed after chemical pretreatment [26]. Biological pretreatment has low energy consumption, no pollution, and mild operating conditions [27]. From the perspective of energy, biological pretreatment has advantages [28]. Except for microbial pretreatment, biological pretreatment is time-consuming and expensive, making it unsuitable for industrial applications [11,29].

Single pretreatment methods often exhibit limitations, while the integration of multiple pretreatment techniques can mitigate these drawbacks. Exploring efficient and environmentally friendly pretreatment methods plays an important role in improving methane production. With the widespread dissemination of sustainable development and circular economy principles, the cost and extra energy consumption during the pretreatment process should be taken into account. Exploring cost-effective and high-efficiency pretreatment methods is likely to become a focal point of future research.

Table 2. Common pretreatment methods and their anaerobic digestion effects.

Pretreatment Methods	Substrate	Processing Conditions	Pretreatment Effect	Reference
Mechanical crushing	Rice straw	20, 1, 0.15, 0.075 mm	0.075 mm biogas production is 1.8 times higher than 20 mm	[30]
Ultrasonic	Wheat straw	20 kHz intermittent treatment for 20 min combined with lye immersion	19% increase in methane production	[31]
Microwave	Rice straw	130 °C–230 °C treatment for 1–5 min	Increased methane production potential	[32]
Thermal pretreatment	Rice straw	200 °C–220 °C for 60–240 s steam explosion	Increased by 51% compared with the control group when pretreated at 200 °C for 200 s	[33]
Acid pretreatment	Rice straw	15% wt critic acid	7.40 times compared with the control group	[34]
Alkali pretreatment	Olive pomace	0.03, 0.07, 0.14 g NaOH/2 g olive pomace	Increased by 30%	[35]
Organic solvents	Pinewood, elmwood, and rice straw	75% ethanol with sulfuric acid as catalyst	Increased by 84%, 73%, and 32%	[36]
Oxidizing agent	Rice straw	1–4% H_2O_2 pre-treated at 25 ± 2 °C for 7 days	Increased by 50–120%	[37]
Ionic liquids	Grass	Imidazolium-based ionic liquids	Higher than the control group	[38]
Electrohydrolysis pretreatment	Rice straw	At 25 V DC voltage for 60 min	Increased by 42.4%	[39]
Compost pretreatment	Corn stover	Stack 1 m for pretreatment	Higher than the control group	[40]
Micro-aerobic pretreatment	Rice straw	0, 2, 4, 6, 8 d aeration	Aeration at 35 °C for 2 days has higher methane production	[41]
Ruminal fluid pretreatment	Stems and leaves of rapeseed	9 g rapeseed mixed with 300 mL rumen fluid at 37 °C	1.5 times more than the control group	[42]
Fungal pretreatment	Japanese cedarwood	*Ceriporiopsis subvermispora*	Four times higher than the control	[43]
Enzyme pretreatment	Corn stover	Enzyme loading of 30 FPU/g, pretreatment for 24 h	Increased by 36.9%	[44]
Combined pretreatment method	Mallow	Microwave heating, conventional heating, alkali–heat pretreatment	Microwave heating and alkali combine to produce more biogas	[45]
Combined pretreatment method	Corn stover	Dual frequency ultrasound combined with alkali pre-treatment	Biogas yield increased by 56.6% compared to the group without pretreatment and by 28.2% compared to the alkali pretreatment	[46]
Combined pretreatment method	Soybean straw	Thermal pretreatment combined with different concentrations of H_2O_2 and lye	Thermal pretreatment combined with combined lye and H_2O_2 pretreatment produces more biogas	[47]

4.2. Co-Digestion

The AD of municipal organic solid waste may result in acidification. To prevent acidification, co-digestion can be selected to balance nutrients and improve the buffering capacity [48]. Cellulose waste such as agricultural waste often exhibits a high C/N ratio, so the degradation rate is usually slow, and the stability of the system is poor when AD is conducted in isolation. Co-digestion can not only improve the process stability by regulating the C/N ratio but also reduce the cost of biogas purification and fermentation residue processing [49,50]. The most common substrates for co-digestion are food waste, livestock manure, and sludge.

The production of food waste is increasing annually, and improper management may result in significant environmental issues [51,52]. Food waste has a high water content and low C/N ratio, making it prone to acidification [53–55]. The co-digestion of food waste and cellulose waste can achieve multiple synergistic effects [56], increase the diversity of methanogenic pathways, and improve methane production. The results of the mono-digestion and co-digestion of AD of corn stover and food waste by Zhang et al. showed that the cumulative methane production at the end of fermentation was increased by 18.5% [57].

The annual production of livestock manure is approximately 3.8 billion tons [4]. The large amount of manure has prompted an urgent need for its disposal. Pig manure is a nitrogen-rich feedstock. Mixing pig manure with rice straw can balance the C/N ratio in the system, thus increasing the production of hydrogen and methane [58–60]. Silvestre et al. conducted the co-digestion of cattle manure and rice straw, and the results showed that the biogas production increased by 4%, 28%, and 54% when rice straw was added to cattle manure at 1%, 2%, and 5%, respectively [61].

In 2020–2025, sludge production is expected to exceed 65 million tons/year, and its low C/N results in low methane production and slow hydrolysis rates when digested alone [62]. Co-digestion can overcome the shortcomings of the single digestion of sewage sludge and can increase methane production. Chu investigated the performance of the dry anaerobic co-digestion of sewage sludge and rice straw, and the results showed that rice straw can be used as a carbon source, thus increasing methane production [63]. Prajapati et al. conducted the co-digestion of sewage sludge and wheat straw under mesophilic and thermophilic conditions and found that co-digestion increased the cumulative biogas production by 6.92 and 5.69 times, respectively [64].

AD is critical for climate change mitigation and energy security. Combined heat and power (CHP) as a way to meet emissions reduction targets and achieve profitable production of biogas is driving the growing demand for co-digestion. Co-digestion may increase transportation costs because substrates need to be transported to anaerobic digestion plants. Li et al. found that the solid-state AD of binary waste from dairy manure and corn stover was less economically attractive under CHP conditions [65]. Meanwhile, the solid-state AD of ternary mixtures under the CHP pathway has a higher net present value (NPV) and internal rate of return (IRR). The AD of ternary mixtures may be economical and efficient. Li et al. studied the solid AD of cow manure, corn stover, and tomato residue and found that the addition of 20% and 40% tomato residue increased the methane production by 30.2% and 46.8%, respectively, compared with the binary co-digestion of cow manure and corn stover. They achieved a short payback period and high methane yield [66].

The application of anaerobic co-digestion and CHP may become widespread with increasing waste production. Perhaps the co-digestion of multiple wastes will be extensively studied in the future. The cost and environmental impact of multi-feedstock co-digestion must be thoroughly considered for sustainable development. Careful selection of feedstock and mixing ratios in the co-digestion of multiple wastes is necessary to enhance methane production and economic viability while mitigating adverse environmental impacts [67].

4.3. Microbial Community

AD is a complex, multi-process metabolic pathway carried out by various microorganisms acting together in an anaerobic environment [68]. With the development of molecular biology technology, increasing studies on microbial community structure are being conducted. The microorganisms of the AD process are often divided into bacteria and archaea [69].

4.3.1. Bacterial Community

Bacteria play an important role in the hydrolysis and acidification phase. The hydrolysis and acidification process involves 20–30 species of microorganisms [70]. The most common bacteria at the phylum level in AD are *Firmicutes* and *Bacteroidetes* [71]; *Bacteroidetes* are especially common in the anaerobic treatment of cellulose waste [72].

Pretreatment plays an important role in improving the efficiency of AD. Pretreatment may affect the abundance of specific bacteria, thus affecting the hydrolysis and acidification process. Zou et al. found that *Bacteroidete* was enriched in corncob AD, and the abundance of *Prevotella*, which plays an important role in the degradation of fibrous matter, was increased after pretreatment with food waste [73]. *Bacillus* is important for lignocellulose degradation. Wang et al. studied the effect of anaerobic and micro-aerobic pretreatment on the AD of giant grass and found that the anaerobic conditions in liquid inoculant pretreatment enriched the abundance of *Bacillus* more than the microaerobic conditions, thus improving the gas production in liquid inoculant anaerobic pretreatment [74].

There are two possible mechanisms for co-digestion to promote AD. One is to promote direct interspecies electron transfer (DIET) for AD, and the other is to enhance the hydrolytic acidification process. Zhang et al. studied the co-digestion of sorghum vinegar residue and livestock manure and observed that the addition of livestock manure could increase the relative abundance of *Syntrophomonas* and *Petrimonas* [75]. *Syntrophomonas* is an important hydrogen- and acetic acid-producing bacterium. The DIET between *Syntrophomonas* and *Methanosaeta* can effectively promote methane production [76]. The study on the co-digestion of waste paper and food waste carried out by Li revealed that the hydrolytic bacterial community gradually changed from carbohydrate/protein-degrading bacteria to cellulose-degrading bacteria as the proportion of waste paper increased, and the carbohydrate content increased greatly [77]. The same results were observed in Zhu's research on waste paper and sludge [78].

4.3.2. Methanogenic Archaeal Community

Methanogenic archaea can convert the products of the hydrolytic acidification stage into methane. The archaeal community is relatively simple compared with the bacterial community. More than 10–20 anaerobic methanogenic microorganisms are often involved in the AD methanogenesis process [70]. Common acetoclastic methanogens include *Methanosaeta*, *Methanosarcina,* and *Methanothrix*. Common hydrogenotrophic methanogens include *Methanobacterium*, *Methanothermobacter,* and *Methanospirillum*.

Pretreatment mainly acts on the hydrolytic acidification stage of AD. Thus, the effect on methanogenic bacteria is not as obvious as that on bacteria. Pretreatment has a great impact on the hydrolytic acidification process, resulting in a variable environment and increased hydrolysis products in the reactor. Hydrogenotrophic methanogens may be tolerant to environmental changes. Therefore, the accumulation of hydrogenotrophic methanogens is often observed [76]. Ma et al. combined CO_2 with biogas slurry to pretreat corn straw and found that the pretreatment increased the cumulative methane yield, which increased by 50.97% compared with the untreated group. Meanwhile, the abundance of *Methanobacterium* increased by 25.04% [79]. Wang et al. performed a study on giant grass pretreatment, and they found that a higher abundance of hydrogenotrophic methanogens was also observed in the group with higher gas production in the liquid inoculant pretreatment [74].

Co-digested substrates have significant effects on archaeal communities. Song et al. studied the co-digestion of food waste, tofu residue, and garden waste and found that an increase in the proportion of garden waste would lead to an increase in the abundance of *Methanosaeta* [80]. Wang et al. conducted a ternary co-digestion study and found that when the proportion of pig manure was constant, the abundance of Methanosaeta and

Methanospirillum would increase with the increase in the proportion of cucumber [81]. *Methanosaeta* is a bacterium that stably produces methanogens at low acetic acid concentrations. In the study of Song and Wang, the enrichment of *Firmicutes* was also observed [80,81]. Therefore, co-digestion may promote methane production by promoting metabolic matching between hydrolytic bacteria and methanogens. In the study of co-digestion of waste paper and other wastes by Li et al. and Zhu et al. [77,78], it was found that the addition of waste paper may lead to an increase in the community of hydrogenotrophic methanogens such as *Methanothermobacter*. Therefore, the mechanism of promoting AD may also have hydrogenotrophic methanogenic pathways promoted by the elevated abundance of hydrogenotrophic methanogens.

4.3.3. Effect of Changing Environmental Conditions on Microbial Communities

Environmental conditions as an important factor affecting microbial growth have been increasingly studied in recent years to characterize microbial communities under different environmental conditions.

Temperature is one of the important causes of changes in microbial communities. Liu et al. conducted the AD of corn stover at temperatures of 35 °C, 38 °C, 41 °C, and 44 °C and found that the abundance of Firmicutes gradually increased with the increase in temperature, and the ratio of Firmicutes to Bacteroidetes changed greatly. The role of hydrogenotrophic methanogens increases with the temperature, revealing the internal reason for increased temperature to promote AD [82].

Usman et al. performed AD at different ammonia concentrations and their results showed that the alpha diversity of different communities decreased with the increase in ammonia concentration, indicating that ammonia could inhibit microbial growth to affect the AD efficiency. The presence of ammonia nitrogen affects the growth of microorganisms [83].

The addition of trace elements can provide the necessary nutrients for the growth of microorganisms [84]. Wei et al. supplemented the anaerobic co-digestion of corn stover and chicken manure with trace elements, and the results indicated that the addition of trace elements can change the microbial community structure and affect the digestion performance [85]. However, we should pay attention to the amount and element type when adding trace elements; otherwise, the changes in the microbial community may not promote AD.

The increase in methane production is usually accompanied by an increased abundance of bacterial and archaeal communities. The analysis of the microbial community during AD can help elucidate the relationship between the community structure and the microbial function. Few studies have been conducted to modulate the microbial community to produce specific AD results [86]. The targeted modulation through the use of functional microorganisms has the potential to significantly enhance anaerobic digestion efficiency and may indeed represent a prospective avenue for future research in this field.

4.4. LCA

LCA can be used to evaluate the environmental sustainability of biogas production [87]. LCA can analyze the inputs, outputs, and potential environmental impacts of AD systems throughout their life cycles [88,89]. Research on LCA has previously concentrated on the assessment of different waste treatment strategies. Wang et al. compared the LCA of producing bioethanol, recycling, and incineration of waste paper and found that bioethanol offered great environmental benefits [90]. However, it's important to note that different pretreatment methods can have varying environmental impacts. Khoshnevisan et al. found that the steam thermal pretreatment procedure has more negative environmental effects than NMMO [88]. De Vries et al. evaluated the LCA results of co-digestion of pig manure with various substrates and discovered that co-digestion with weeds had better environmental performance than co-digestion with maize silage and sugar beet residue [91]. Pehme et al. discovered that AD of manure had fewer negative environmental effects than conventional treatment, but that co-digestion of manure with planted grasses was associated with stronger global warming trends and nitrogen eutrophication than co-digestion of manure with natural grasses [92]. Quantitative and direct comparison of different LCA results is challenging due to the diversity of system boundaries, assumptions, and methods [93]. In the future, the further development of standardized LCA analysis methods may promote the development of LCA analysis, making results more comparable.

The cradle-to-gate approach encompasses feedstock to biogas production, while cradle-to-grave covers the biogas utilization phase [87]. The effective use of biogas by-products is a critical component of the cradle-to-grave approach as biogas by-products are considered essential for sustainable development. The major ways that biogas by-products are now effectively used are as fertilizer feed, materials, and biopesticides, all of which help to lessen the harmful effects of AD on the environment. Biogas slurry is rich in nitrogen, phosphorus, potassium nutrients, and trace elements [94–97], so it can be used for the production of fertilizer, insect or aquatic feed, and biochar, thereby increasing the resource efficiency of waste and reducing the negative impact on the environment to achieve sustainable development. Biogas slurry and biogas residue can be used as fertilizer for fruit and vegetable planting, which can effectively improve the ability of crops to resist pests and diseases and the yield and quality of crops and reduce the cost of planting crops [98–101]. Microalgae can also be used to produce bioenergy and power [102–104]. Feeding digestate as feed to microalgae reduces the cost of feed and gives a higher protein content [105]. Biochar can be used as fuel, adsorbent, and soil conditioner and has good application prospects [106]. The production of biochar from digestate can be used to purify wastewater [107,108]. Dicke et al. used hydrothermal charcoal prepared from wheat straw digestate and applied it to soil and found that it improved carbon and nitrogen stability and reduced greenhouse gas emissions such as N_2O and CO_2 [109]. Biogas contains many organic acids as well as gibberellins, vitamin B, indole acetic acid, ammonia, and ammonium salts, and the presence of microorganisms makes it possible to use biogas for the control of many pests and diseases in fruit and vegetable crops [110–113]. However, it is important to note that the presence of antibiotics, heavy metals, and salts in AD residues may accumulate in the soil and food chain, causing harm to the environment [114].

5. Conclusions

Cellulose waste is considered an excellent substrate for AD, due to its high organic content and methane production potential. This review presents a statistical analysis of research trends in the AD of cellulose waste in 2002–2021 using a bibliometric method. The results show that the overall research related to the AD of cellulose waste is increasing. Pretreatment, co-digestion, microbial communities, and LCA analysis of cellulose waste are hotspots of research. One of the trends for future research to assist AD may be the employment of appropriate environmental conditions and integrated treatment techniques. Co-digestion facilitates AD by adjusting the C/N ratio to enhance system stability, but the cost implications of the co-digestion process may lead to an increase in research into multi-waste co-digestion. LCA analysis is crucial for determining if AD is environmentally sustainable, and the research on LCA in developing countries is becoming increasingly specific.

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References

1. Top Countries in Paperboard and Packaging Paper Production. Available online: https://www.nationmaster.com/nmx/ranking/paperboard-and-packaging-paper-production (accessed on 20 October 2021).
2. The Main by-Products of Rice Are Rice Straw, Rice Husk or Hull, and Rice Bran. Available online: http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products (accessed on 6 June 2022).
3. Chen, B.; Mohrmann, S.; Li, H.; Gaff, M.; Lorenzo, R.; Corbi, I.; Corbi, O.; Fang, K.; Li, M. Research and Application Progress of Straw. *J. Renew. Mater.* **2023**, *11*, 599–623. [CrossRef]
4. Xu, M.; Yang, M.; Xie, D.; Ni, J.; Meng, J.; Wang, Q.; Gao, M.; Wu, C. Research trend analysis of composting based on Web of Science database. *Environ. Sci. Pollut. Res.* **2021**, *28*, 59528–59541. [CrossRef] [PubMed]
5. Gao, Z.; Ma, Y.; Liu, Y.; Wang, Q. Waste cooking oil used as carbon source for microbial lipid production: Promoter or inhibitor. *Environ. Res.* **2022**, *203*, 111881. [CrossRef] [PubMed]
6. Liu, Q.; Wang, X.; Gao, M.; Guan, Y.; Wu, C.; Wang, Q.; Rao, Y.; Liu, S. Heavy metal leaching behaviour and long-term environmental risk assessment of cement-solidified municipal solid waste incineration fly ash in sanitary landfill. *Chemosphere* **2022**, *300*, 134571. [CrossRef]
7. Song, C.; Li, W.; Cai, F.; Liu, G.; Chen, C. Anaerobic and Microaerobic Pretreatment for Improving Methane Production from Paper Waste in Anaerobic Digestion. *Front. Microbiol.* **2021**, *12*, 688290. [CrossRef]
8. Guo, M.; Song, W.; Buhain, J. Bioenergy and biofuels: History, status, and perspective. *Renew. Sustain. Energy Rev.* **2015**, *42*, 712–725. [CrossRef]
9. Fauzi, M.A.; Abidin, N.H.Z.; Omer, M.M.; Kineber, A.F.; Rahman, A.R.A. Role of sustainable development goals in advancing the circular economy: A state-of-the-art review on past, present and future directions. *Waste Manag. Res.* **2023**, 0734242X231196765. [CrossRef]
10. Xi, Y.; Liu, Y.; Ye, X.; Du, J.; Kong, X.; Guo, D.; Xiao, Q. Enhanced Anaerobic Biogas Production from Wheat Straw by Herbal-Extraction Process Residues Supplementation. *Front. Bioeng. Biotechnol.* **2021**, *9*, 623594. [CrossRef]
11. Hendriks, A.; Zeeman, G. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour. Technol.* **2009**, *100*, 10–18. [CrossRef]
12. Mothe, S.; Polisetty, V.R. Review on anaerobic digestion of rice straw for biogas production. *Environ. Sci. Pollut. Res.* **2020**, *28*, 24455–24469. [CrossRef]
13. Fauzi, M.A.; Nguyen, M.; Malik, A. Knowledge sharing and theory of planned behavior: A bibliometric analysis. *J. Knowl. Manag.* **2023**. *ahead-of-print*. [CrossRef]
14. Ho, Y.-S. The top-cited research works in the Science Citation Index Expanded. *Scientometrics* **2013**, *94*, 1297–1312. [CrossRef]
15. Mao, N.; Wang, M.-H.; Ho, Y.-S. A Bibliometric Study of the Trend in Articles Related to Risk Assessment Published inScience Citation Index. *Hum. Ecol. Risk Assess. Int. J.* **2010**, *16*, 801–824. [CrossRef]
16. Current and Planned Joint Actions within UN-Energy. Available online: https://www.un.org/chinese/esa/energy/background.shtml (accessed on 16 March 2022).
17. Notice of the State Council on the Issuance of the 12th Five-Year Plan for Energy Development. Available online: http://www.gov.cn/zwgk/2013-01/23/content_2318554.htm (accessed on 16 March 2022). (In Chinese)
18. Notice on the Publication of the 13th Five-Year Plan for Ecological and Environmental Protection. Available online: http://www.gov.cn/zhengce/content/2016-12/05/content_5143290.htm (accessed on 16 March 2022). (In Chinese)
19. Notice of the State Council on the Issuance of the 14th Five-Year Plan for Energy Conservation and Emission Reduction. Available online: http://www.gov.cn/zhengce/content/2022-01/24/content_5670202.htm (accessed on 16 March 2022). (In Chinese)
20. Ye, N.; Kueh, T.-B.; Hou, L.; Liu, Y.; Yu, H. A bibliometric analysis of corporate social responsibility in sustainable development. *J. Clean. Prod.* **2020**, *272*, 122679. [CrossRef]
21. Cirne, D.; Lehtomäki, A.; Björnsson, L.; Blackall, L. Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops. *J. Appl. Microbiol.* **2007**, *103*, 516–527. [CrossRef]
22. Mshandete, A.; Björnsson, L.; Kivaisi, A.K.; Rubindamayugi, M.; Mattiasson, B. Effect of particle size on biogas yield from sisal fibre waste. *Renew. Energy* **2006**, *31*, 2385–2392. [CrossRef]
23. Sapci, Z. The effect of microwave pretreatment on biogas production from agricultural straws. *Bioresour. Technol.* **2013**, *128*, 487–494. [CrossRef]
24. Duff, S.J.; Murray, W.D. Bioconversion of forest products industry waste cellulosics to fuel ethanol: A review. *Bioresour. Technol.* **1996**, *55*, 1–33. [CrossRef]
25. Behera, S.; Arora, R.; Nandhagopal, N.; Kumar, S. Importance of chemical pretreatment for bioconversion of lignocellulosic biomass. *Renew. Sustain. Energy Rev.* **2014**, *36*, 91–106. [CrossRef]
26. Kaur, K.; Phutela, U.G. Enhancement of paddy straw digestibility and biogas production by sodium hydroxide-microwave pretreatment. *Renew. Energy* **2016**, *92*, 178–184. [CrossRef]

27. Shrestha, S.; Fonoll, X.; Khanal, S.K.; Raskin, L. Biological strategies for enhanced hydrolysis of lignocellulosic biomass during anaerobic digestion: Current status and future perspectives. *Bioresour. Technol.* **2017**, *245*, 1245–1257. [CrossRef]
28. Battista, F.; Bolzonella, D. Some critical aspects of the enzymatic hydrolysis at high dry-matter content: A review. *Biofuels Bioprod. Biorefin.* **2018**, *12*, 711–723. [CrossRef]
29. Peng, J.; Abomohra, A.E.-F.; Elsayed, M.; Zhang, X.; Fan, Q.; Ai, P. Compositional changes of rice straw fibers after pretreatment with diluted acetic acid: Towards enhanced biomethane production. *J. Clean. Prod.* **2019**, *230*, 775–782. [CrossRef]
30. Dai, X.; Hua, Y.; Dai, L.; Cai, C. Particle size reduction of rice straw enhances methane production under anaerobic digestion. *Bioresour. Technol.* **2019**, *293*, 122043. [CrossRef]
31. Wahid, R.; Romero-Guiza, M.; Moset, V.; Møller, H.B.; Fernández, B. Improved anaerobic biodegradability of wheat straw, solid cattle manure and solid slaughterhouse by alkali, ultrasonic and alkali-ultrasonic pre-treatment. *Environ. Technol.* **2020**, *41*, 997–1006. [CrossRef] [PubMed]
32. Kainthola, J.; Shariq, M.; Kalamdhad, A.S.; Goud, V.V. Enhanced methane potential of rice straw with microwave assisted pretreatment and its kinetic analysis. *J. Environ. Manag.* **2019**, *232*, 188–196. [CrossRef]
33. Zhou, J.; Yan, B.H.; Wang, Y.; Yong, X.Y.; Yang, Z.H.; Jia, H.H.; Jiang, M.; Wei, P. Effect of steam explosion pretreatment on the anaerobic digestion of rice straw. *RSC Adv.* **2016**, *6*, 88417–88425. [CrossRef]
34. Amnuaycheewa, P.; Hengaroonprasan, R.; Rattanaporn, K.; Kirdponpattara, S.; Cheenkachorn, K.; Sriariyanun, M. Enhancing enzymatic hydrolysis and biogas production from rice straw by pretreatment with organic acids. *Ind. Crop. Prod.* **2016**, *87*, 247–254. [CrossRef]
35. Elalami, D.; Carrere, H.; Abdelouahdi, K.; Garcia-Bernet, D.; Peydecastaing, J.; Vaca-Medina, G.; Oukarroum, A.; Zeroual, Y.; Barakat, A. Mild microwaves, ultrasonic and alkaline pretreatments for improving methane production: Impact on biochemical and structural properties of olive pomace. *Bioresour. Technol.* **2020**, *299*, 122591. [CrossRef]
36. Mirmohamadsadeghi, S.; Karimi, K.; Zamani, A.; Amiri, H.; Horváth, I.S. Enhanced Solid-State Biogas Production from Lignocellulosic Biomass by Organosolv Pretreatment. *BioMed Res. Int.* **2014**, *2014*, 350414. [CrossRef]
37. Song, Z.; Yang, G.; Guo, Y.; Zhang, T. Comparison of two chemical pretreatments of rice straw for biogas production by anaerobic digestion. *BioResources* **2012**, *7*, 3223–3236. [CrossRef]
38. Li, W.; Xu, G. Enhancement of anaerobic digestion of grass by pretreatment with imidazolium-based ionic liquids. *Environ. Technol.* **2016**, *38*, 1843–1851. [CrossRef] [PubMed]
39. Kainthola, J.; Shariq, M.; Kalamdhad, A.S.; Goud, V.V. Electrohydrolysis pretreatment methods to enhance the methane production from anaerobic digestion of rice straw using graphite electrode. *Renew. Energy* **2019**, *142*, 1–10. [CrossRef]
40. Zhou, S.; Zhang, Y.; Dong, Y. Pretreatment for biogas production by anaerobic fermentation of mixed corn stover and cow dung. *Energy* **2012**, *46*, 644–648. [CrossRef]
41. Zhou, Y.; Li, C.; Nges, I.A.; Liu, J. The effects of pre-aeration and inoculation on solid-state anaerobic digestion of rice straw. *Bioresour. Technol.* **2017**, *224*, 78–86. [CrossRef]
42. Baba, Y.; Matsuki, Y.; Mori, Y.; Suyama, Y.; Tada, C.; Fukuda, Y.; Saito, M.; Nakai, Y. Pretreatment of lignocellulosic biomass by cattle rumen fluid for methane production: Bacterial flora and enzyme activity analysis. *J. Biosci. Bioeng.* **2017**, *123*, 489–496. [CrossRef]
43. Amirta, R.; Tanabe, T.; Watanabe, T.; Honda, Y.; Kuwahara, M.; Watanabe, T. Methane fermentation of Japanese cedar wood pretreated with a white rot fungus, Ceriporiopsis subvermispora. *J. Biotechnol.* **2006**, *123*, 71–77. [CrossRef]
44. Wang, S.; Li, F.; Wu, D.; Zhang, P.; Wang, H.; Tao, X.; Ye, J.; Nabi, M. Enzyme Pretreatment Enhancing Biogas Yield from Corn Stover: Feasibility, Optimization, and Mechanism Analysis. *J. Agric. Food Chem.* **2018**, *66*, 10026–10032. [CrossRef]
45. Nowicka, A.; Zieliński, M.; Dębowski, M.; Dudek, M.; Rusanowska, P. Progress in the production of biogas from Virginia mallow after alkaline-heat pretreatment. *Biomass-Bioenergy* **2019**, *126*, 174–180. [CrossRef]
46. Dong, C.; Chen, J.; Guan, R.; Li, X.; Xin, Y. Dual-frequency ultrasound combined with alkali pretreatment of corn stalk for enhanced biogas production. *Renew. Energy* **2018**, *127*, 444–451. [CrossRef]
47. Xiong, J.; Hassan, M.; Wang, W.; Ding, W. Methane enhancement by the co-digestion of soybean straw and farm wastewater under different thermo-chemical pretreatments. *Renew. Energy* **2020**, *145*, 116–123. [CrossRef]
48. Wang, Y.; Yang, L.; Li, Y.; Fu, L.; Yuan, C.; Yao, L.; Luo, J. Reactor performance and economic evaluation of singular, binary, and ternary mixing of feedstocks for anaerobic digestion. *Environ. Technol.* **2021**, *42*, 318–328. [CrossRef] [PubMed]
49. Kapoor, R.; Ghosh, P.; Kumar, M.; Sengupta, S.; Gupta, A.; Kumar, S.S.; Vijay, V.; Kumar, V.; Vijay, V.K.; Pant, D. Valorization of agricultural waste for biogas based circular economy in India: A research outlook. *Bioresour. Technol.* **2020**, *304*, 123036. [CrossRef]
50. Henard, C.A.; Smith, H.K.; Guarnieri, M.T. Phosphoketolase overexpression increases biomass and lipid yield from methane in an obligate methanotrophic biocatalyst. *Metab. Eng.* **2017**, *41*, 152–158. [CrossRef]
51. Ma, X.; Gao, M.; Liu, S.; Li, Y.; Sun, X.; Wang, Q. An innovative approach for reducing the water and alkali consumption in the lactic acid fermentation via the reuse of pretreated liquid. *Bioresour. Technol.* **2020**, *352*, 127108. [CrossRef]
52. Zhang, S.; Guan, W.; Sun, H.; Zhao, P.; Wang, W.; Gao, M.; Sun, X.; Wang, Q. Intermittent energization improves microbial electrolysis cell-assisted thermophilic anaerobic co-digestion of food waste and spent mushroom substance. *Bioresour. Technol.* **2023**, *370*, 128577. [CrossRef]
53. Zala, M.; Solanki, R.; Bhale, P.V.; Vaishak, S. Experimental investigation on anaerobic co-digestion of food waste and water hyacinth in batch type reactor under mesophilic condition. *Biomass Convers. Biorefin.* **2019**, *10*, 707–714. [CrossRef]

54. Ma, X.; Gao, M.; Wang, N.; Liu, S.; Wang, Q.; Sun, X. Lactic acid production from co-fermentation of food waste and spent mushroom substance with Aspergillus niger cellulase. *Bioresour. Technol.* **2021**, *337*, 125365. [CrossRef]
55. Kawai, M.; Nagao, N.; Tajima, N.; Niwa, C.; Matsuyama, T.; Toda, T. The effect of the labile organic fraction in food waste and the substrate/inoculum ratio on anaerobic digestion for a reliable methane yield. *Bioresour. Technol.* **2014**, *157*, 174–180. [CrossRef]
56. Zhang, W.; Kong, T.; Xing, W.; Li, R.; Yang, T.; Yao, N.; Lv, D. Links between carbon/nitrogen ratio, synergy and microbial characteristics of long-term semi-continuous anaerobic co-digestion of food waste, cattle manure and corn straw. *Bioresour. Technol.* **2022**, *343*, 126094. [CrossRef]
57. Zhang, W.; Wang, X.; Xing, W.; Li, R.; Yang, T.; Yao, N.; Lv, D. Links between synergistic effects and microbial community characteristics of anaerobic co-digestion of food waste, cattle manure and corn straw. *Bioresour. Technol.* **2021**, *329*, 124919. [CrossRef] [PubMed]
58. Li, D.; Liu, S.; Mi, L.; Li, Z.; Yuan, Y.; Yan, Z.; Liu, X. Effects of feedstock ratio and organic loading rate on the anaerobic mesophilic co-digestion of rice straw and pig manure. *Bioresour. Technol.* **2015**, *187*, 120–127. [CrossRef] [PubMed]
59. Chen, H.; Huang, R.; Wu, J.; Zhang, W.; Han, Y.; Xiao, B.; Wang, D.; Zhou, Y.; Liu, B.; Yu, G. Biohythane production and microbial characteristics of two alternating mesophilic and thermophilic two-stage anaerobic co-digesters fed with rice straw and pig manure. *Bioresour. Technol.* **2021**, *320*, 124303. [CrossRef] [PubMed]
60. Liu, R.; Chen, X.; Zhang, K.; Han, Y.; Tong, Y.; Wang, J.; Xiao, B.; Liu, J. Effect of mixing ratio and total solids content on temperature-phased anaerobic codigestion of rice straw and pig manure: Biohythane production and microbial structure. *Bioresour. Technol.* **2022**, *344*, 126173. [CrossRef]
61. Silvestre, G.; Gómez, M.P.; Pascual, A.; Ruiz, B. Anaerobic co-digestion of cattle manure with rice straw: Economic & energy feasibility. *Water Sci. Technol.* **2013**, *67*, 745–755. [CrossRef]
62. Elsayed, M.; Andres, Y.; Blel, W.; Gad, A.; Ahmed, A. Effect of VS organic loads and buckwheat husk on methane production by anaerobic co-digestion of primary sludge and wheat straw. *Energy Convers. Manag.* **2016**, *117*, 538–547. [CrossRef]
63. Chu, X.; Wu, G.; Wang, J.; Hu, Z.-H. Dry co-digestion of sewage sludge and rice straw under mesophilic and thermophilic anaerobic conditions. *Environ. Sci. Pollut. Res.* **2015**, *22*, 20143–20153. [CrossRef]
64. Prajapati, K.B.; Singh, R. Co-digestion of sewage sludge and wheat straw in presence of iron scraps in mesophilic and thermophilic conditions for generating methane. *Biomass-Convers. Biorefin.* **2022**, 1–12. [CrossRef]
65. Li, Y.; Han, Y.; Zhang, Y.; Luo, W.; Li, G. Anaerobic digestion of different agricultural wastes: A techno-economic assessment. *Bioresour. Technol.* **2020**, *315*, 123836. [CrossRef]
66. Li, Y.; Xu, F.; Li, Y.; Lu, J.; Li, S.; Shah, A.; Zhang, X.; Zhang, H.; Gong, X.; Li, G. Reactor performance and energy analysis of solid state anaerobic co-digestion of dairy manure with corn stover and tomato residues. *Waste Manag.* **2018**, *73*, 130–139. [CrossRef]
67. Siddique, N.I.; Wahid, Z.A. Achievements and perspectives of anaerobic co-digestion: A review. *J. Clean. Prod.* **2018**, *194*, 359–371. [CrossRef]
68. Theuerl, S.; Klang, J.; Prochnow, A. Process Disturbances in Agricultural Biogas Production—Causes, Mechanisms and Effects on the Biogas Microbiome: A Review. *Energies* **2019**, *12*, 365. [CrossRef]
69. Mata-Alvarez, J.; Dosta, J.; Romero-Güiza, M.; Fonoll, X.; Peces, M.; Astals, S. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renew. Sustain. Energy Rev.* **2014**, *36*, 412–427. [CrossRef]
70. Ma, G.; Chen, Y.; Ndegwa, P. Association between methane yield and microbiota abundance in the anaerobic digestion process: A meta-regression. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110212. [CrossRef]
71. Calabrò, P.S.; Fazzino, F.; Folino, A.; Scibetta, S.; Sidari, R. Improvement of semi-continuous anaerobic digestion of pre-treated orange peel waste by the combined use of zero valent iron and granular activated carbon. *Biomass Bioenergy* **2019**, *129*, 105337. [CrossRef]
72. Schellenberger, S.; Kolb, S.; Drake, H.L. Metabolic responses of novel cellulolytic and saccharolytic agricultural soil Bacteria to oxygen. *Environ. Microbiol.* **2010**, *12*, 845–861. [CrossRef]
73. Zou, H.; Jiang, Q.; Zhu, R.; Chen, Y.; Sun, T.; Li, M.; Zhai, J.; Shi, D.; Ai, H.; Gu, L.; et al. Enhanced hydrolysis of lignocellulose in corn cob by using food waste pretreatment to improve anaerobic digestion performance. *J. Environ. Manag.* **2020**, *254*, 109830. [CrossRef]
74. Wang, L.; Liu, C.; Wei, B.; Song, C.; Cai, F.; Liu, G.; Chen, C. Effects of different microbial pretreatments on the anaerobic digestion of giant grass under anaerobic and microaerobic conditions. *Bioresour. Technol.* **2021**, *337*, 125456. [CrossRef]
75. Zhang, J.; Qi, C.; Wang, Y.; Li, Y.; Han, T.; Gong, X.; Shan, M.; Li, G.; Luo, W. Enhancing biogas production from livestock manure in solid-state anaerobic digestion by sorghum-vinegar residues. *Environ. Technol. Innov.* **2022**, *26*, 102276. [CrossRef]
76. Zhang, S.; Ma, X.; Xie, D.; Guan, W.; Yang, M.; Zhao, P.; Gao, M.; Wang, Q.; Wu, C. Adding activated carbon to the system with added zero-valent iron further improves anaerobic digestion performance by alleviating ammonia inhibition and promoting DIET. *J. Environ. Chem. Eng.* **2021**, *9*, 106616. [CrossRef]
77. Li, L.; Qin, Y.; Kong, Z.; Wu, J.; Kubota, K.; Li, Y.-Y. Characterization of microbial community and main functional groups of prokaryotes in thermophilic anaerobic co-digestion of food waste and paper waste. *Sci. Total. Environ.* **2019**, *652*, 709–717. [CrossRef] [PubMed]
78. Zhu, A.; Qin, Y.; Wu, J.; Ye, M.; Li, Y.-Y. Characterization of biogas production and microbial community in thermophilic anaerobic co-digestion of sewage sludge and paper waste. *Bioresour. Technol.* **2021**, *337*, 125371. [CrossRef] [PubMed]

79. Ma, S.; Wang, H.; Wang, B.; Gu, X.; Zhu, W. Biomethane enhancement from corn straw using anaerobic digestion by-products as pretreatment agents: A highly effective and green strategy. *Bioresour. Technol.* **2022**, *344*, 126177. [CrossRef] [PubMed]
80. Song, Y.; Meng, S.; Chen, G.; Yan, B.; Zhang, Y.; Tao, J.; Li, Y.; Li, J. Co-digestion of garden waste, food waste, and tofu residue: Effects of mixing ratio on methane production and microbial community structure. *J. Environ. Chem. Eng.* **2021**, *9*, 105901. [CrossRef]
81. Wang, Y.; Li, G.; Chi, M.; Sun, Y.; Zhang, J.; Jiang, S.; Cui, Z. Effects of co-digestion of cucumber residues to corn stover and pig manure ratio on methane production in solid state anaerobic digestion. *Bioresour. Technol.* **2018**, *250*, 328–336. [CrossRef]
82. Liu, C.; Wachemo, A.C.; Tong, H.; Shi, S.; Zhang, L.; Yuan, H.; Li, X. Biogas production and microbial community properties during anaerobic digestion of corn stover at different temperatures. *Bioresour. Technol.* **2018**, *261*, 93–103. [CrossRef]
83. Usman, M.; Shi, Z.; Ji, M.; Ren, S.; Luo, G.; Zhang, S. Microbial insights towards understanding the role of hydrochar in alleviating ammonia inhibition during anaerobic digestion. *Chem. Eng. J.* **2021**, *419*, 129541. [CrossRef]
84. Zhang, S.; Ren, Y.; Ma, X.; Guan, W.; Gao, M.; Li, Y.-Y.; Wang, Q.; Wu, C. Effect of zero-valent iron addition on the biogas fermentation of food waste after anaerobic preservation. *J. Environ. Chem. Eng.* **2021**, *9*, 106013. [CrossRef]
85. Wei, Y.; Li, Z.; Ran, W.; Yuan, H.; Li, X. Performance and microbial community dynamics in anaerobic co-digestion of chicken manure and corn stover with different modification methods and trace element supplementation strategy. *Bioresour. Technol.* **2021**, *325*, 124713. [CrossRef]
86. Ren, Y.; Yu, M.; Wu, C.; Wang, Q.; Gao, M.; Huang, Q.; Liu, Y. A comprehensive review on food waste anaerobic digestion: Research updates and tendencies. *Bioresour. Technol.* **2018**, *247*, 1069–1076. [CrossRef]
87. Aziz, N.I.H.A.; Hanafiah, M.M.; Gheewala, S.H. A review on life cycle assessment of biogas production: Challenges and future perspectives in Malaysia. *Biomass Bioenergy* **2019**, *122*, 361–374. [CrossRef]
88. Khoshnevisan, B.; Shafiei, M.; Rajaeifar, M.A.; Tabatabaei, M. Biogas and bioethanol production from pinewood pre-treated with steam explosion and N-methylmorpholine-N-oxide (NMMO): A comparative life cycle assessment approach. *Energy* **2016**, *114*, 935–950. [CrossRef]
89. Khoshnevisan, B.; Rafiee, S.; Omid, M.; Mousazadeh, H.; Clark, S. Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. *J. Clean. Prod.* **2014**, *73*, 183–192. [CrossRef]
90. Wang, L.; Templer, R.; Murphy, R.J. A Life Cycle Assessment (LCA) comparison of three management options for waste papers: Bioethanol production, recycling and incineration with energy recovery. *Bioresour. Technol.* **2012**, *120*, 89–98. [CrossRef] [PubMed]
91. De Vries, J.; Vinken, T.; Hamelin, L.; De Boer, I. Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy—A life cycle perspective. *Bioresour. Technol.* **2012**, *125*, 239–248. [CrossRef]
92. Pehme, S.; Veromann, E.; Hamelin, L. Environmental performance of manure co-digestion with natural and cultivated grass—A consequential life cycle assessment. *J. Clean. Prod.* **2017**, *162*, 1135–1143. [CrossRef]
93. Fei, X.; Jia, W.; Chen, T.; Ling, Y. Life-cycle assessment of two food waste disposal processes based on anaerobic digestion in China. *J. Clean. Prod.* **2021**, *293*, 126113. [CrossRef]
94. Wenke, L.; Lianfeng, D.; Qichang, Y. Biogas slurry added amino acids decreased nitrate concentrations of lettuce in sand culture. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2009**, *59*, 260–264. [CrossRef]
95. Möller, K.; Müller, T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Eng. Life Sci.* **2012**, *12*, 242–257. [CrossRef]
96. Alburquerque, J.A.; de la Fuente, C.; Ferrer-Costa, A.; Carrasco, L.; Cegarra, J.; Abad, M.; Bernal, M.P. Assessment of the fertiliser potential of digestates from farm and agroindustrial residues. *Biomass Bioenergy* **2012**, *40*, 181–189. [CrossRef]
97. Coban, H.; Miltner, A.; Elling, F.; Hinrichs, K.-U.; Kästner, M. The contribution of biogas residues to soil organic matter formation and CO_2 emissions in an arable soil. *Soil Biol. Biochem.* **2015**, *86*, 108–115. [CrossRef]
98. Abubaker, J.; Risberg, K.; Pell, M. Biogas residues as fertilisers—Effects on wheat growth and soil microbial activities. *Appl. Energy* **2012**, *99*, 126–134. [CrossRef]
99. Ronga, D.; Setti, L.; Salvarani, C.; De Leo, R.; Bedin, E.; Pulvirenti, A.; Milc, J.; Pecchioni, N.; Francia, E. Effects of solid and liquid digestate for hydroponic baby leaf lettuce (*Lactuca sativa* L.) cultivation. *Sci. Hortic.* **2019**, *244*, 172–181. [CrossRef]
100. Cheong, J.C.; Lee, J.T.; Lim, J.W.; Song, S.; Tan, J.K.; Chiam, Z.Y.; Yap, K.Y.; Lim, E.Y.; Zhang, J.; Tan, H.T.; et al. Closing the food waste loop: Food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (*Brassica rapa*). *Sci. Total. Environ.* **2020**, *715*, 136789. [CrossRef] [PubMed]
101. Iocoli, G.A.; Zabaloy, M.C.; Pasdevicelli, G.; Gómez, M.A. Use of biogas digestates obtained by anaerobic digestion and co-digestion as fertilizers: Characterization, soil biological activity and growth dynamic of *Lactuca sativa* L. *Sci. Total. Environ.* **2019**, *647*, 11–19. [CrossRef]
102. Bauer, L.; Ranglová, K.; Masojídek, J.; Drosg, B.; Meixner, K. Digestate as Sustainable Nutrient Source for Microalgae—Challenges and Prospects. *Appl. Sci.* **2021**, *11*, 1056. [CrossRef]
103. Ghimire, A.; Kumar, G.; Sivagurunathan, P.; Shobana, S.; Saratale, G.D.; Kim, H.W.; Luongo, V.; Esposito, G.; Munoz, R. Biohythane production from microalgae biomass: Key challenges and potential opportunities for algal bio-refineries. *Bioresour. Technol.* **2017**, *241*, 525–536. [CrossRef] [PubMed]
104. Saratale, R.G.; Kuppam, C.; Mudhoo, A.; Saratale, G.D.; Periyasamy, S.; Zhen, G.; Koók, L.; Bakonyi, P.; Nemestóthy, N.; Kumar, G. Bioelectrochemical systems using microalgae—A concise research update. *Chemosphere* **2017**, *177*, 35–43. [CrossRef]

105. Seelam, J.S.; de Souza, M.F.; Chaerle, P.; Willems, B.; Michels, E.; Vyverman, W.; Meers, E. Maximizing nutrient recycling from digestate for production of protein-rich microalgae for animal feed application. *Chemosphere* **2022**, *290*, 133180. [CrossRef]
106. Kumar, A.; Singh, E.; Mishra, R.; Kumar, S. Biochar as environmental armour and its diverse role towards protecting soil, water and air. *Sci. Total. Environ.* **2022**, *806*, 150444. [CrossRef]
107. Belete, Y.Z.; Mau, V.; Spitzer, R.Y.; Posmanik, R.; Jassby, D.; Iddya, A.; Kassem, N.; Tester, J.W.; Gross, A. Hydrothermal carbonization of anaerobic digestate and manure from a dairy farm on energy recovery and the fate of nutrients. *Bioresour. Technol.* **2021**, *333*, 125164. [CrossRef] [PubMed]
108. Sheng, X.; Wang, J.; Cui, Q.; Zhang, W.; Zhu, X. A feasible biochar derived from biogas residue and its application in the efficient adsorption of tetracycline from an aqueous solution. *Environ. Res.* **2022**, *207*, 112175. [CrossRef] [PubMed]
109. Dicke, C.; Lanza, G.; Mumme, J.; Ellerbrock, R.; Kern, J. Effect of Hydrothermally Carbonized Char Application on Trace Gas Emissions from Two Sandy Soil Horizons. *J. Environ. Qual.* **2014**, *43*, 1790–1798. [CrossRef]
110. Feng, H.; Qu, G.-F.; Ning, P.; Xiong, X.-F.; Jia, L.-J.; Shi, Y.-K.; Zhang, J. The Resource Utilization of Anaerobic Fermentation Residue. *Procedia Environ. Sci.* **2011**, *11*, 1092–1099. [CrossRef]
111. Tao, X.; Shang, B.; Dong, H.; Chen, Y.; Xin, H. Effects of Digestate from Swine Manure Digester on in Vitro Growth of Crop Fungal Pathogens: A Laboratory Study. *Trans. ASABE* **2014**, *57*, 1803–1810. [CrossRef]
112. Pan, Z.; Qi, G.; Andriamanohiarisoamanana, F.J.; Yamashiro, T.; Iwasaki, M.; Nishida, T.; Tangtaweewipat, S.; Umetsu, K. Potential of anaerobic digestate of dairy manure in suppressing soil-borne plant disease. *Anim. Sci. J.* **2018**, *89*, 1512–1518. [CrossRef]
113. Min, Y.Y.; Toyota, K.; Sato, E.; Takada, A. Effects of Anaerobically Digested Slurry on *Meloidogyne incognita* and *Pratylenchus penetrans* in Tomato and Radish Production. *Appl. Environ. Soil Sci.* **2011**, *2011*, 528712. [CrossRef]
114. Xu, M.; Sun, H.; Yang, M.; Xie, D.; Sun, X.; Meng, J.; Wang, Q.; Wu, C. Biodrying of biogas residue through a thermophilic bacterial agent inoculation: Insights into dewatering contribution and microbial mechanism. *Bioresour. Technol.* **2022**, *355*, 127256. [CrossRef]