Sustainable Conversion of Agricultural Biomass into Renewable Energy Products: A Discussion

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This paper discusses the use of agricultural biomass as a promising resource for renewable energy production, *e.g.*, bio-oil and biogas *via* pyrolysis and catalysis, among other technologies. In order to prevent the accumulation of agricultural biomass, most countries still use traditional disposal or processing methods, *e.g.*, burning in the field, which not only has a low energy conversion rate, but also releases harmful gases, *e.g.*, CO_2, CO, and NH_3. These traditional methods are regarded as inefficient with respect to the low utilization of waste; they also pose a threat to human health. The energy conversion of agricultural biomass makes full use of resources and accelerates the development of green energy. In particular, agricultural biomass can lead to the production of high-quality renewable fuels and chemical raw materials through catalytic pyrolysis technologies. The fuel produced using catalytic pyrolysis has a low sulfur and alkali metal contents and techno-economic analysis shows that catalytic pyrolysis greatly reduces the production cost and improves the utilization rate of agricultural biomass. The production of bio-oil and gas *via* catalytic pyrolysis and agricultural biomass are environmentally friendly and economically feasible for clean energy production. Therefore, additional research is needed to enable the upscaling of renewable energy products.

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INTRODUCTION

Biomass is an important natural source used for conversion into renewable energy products in the form of biochar, fuel pellets, bioethanol, and hydrogen fuel, all which help the sustainable development of energy. This is an important research area (as shown in Figs. S1 and S2 in the Appendix). The global potential of biomass energy production is 100 to 440 EJ/year, which accounts for approximately 30% of the total energy needs of the world (Buyanov 2011; Kant *et al*. 2021; Ferraz *et al*. 2021; Swetha *et al*. 2021; Elnajjar *et al*. 2021). In some developing countries, the direct burning of agricultural biomass is a common practice, but this leads to serious environmental impacts, *e.g.*, the emission of carbon dioxide, nitrogen oxides, and particulate matter (PM2.5) (Bhatia *et al*. 2020; Khan *et al*. 2021). The increase in particulate matter (PM2.5) concentration will even lead to the risk of cardiovascular and respiratory diseases (Karanasiou *et al*. 2021). China is one of the largest agricultural countries in the world, with an annual output of agricultural biomass of 889 million tons, of which 75% is directly combusted (REN21 2018; Wang *et al*. 2020). India is the second largest agriculture-based economy, growing crops all year round. The agricultural sector produces a large amount of agricultural biomass, and in order to deal with them, India needs to burn approximately 92 million tons of agricultural biomass every year, leading to a considerable impact on air quality and health (Bhuvaneshwari *et al*. 2019; Dey *et al*. 2020).

Since 1991, food-based ethanol production accounted for 92% of the actual production capacity, with corn and wheat being the dominating biomass resource (Ingrao *et al*. 2021). In the EU and North America, approximately 80 megatons/year of straw is available for energy production. For example, wheat production in Canada has great potential for wheat straw recycling into power generation. Such technology has potential to provide ecological benefits from the production of bioethanol and hydrogen fuels (Mupondwa *et al*. 2018; Havrysh *et al*. 2021). The annual output of rice and straw in Vietnam reaches 97 million tons, and its energy potential exceeds 380 Twh (Beňová *et al*. 2021). Many countries have gradually found that agricultural biomass can be used as a substitute for traditional fuels, offering a way to reduce the net amount of pollution caused by incineration (Bot *et al*. 2021; Rabea *et al*. 2021).

Table 1. Different Ways to Handle Agricultural Biomass and Development of Energy Products in Seven of the Larger Technology Leading Countries

Country	Biomass Species	Technology	Product	Reference
China	Wheat/corn straw	Mechanical compaction	Biofuels	Ren *et al*. (2019)
Poland	Wheat straw	Compaction	Fuel	Styks *et al*. (2020)
Canada	Wheat straw	Pyrolysis	Bioethanol	Canadian Bioenergy Association (2010)
Brazil	Rice husk	Pyrolysis	Bio-oil	Fleig *et al*. (2021)
America	Sweet sorghum	Pyrolysis	Bio-oil	Morrissey *et al*. (2021)
United Arab Emirates	Allig date seed pits	Pyrolysis	Bio-syngas	Elnajjar *et al*. (2021)
Cambodia	Rice husk	Gasification	Gaseous fuel	Field *et al*. (2016)
Brazil	Sugarcane	Gasification	Fuel	Rey *et al*. (2021)
Pakistan	Corn stover	Gasification	Fuel	Qamar *et al*. (2021)
Thailand	Straw	Baling direct combustion	Fuel	Cheewaphongphan *et al*. (2018)
Denmark	Straw	Gasification	Gaseous fuel	Thomsen *et al*. (2015)

Among the 17 sustainable development goals proposed by the United Nations in 2015, it was proposed that promoting the development of sustainable agriculture and sustainable modern energy will help to improve rural development, environmental protection, and economic operation. The disposal of agricultural biomass determines the development direction of sustainable energy (Vasileiadou *et al*. 2021). As a result, countries began to use different methods to treat agricultural biomass (as shown in Table 1).

There are various ways to utilize agricultural biomass, and scholars from all over the world are committed to studying the utilization methods of agricultural biomass resources to achieve high output and maximum benefit of products (Zhang *et al*. 2015; Wang *et al*. 2020; Li *et al*. 2021). Straw from corn and wheat, which is used as one of the most important biomass resources, can be used in the production of fuel products through mechanical compaction or pyrolysis technology. In addition to the high-yield of corn and wheat, these agricultural biomasses are used as raw materials for energy production in some areas. For example, sugarcane is widely planted in southeast Brazil, where it is being used for conversion into liquid and gas fuels as well biochar materials (Muigai *et al*. 2020; Santana *et al*. 2020; Mohapatra *et al*. 2021; Rey *et al*. 2021). Straw, rice husk, bagasse, fruit husk, and crops are converted into biofuels using catalytic cracking, pyrolysis, and anaerobic digestion (as shown in Fig. 1) (Mahari *et al*. 2018; Lam *et al*. 2019; Baharin *et al*. 2020; Miranda *et al*. 2021). The catalytic cleavage of liquefied products from agricultural biomass under certain temperature and catalyst conditions is also able to produce fuels of higher value. For example, bio-oil can be obtained *via* the liquefaction process and biogas can be produced *via* gasification technology (Akhtar *et al*. 2010).

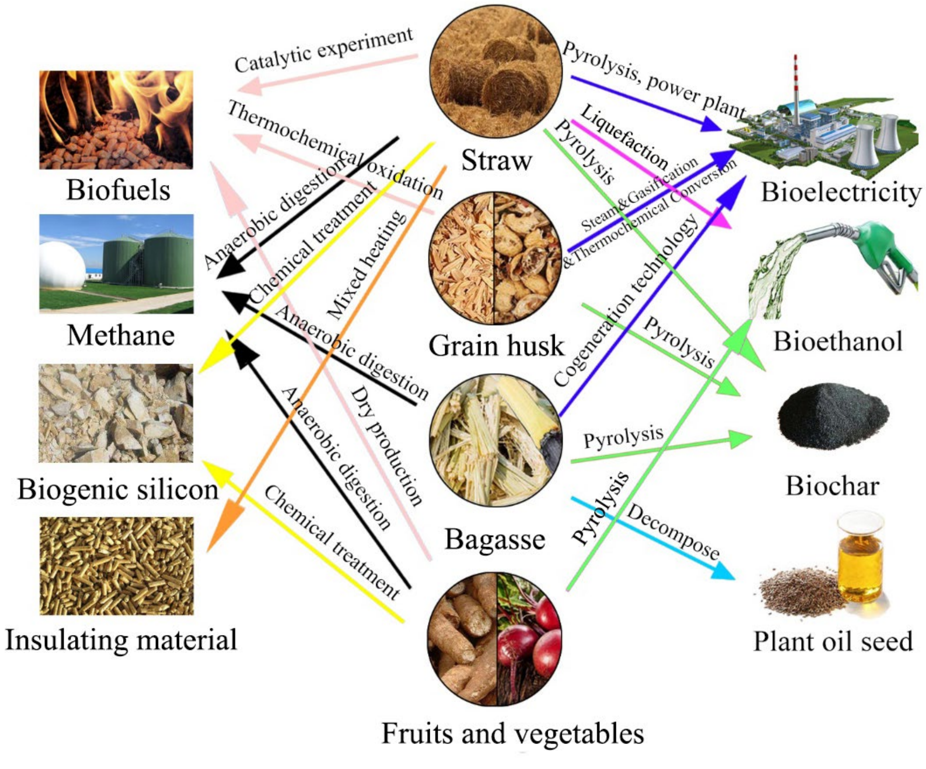

Fig. 1. Current situation of agricultural biomass utilization. The primary sources of agricultural biomass are straw, chaff, and crop residues (Mittal *et al*. 2017). (Note: the arrows in different colors indicate a different energy production method, and the arrows point to the target product indicate that the agricultural biomass has rich energy development potential)

CONVERSION OF AGRICULTURAL BIOMASS INTO AN ENERGY SOURCE

Incineration and Pellet Fuel

The most traditional energy conversion method for biomass is incineration, which has many advantages, *i.e.*, in Japan, the use of incineration reduces the land occupation due to a shortage of land. Incineration refers to the process of thermal decomposition through thermal oxidation under high temperature conditions of 900 °C or higher. Generally, combustible wastes or wastes with high organic content are considered to be the most suitable for incineration (Oppelt *et al*. 2014). The cost of energy increased in the 1950s, and as a result many countries chose to use the incineration of agricultural biomass to generate household energy and heating (Yui *et al*. 2018; Nesterovic *et al*. 2021). The atmospheric pollution generated *via* incineration, *e.g.*, the open-air combustion of straw, has become a major environmental problem (Zhang *et al*. 2016; Wu *et al*. 2020; Guo and Zhao 2021; Huang *et al*. 2021). Particulate matter, including PM2.5 and PM10, emitted from such incineration increases global warming and reduces air quality, which leads to the premature death of organisms among other effects (Beig *et al*. 2021; Liu *et al*. 2021; Manojkumar and Srimuruganandam 2021). The incineration of crop residues is one of the primary sources of atmospheric particulate matter (Song *et al*. 2021). In Thailand, the incineration of 9 million tons to 14 million tons of straw per year results in approximately 5 million tons to 9 million tons of CO_2 emission, and the incineration of agricultural crops in India has been reported to reach 92 million tons per year, with the excess particulate matter emissions causing serious air pollution problems (Suramaythangkoor and Gheewala 2008; Junpen *et al*. 2018; Bhuvaneshwari *et al*. 2019). This shows an urgent need for countries worldwide to produce sustainable and renewable energy with considerably less environmental impacts.

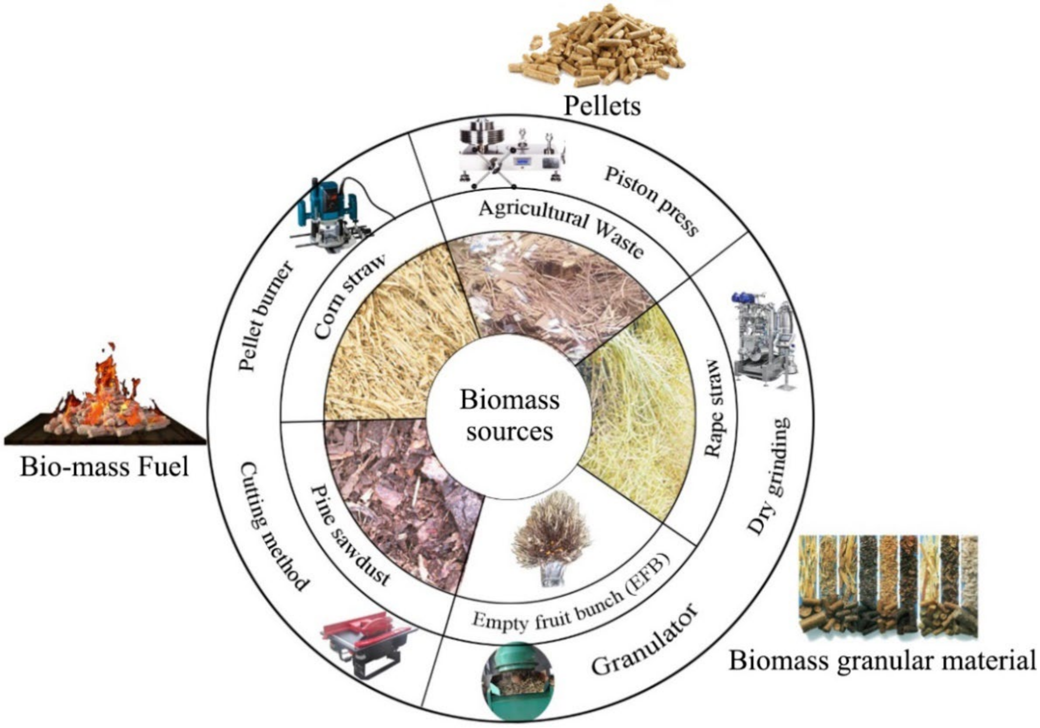

Fig. 2. The conversion of agricultural biomass into fuel pellets (Brunerova *et al*. 2018). It is seen that the five types of agricultural biomass shown in the figure produce biomass pellet fuel *via* compression, combustion, cutting, and other methods.

Facing the emission of air pollutants, a study in North America used densification, compaction, and agglomeration methods to process biomass into smaller biomass pellets. This study reported that the combustion time of the biomass pellets was shorter than the combustion time of agricultural biomass direct combustion, which effectively reduced the emission of air pollutants (Marrugo *et al*. 2019; Tan *et al*. 2020; Yu *et al*. 2021; Dragutinovic *et al*. 2021). Biomass pellets also have a small volume, which are more convenient in terms of fuel transportation (Liu *et al*. 2020). Some countries also gradually began to use local agricultural biomass to make smaller biomass pellets to replace coal and natural gas as fuel for industrial boilers and kilns (as shown in Fig. 2) (Wattana *et al*. 2017; Dragutinovic *et al*. 2019; Vamvuka *et al*. 2020; Brand and Jacinto 2020). For example, bagasse and straw are widely burned as energy in boilers and power plants in Brazil (Kelly *et al*. 2021). Most straw is directly converted into granular fuel without prior drying due to its low water content (Chico-Santamarta *et al*. 2013; Djatkov *et al*. 2018).

Bio-oil

At the end of the 1970s, pyrolysis technology was being applied to the production of bio-oil from agricultural biomass. In the pyrolysis process, in addition to the production of bio oil, there are bio-char and gaseous products. Different raw materials and process conditions affect the yield of each product (Alper *et al*. 2015). Rapeseed, sunflower (Mathias *et al*. 2017; Thers *et al*. 2019; Urrutia *et al*. 2021), straw (Dimitriadis *et al*. 2021), rice husk (Das and Goud 2021), cotton stalk (Mandapati and Ghodke 2021), corn stalk (Akhtar *et al*. 2021), bagasse, and coconut shell have been used as raw materials for bio-oil production (Sarkar and Wang 2020; Almeida and Colombo 2021; Negrao *et al*. 2021). The production of bio-oil from agricultural biomass is also considerable (Table 2).

Table 2. Oil Production Rate of Agricultural Biomass Pyrolysis, Which Shows that the Oil Yield of Agricultural Biomass Pyrolysis Technology is Greater than 28 wt%, and the Average Yield Reported is 45 wt%

Biomass	Method	Condition (°C)	Bio-oil Yield (wt%)	Yield of other products (wt%)	Reference
Rapeseed	Rapid pyrolysis	500	34.6	Solid:20.1 Gas:35.4 Other liquids:9.9	David and Kopac (2018)
Rice husk	Rapid pyrolysis	450	56.0	Gas:15.0 Charcoal:29.0	Zheng (2007)
Barley straw	Rapid pyrolysis	Approx. 500	56.0	Biochar:16.0 Noncondensable gas:28.0	Mullen *et al*. (2010)
Barley hulls	Rapid pyrolysis	Approx. 500	49.0	Biochar:21.0 Noncondensable gas:30.0	Mullen *et al*. (2010)
Groundnut shell	Pyrolysis	500	62.8	Biochar:19.5 Biogas:17.7	Hai *et al*. (2021)
Corn cob	Pyrolysis	450	47.3	Gas:28.7 Biochar:24.0	Biswas *et al*. (2017)
Wheat straw	Pyrolysis	400	36.7	Gas:28.9 Biochar:34.4	Biswas *et al*. (2017)
Rice straw	Pyrolysis	400	28.4	Gas:38.1 Biochar:33.5	Biswas *et al*. (2017)
Rice husk	Pyrolysis	450	38.1	Gas:26.9 Biochar:35.0	Biswas *et al*. (2017)

A biofuel refinery uses wheat straw and rice straw to produce bio-oil with an output of 75 million liters. A case study in Argentina shows that the production potential of soybeans used for bio-oil production on 32 Mha land can reach 472 PJ in 2030 (Diogo *et al*. 2014). The production of bio-oil from agricultural biomass has considerably increased the production of bio-oil in various countries. The bio-oil from bagasse is widely used as light vehicle fuel in Brazil (Stattman *et al*. 2013), and in Malaysia, bio-oil is used as engine and boiler fuel (Tye 2011; Gao *et al*. 2018; Sanchez-Borrego *et al*. 2021). Therefore, more and more countries are expected to produce bio-oil from agricultural biomass (Moghtaderi *et al*. 2007; Abdullah *et al*. 2020). The United States has set a target of 136 billion liters of biofuel by 2022 (Lora and Andrade 2009; OECD 2011). Liquefaction technology is another way to prepare high-quality bio-oil. The bio-oil made from agricultural biomass under certain conditions can also replace transportation fuel (Perkins *et al*. 2019; Cervi *et al*. 2020; Wang and Tuohedi 2020). In addition, studies have shown that the yield of bio-oil obtained from the liquefaction experiment of agricultural biomass catalyzed by metal oxides is about 1.4 times that without catalysis (Yim *et al*. 2016). In an experiment using rice husks as a raw material, the bio-oil was liquefied at a temperature of 320 °C for 30 min, and the biomass conversion rate was approximately 83% (Shin *et al*. 2013).

Biogas

Agricultural biomass can be used to produce biogas through gasification technology. Biomass gasification is a process in which the hydrocarbons that make up the biomass are converted into combustible gases containing CO, H_2, and CH_4 under certain thermodynamic conditions, and most of the energy in the biomass is transferred to gas. However, in the actual production of biogas, some raw materials will be converted into biochar, which means that 100% biogas production is not possible (Brewer *et al*. 2009). Compared with the incineration of agricultural biomass, gasification can be more environmentally friendly, as the amount of SO_2, NO_x, and dust released from the combustion of the biogas generated from gasification can be 90% lower than the amounts released from the incineration of agricultural biomass. Gasification also converts the biomass into a cleaner fuel, *e.g.*, syngas, which is comprised of hydrogen, carbon monoxide, methane, water, and carbon dioxide (Bridgwater 1995; Molino *et al*. 2016; Okolie *et al*. 2020a; Reao and Halog 2020). The gas produced *via* agricultural biomass gasification is widely used for centralized gas supply, power generation, and may even replace fossil fuels (Evaristo *et al*. 2020; Okolie *et al*. 2020b; Guo *et al*. 2021). The biogas produced *via* straw gasification is used in large biogas plants and as energy for power generation (Chen and Xie 2014; Trivedi *et al*. 2017; Hoque *et al*. 2021). In addition, studies have shown that the measures of biogas replacing fossil fuel power generation can greatly reduce the emission of greenhouse gases in the atmosphere (Gosens *et al.* 2013). Kaspersen *et al*. (2016) evaluated the carbon dioxide emissions of biogas power plants in the Municipality of Solrød in Denmark and found that biogas power plants can reduce about 40000 tons of carbon dioxide per year through this way of power generation.

CATALYTIC PYROLYSIS CONVERSION OF AGRICULTURAL BIOMASS INTO ENERGY MATERIALS

Bio-oil from agricultural biomass pyrolysis has strong chemical corrosivity; instead, high-quality bio-oil can be prepared *via* catalytic pyrolysis technology, which is more conducive to energy utilization (Zheng *et al*. 2019; Moreno *et al*. 2020; Olatunji *et al*. 2021). Wang *et al*. (2015) prepared jet fuel *via* the catalytic conversion of bio-oil from straw, providing energy for military and commercial aviation fuel applications. Various energy products, *e.g.*, liquid fuel and fuel cells, are produced using a number of different catalysts or reaction conditions of catalytic cracking technology (as shown in Table 3). When the catalytic medium used is steam, a series of reactions, *e.g.*, biomass steam gasification, catalytic cracking, carbon dioxide reforming, and steam reforming, are carried out in a fixed bed gasifier with straw as a raw material. The gasification efficiency can reach 99.93%, and more stable hydrogen rich gas can be obtained compared to using gasification technology (Ma 2016). In a study by Wang *et al*. (2010), rice husk was catalytically cracked in a continuous pyrolysis unit. During the pyrolysis process, as the pyrolysis temperature increased, the hydrogen production increased, and hydrogen rich gas with a stable yield of approximately 30% was obtained.

However, in the process of catalytic cracking, the alkali metals and alkaline earth metals contained in agricultural biomass may volatilize and deposit on the catalyst, resulting in the reduction of catalyst performance (Mullen *et al*. 2010). In addition, the deactivation of the catalyst will also affect the performance of the catalyst, including coking deactivation and hydrothermal deactivation. Coking deactivation refers to the rapid formation of coke on the catalyst, which blocks the pores of the catalyst and leads to deactivation (Horne and Williams 1995). The hydrothermal deactivation of the catalyst is caused by the presence of water vapor in the catalytic cracking process and the exposure of the catalyst to high temperature. The water vapor comes from the reactions such as water and thermal decomposition of biomass structure in agricultural biomass raw materials (Stefanidis *et al*. 2016). Therefore, metal contamination and deactivation of the catalyst will change the functionality of the catalyst.

Table 3. Catalytic Cracking of Agricultural Biomass to Produce Energy Products. Various Types of Fuels can be Obtained from Agricultural Biomass Under the Action of Different Types of Catalysts

Biomass	Catalyzer	Product	Reference
Straw	Dolomite	Hydrogen-rich gas	Ma (2016)
Rice husk	Rice husk char and its supported metallic	Biogas	Zhang *et al*. (2015)
Straw	NiO	Bio-oil	Younas *et al*. (2017)
Straw	$NiMo/Al_2O_3$	Bio-oil	Auersvald *et al*. (2019)
Rice husk	HZSM-5	Liquid fuel	Yang and Liu (2018)
Barley straw	Carbon fiber cloth, nickel foam	Fuel cell	Li and Song (2018)
Sawdust	NiMo	Aviation kerosene	Shah *et al*. (2019)

CHALLENGES AND FUTURE DIRECTIONS

The burning of agricultural biomass causes serious environmental pollution, which leads to the destruction of the ecosystem and poses a threat to human health. Therefore, countries all over the world need to adopt advanced technologies to obtain renewable bioenergy (Quispe *et al*. 2018; Duc *et al*. 2021). The conversion of agricultural biomass into energy related products *via* different methods will help to reduce greenhouse gas emissions and obtain renewable energy, as well as improve the economic situation of some rural farmers (Bhatia *et al*. 2020). In addition, converting agricultural biomass into liquid fuel, biogas, and other energy sources also has social benefits, *e.g.*, improving rural living standards, effectively managing agricultural biomass waste, and improving sanitary conditions (Taghizadeh-Alisaraei *et al*. 2017; Bhatia *et al*. 2020). The production of fuel from agricultural biomass was improved *via* catalytic cracking, but the structure or property of fuel may be changed in the process of catalytic cracking (Ong *et al*. 2019; Yang *et al*. 2020). Therefore, it is necessary to study the mechanism of catalyst in the process of treating agricultural biomass and determine the factors affecting the quality of fuel in order to obtain high-quality renewable fuels and chemical raw materials.

The way agricultural biomass is converted into energy still faces many challenges. In the gasification process, in addition to gaseous fuel, some toxic pollutants are produced, such as acid gas, tar, and alkaline compounds. These pollutants need to be treated before being released into the atmosphere, so there will be additional costs (Ajay *et al*. 2009). Moreover, some bio-oil products produced by pyrolysis technology have poor thermal stability, and the product characteristics need to be improved to meet better applications (McKendry 2002). Therefore, in the process of converting agricultural biomass into energy, deeper and broader research solutions are needed to develop efficient and economical new technologies as soon as possible. At the same time, it is also necessary to overcome various social and commercial constraints, properly implement and promote government policies or plans, and contact stakeholders to the greatest extent, *e.g.*, providing preferential treatment for the public and some energy industries in terms of commodities and taxes. This will not only help to ensure the future implementation of agricultural biomass to energy projects but will also achieve sustainable development by protecting the environment (Kumari 2016).

CONCLUDING STATEMENTS

1. Atmospheric emissions from the incineration of agricultural biomass increases global warming and air pollution. It is therefore necessary to use advanced technologies to achieve a sustainable energy-based utilization of agricultural biomass. This paper has discussed the application progress of agricultural biomass as biomass fuel, bio-oil, biogas, and the development of catalytic technology. The energy conversion of agricultural biomass improves the utilization rate of agricultural biomass and the output of renewable fuels.
2. Agricultural biomass is processed into smaller biomass pellets by mechanical compaction, which not only can simplify the storage and transportation of biomass, but also can shorten the combustion time of agricultural biomass and reduce the emission of pollutants in the combustion process.

3. Agricultural biomass is used as raw material to produce bio oil by pyrolysis technology and liquefaction technology, and the conditions suitable for different raw materials are selected to improve the conversion and yield of bio oil.
4. The production of biogas can be used in power plants as an energy source through gasification or catalytic pyrolysis, in which the catalytic pyrolysis technology has obtained bio-oil and biogas with high yields and stability. In summary, future work should focus on the promotion of agricultural biomass, catalytic cracking technology, and the pursuit of high-quality products.

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APPENDIX

Supplementary

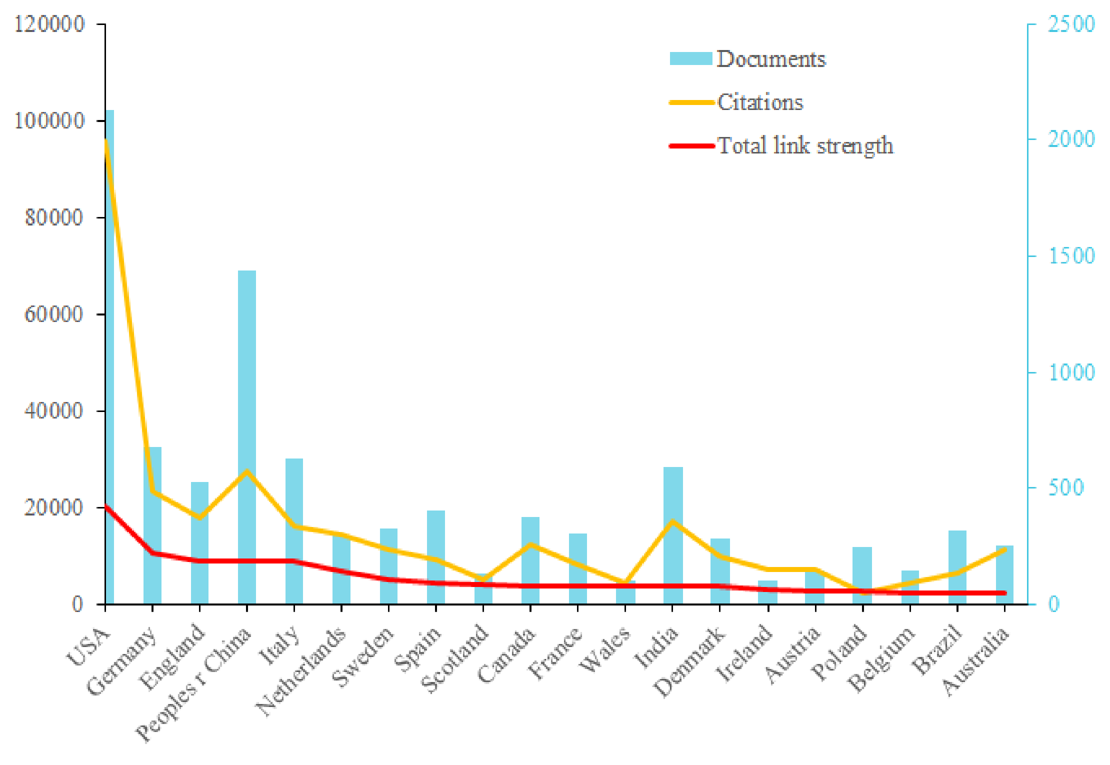

Fig. S1. Number of scientific publications, citations, and total link strength in the area of agricultural biomass energy conversion. The blue bars indicate the number of published articles; the yellow line indicates the number of articles in this field quoted by each country; and the red line show the number of co-occurrences of key words related to agricultural biomass energy in published articles in various countries. (Note: Key words used in searching articles on the Web of Science are TS = agriculture or TS = straw or TS = rice or TS = wheat or TS = wheat or TS = crops)

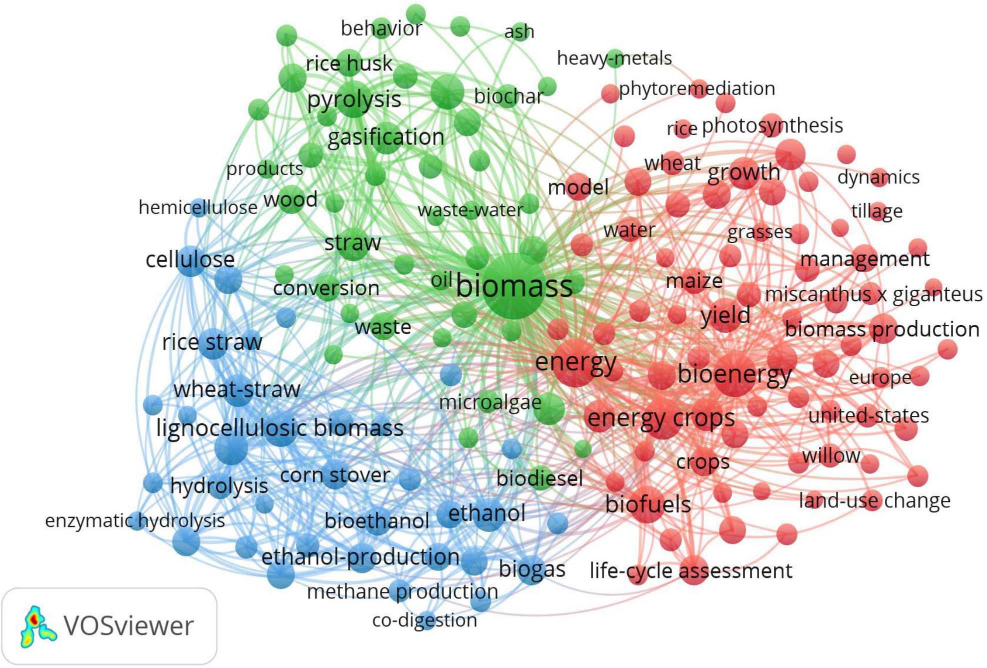

Fig. S2. Network visualization of the keywords related to agricultural biomass energy production