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# Recent Advances in the Bioconversion of Waste Straw Biomass with Steam Explosion Technique: A Comprehensive Review

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**Abstract:** Waste straw biomass is an abundant renewable bioresource raw material on Earth. Its stubborn wooden cellulose structure limits straw lignocellulose bioconversion into value-added products (e.g., biofuel, chemicals, and agricultural products). Compared to physicochemical and other preprocessing techniques, the steam explosion method, as a kind of hydrothermal method, was considered as a practical, eco-friendly, and cost-effective method to overcome the above-mentioned barriers during straw lignocellulose bioconversion. Steam explosion pretreatment of straw lignocellulose can effectively improve the conversion efficiency of producing biofuels and value-added chemicals and is expected to replace fossil fuels and partially replace traditional chemical fertilizers. Although the principles of steam explosion destruction of lignocellulosic structures for bioconversion to liquid fuels and producing solid biofuel were well known, applications of steam explosion in productions of value-added chemicals, organic fertilizers, biogas, etc. were less identified. Therefore, this review provides insights into advanced methods of utilizing steam explosion for straw biomass conversion as well as their corresponding processes and mechanisms. Finally, the current limitations and prospects of straw biomass conversion with steam explosion technology were elucidated.

**Keywords:** steam explosion; straw biomass; bioconversion; organic waste valorization



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## 1. Introduction

The development of the global economy has brought about a huge demand for energy, but currently more than 80% of the energy is provided by fossil fuels [1]. The depletion of fossil fuels and the greenhouse effect associated with greenhouse gas emissions have raised serious concerns in the global community [2]. As the fourth largest energy source in the world, bioenergy is playing an increasingly important role in the emerging renewable energy sources in the world [3]. Straw waste is an important by-product in agricultural production. As crop yields increase, so do agricultural straw yields [4]. However, after crops are harvested, most straw waste is discarded or burned [5]. This results in the waste of resources and environmental pollution, such as emissions of greenhouse gases ($CO_2$, $N_2O$, $CH_4$) and atmospheric pollutants (particulate matter, sulfur dioxide, etc.) [6,7]. The utilization of waste straw can not only reduce pollution, but also ease the energy crisis [8].

Straw biomass is primarily composed of cellulose (40–50%), hemicellulose (20–40%), and lignin (Figure 1) [9]. Among them, cellulose is the skeleton of straw biomass, and lignin is the protective layer. They are interconnected by covalent (anisole bonds) and non-covalent bonds (hydrogen bonds) to form a lignin-carbohydrate complex structure [10]. These three components are strongly bound together to form the lignocellulosic matrix [11]. Therefore, the physical and chemical complexity of the components requires effective measures to fully expose the cellulose structure, increase the effective contact of cellulose with reactants, and improve the conversion rate of straw biomass [12]. In recent years, some pretreatment techniques have been developed to destroy lignocellulosic structure, including biological, physical, and chemical methods [10]. However, they all have their own shortcomings. Among them, the biological treatment is time-consuming and the degradation efficiency is low [12]. The physical method has a high energy consumption and a low lignin removal rate [13]. The chemical method has the disadvantages of easy corrosion of equipment and complicated post-processing [14]. Therefore, we urgently need to find an effective, green, and pollution-free straw biomass pretreatment technology.

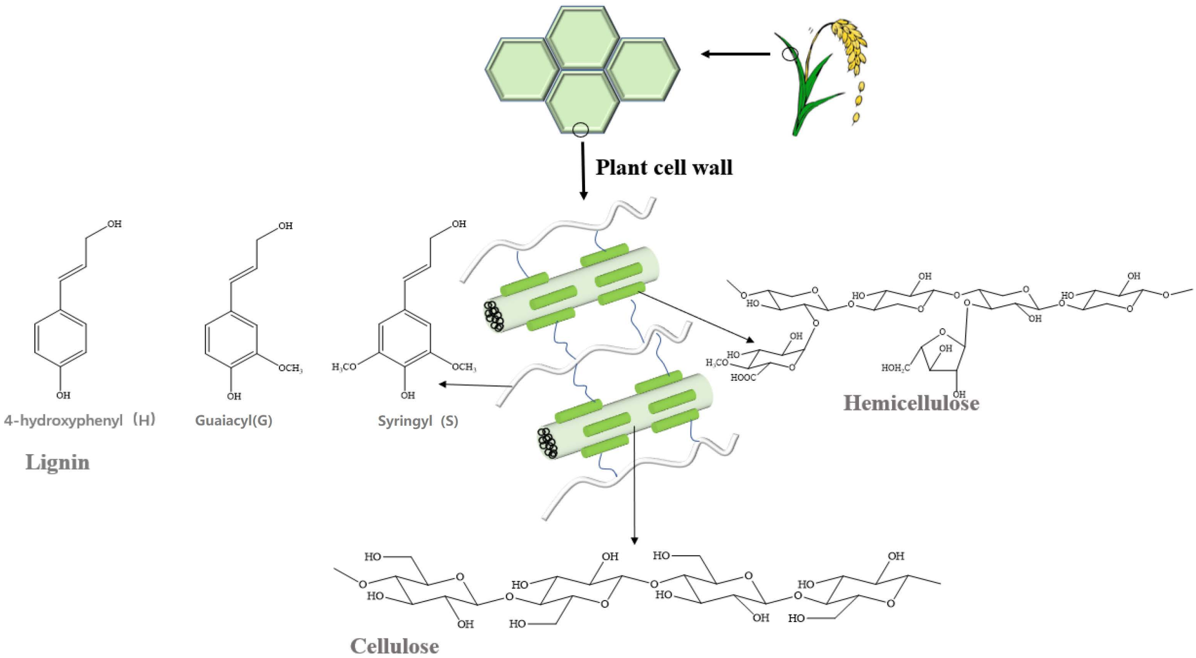


**Figure 1.** Micro-structure of straw biomass.

In 1926, Mason invented and patented the steam explosion (SE) technology, which was applied to the production of artificial fiber boards. SE technology is a physicochemical method that combines steam cracking and explosive decompression to depolymerize lignocellulose [14]. The SE pressure was 7–8 MPa, but the technology was limited due to the high requirements for the instruments and equipment. With the in-depth study of this technology, the steam pressure is reduced and the production process is further optimized [15]. In the SE process, the waste straw is subjected to the action of high-pressure saturated steam, and the structure of straw biomass is destroyed and decomposed by steam heating, with the sudden release of pressure and mechanical shearing [16]. Through SE, biomass is depolymerized and dispersed through physical action, and glycosidic bonds and hydrogen bonds are destroyed [17]. On the other hand, acetic acid from the hydrolysis of acetyl groups in hemicellulose leads to the partial cleavage of other glycosidic bonds and β-aryl ether bonds in lignin [18]. The destruction of lignocellulose structure, the decomposition of partial hemicellulose, and the low environmental impact attribute great potential to SE straw pretreatment technology for waste straw biomass valorization [14].

The method of converting waste straw into various bio-products and energy substances through SE pretreatment has attracted great research interest. It was reported that SE technology improves the physicochemical properties of straw, making it beneficial for practical production (Figure 2) [19–21]. For example, SE increases the surface area of biomass by removing hemicellulose and relocating lignin, and promotes the hydrolysis of cell wall polysaccharides, resulting in a glucan conversion rate as high as 89.6% [22]. The fermented ethanol yield can be significantly increased after SE pretreatment [23]. Another study found that after SE pretreatment, the disrupted macromolecular structure can be further degraded during anaerobic digestion [24]. As a universally applicable pretreatment method, SE has become an ideal technology for handling many types of bioenergy conversion processes, which provides a strong support for the development of the bioenergy industry [25]. In addition, straw is not only high in calorific value, but also rich in nutrients (N, P, and K) [26]. Therefore, the method of returning straw to the field can increase the content of soil organic matter and nutrients, improve soil physical and chemical properties, and improve soil fertility [27]. However, returning straw for rapid decomposition is usually difficult, and the accumulation of straw can easily affect the normal development of crops and increase crop diseases and insect pests [28]. After SE treatment, the cellulose of straw was greatly exposed, the surface area increased, and the crystallinity of lignocellulose decreased [29–31]. This may facilitate the rapid decomposition of straw, improve the soil and promote the growth of beneficial microorganisms, prevent the overuse of chemical fertilizers, and overcome the challenges faced by traditional methods of returning straw to the field [32].

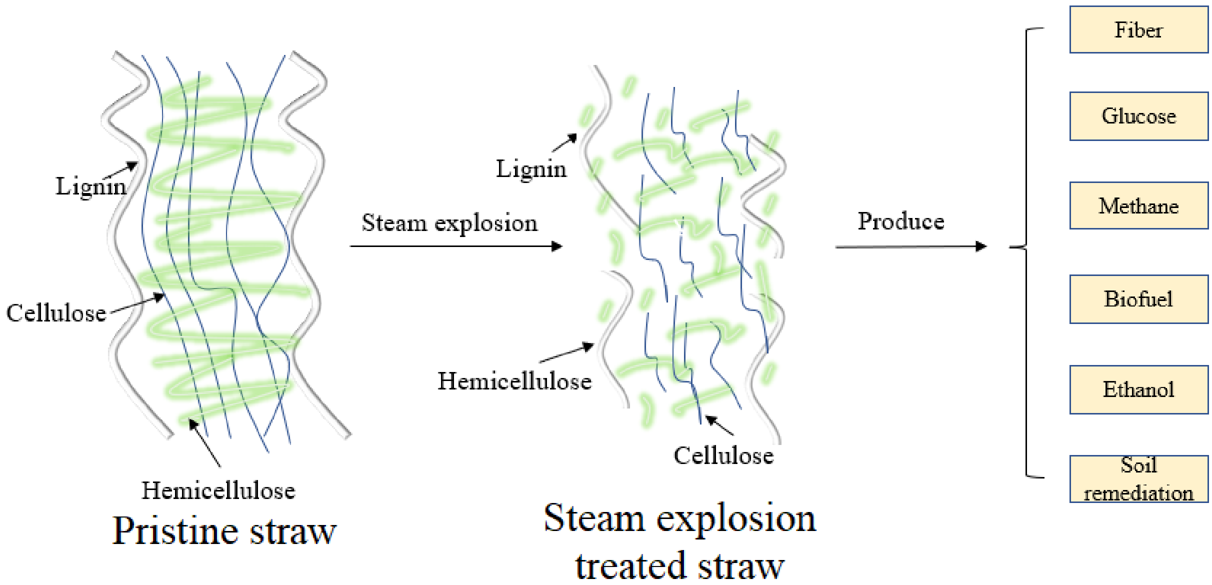


**Figure 2.** Roles of steam explosion in the production of bioproducts and energy substances.

Although SE technology is considered as an effective strategy for straw biomass conversion pretreatment, the knowledge of SE is less known in the production of value-added chemicals, organic fertilizers, biogas, etc. Herein, the effect of SE treatment on biomass conversion of straw and its mechanism needs to be further understood and clarified. This review firstly summarized the sources and properties of different straw biomass; secondly, it concluded the characteristic changes after SE of straw biomass, and finally, it provided insights into the advanced methods and corresponding processes and mechanisms of straw biomass conversions by SE, while clarifying the current limitations and prospects of SE technology for the conversion of straw biomass.

## 2. Diverse Straw Biomass Source and Properties

The energy and density of straw biomass (bulk density of about 20–40 kg/m$^3$) is less than that of fossil fuels [33]. Straw is recalcitrant in nature, and its cell wall is resistant to harsh external environments [34]. Among them, cellulose provides mechanical support to the cell wall, and the mechanical strength of cellulose is related to its degree of polymerization and glucose chain length [35]. Hemicellulose is linked to cellulose by hydrogen bonds and covalently linked to lignin [36]. Lignin contains aromatic and amorphous properties, and covalent bonds between lignin and cellulose prevent carbohydrate exposure to enzymatic hydrolysis [36]. Elemental analysis shows that the carbon content of straw is about 40%, the hydrogen content is about 5–6%, the oxygen content is close to carbon, and the nitrogen content is about 0.2–1%. The N content is responsible for the formation of $NO_x$ and is the main environmental factor for biomass combustion. Generally speaking, the ash and silica content of rice straw is significantly higher than that of other straws, and the ash content of sugarcane straw and corn stover is lower [34,37].

There are many types of straw, including corn straw, wheat straw, rice straw, sugarcane straw, etc. [37]. Sugarcane is the most widely planted crop in the world. The harvested sugarcane is mainly used to produce sugar. As much as 80% of the world's sugar is produced from sugarcane [38]. It is estimated that every ton of sugarcane produced will produce 0.17 tons of straw waste (top and leaves). In addition, a large amount of bagasse is produced in the sugar production process [39]. Corn is one of the main food crops in most countries (Figure 3A). Cellulose and hemicellulose from corn stover can be used to produce ethanol and sugar, while residual lignin can be used for soil improvement and combustion as boiler fuel [40]. In addition, hemicellulose is also used to produce xylose and furfural due to the highly branched, amorphous nature of hemicellulose and its easy-to-convert nature [40,41]. According to reports, for every ton of wheat or rice produced, 1.5 tons of straw are produced [38]. As the second largest agricultural waste resource in the world, the bioconversion of wheat straw into biofuels, bioethanol, and bio-methanol has made great achievements in practice [42]. Rice straw is one of the most popular biomasses for bioethanol production, producing approximately 282 billion liters of ethanol per year based on global rice straw production [43] (Figure 3B).

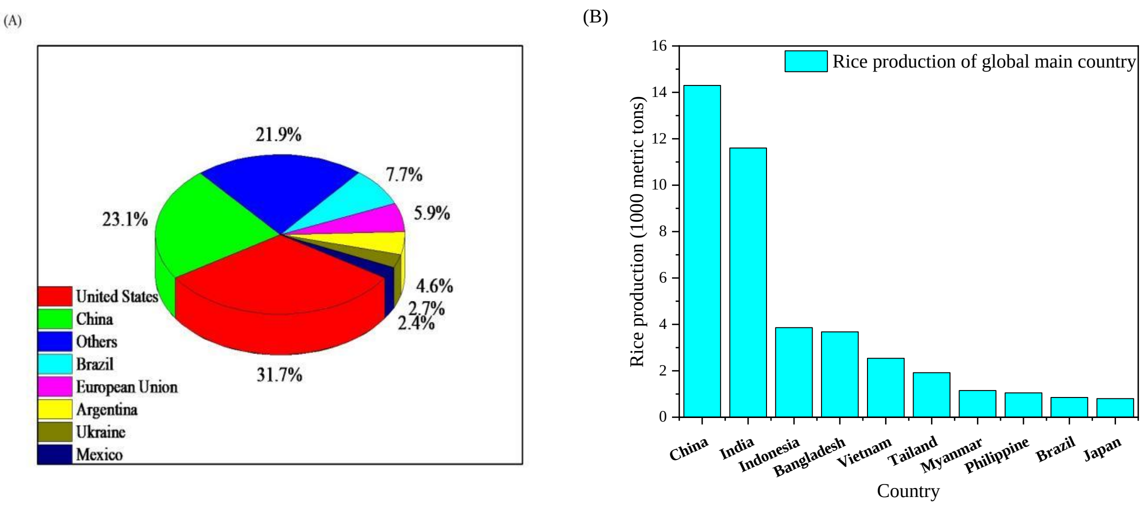


**Figure 3.** Annual corn production by country in the world in 2020 (**A**) and global annual rice production in 2016 (**B**).

## 3. Characteristic Changes of Straw Biomass after Explosion Treatment

For the pretreatment of straw SE, the chemical composition of wheat straw was determined according to the methods reported by the Technical Association of Pulp and Paper Industry (TAPPI) (T 429 cm-01 for cellulose content, T 223 cm-01 for hemi-cellulose content, and T 222 cm-02 for lignin content), and the steam temperature and residence time (the temperature of steam burst technology is usually 160–260 °C, and the pressure is usually 0.69–4.83 MPa [44]) were inversely proportional to the hemicellulose content, while the lignin change was not obvious, and the cellulose content increased [45]. The SE (2.5 MPa/200 s) pretreatment of corn straw can reduce the lignin, cellulose, and hemicellulose content by 36.65%, 50.45%, and 8.47%, respectively [46]. During a fiber extraction case, it can be found that treating the straw with a NaOH solution and thermal SE can make the lignin and hemicellulose larger than those left over from the chemical treatment [21]. After

SE, the alkalinity of the straw, the ratio of the large particles, and the hydrophobicity of the straw were reduced [47].

The scanning electron microscopy (SEM), fiber testing, and FTIR results from the SE treated wheat straw found that the SE treated wheat straw microparticles increased, its porosity was enhanced, and the specific surface area was higher [45]. For SE-treated rapeseed straw, its crystallization index was 64.72%, an increase of 7.24% compared with the control [48]. The effect of SE on corn stalks was studied using terahertz time domain spectroscopy and SEM, and it was found that the parenchymal cells and epidermis of the SE-treated corn stems were crushed and separated by SE, and the specific surface area increased significantly, which could accelerate the fermentation speed when producing biogas and biofuels [49]. SE treatment damaged the rice straw structure and a large number of holes appeared, and the permeability coefficient was improved while the calcium oxide treatment did not exhibit a large number of holes [50]. In addition, the SE-treated cellulose has recrystallization and hydrogen bond rearrangement, which indicates that the regularity of the cellulose lattice structure is improved. The SE treatment can make the binding of the eucalyptus fiber become loose, the surface area increase, and the pore membrane rupture. Herein, the cellulose is largely unaffected, with the exception of a small amount of degradation in the amorphous area, which is conducive to improving the enzymatic lysis rate.

## 4. Straw Valorization with SE Treatment

SE is a technology that uses the principle of a steam catapult to pretreat biomass such as straw. Thermal degradation and hemicellulose autocatalysis occur under high temperature and high humidity conditions, when the straw is heated with steam at a high temperature (180–235 °C) under a high pressure (which is maintained for a while). After the straw is crushed and added to the instrument, the water is heated and pressurized, and once a certain pressure is reached, it is maintained for a while, before the instantaneous steam release is realized to achieve a "flash explosion". Water vapor can heat the straw to a predetermined temperature in a high-pressure environment and diffuses into the lignocellulose cell wall, turning into liquid water when cold. During steam explosion, the structure will be destroyed, the liquid water will soften the lignin and reduce the strength of the connection between fibers. Additionally, part of the hemicellulose will be hydrolyzed to produce organic acids such as glucuronic acid. In addition, there will be partial cellulose degradation to produce glucose. The main processes are as follows: (i) the acid hydrolysis and pyrolysis process reduces the polymerization degree of straw fiber; (ii) the crystal zone of the fiber's mechanical fracture is destroyed in the process of quasi-mechanical fracture; (iii) the hydrogen bond breakage process rearranges the fibers [51–53]. Compared with other pretreatments, SE has the characteristic of completely dissolving hemicellulose. For example, mechanical grinding destroys the crystallinity of lignocellulose and fails to remove hemicellulose. Alkaline pretreatment is able to remove 80% of the hemicellulose [19].

The degradation rate of hemicellulose was 55.2% when the steam pressure was 1.6 MPa and the packing time was 90 s [54]. Under the conditions of two-step steam burst pressure of 1.1 MPa/4 min and 1.2 MPa/4 min, the enzymatic digestion rate of corn stalks increased by 12.8%, and the conversion rate of fermentation product was increased by 209% [55]. After SE at 200 °C for 15 min, the decomposition rate of hemicellulose was up to 92.7% [56,57]. Herein, steam explosion technology can effectively destroy the dense structure of the material in a short time and change its chemical composition, which is conducive to the subsequent treatment of the required substances, so it is widely used as a pretreatment method for straw biomass bioconversion. The following will be a separate introduction to the steam explosion technology.

### *4.1. Fiber Production*

Straw is processed to extract natural fibers as the raw material for sustainable products such as paper, ecological composites, heat shields, etc. SE treatment can effectively pretreat straw fibers, destroy the proportion of straw lignin, and increase fiber bundles [58]. When the steam temperature is higher and the residence time is longer, the fibers are more uniform, the surface wetness is improved, and the quality of the fibers is enhanced by reduced ash and phenethyl alcohol extractives [47,59]. The thermal stability of wheat straw fiber is improved by 5% and its surface modification by 7–9% after SE (Kellersztein et al., 2019). When the SE-treated wheat straw remained at 200 °C for 3 min, more than 90% of the fiber bundles were observed, maintaining a more uniform material, and after blasting treatment, the reduction in straw acidity and wettability as well as the reduction in silicon content effectively improved the adhesion between straw particles and water-soluble adhesives [47]. The coconut shells and bagasse can be used to make insulation materials without the need for adhesives. Coconut shell and bagasse were treated at a hot pressing temperature of 200 °C for 13 min each to make a low-density adhesive-free insulation board with a density of 250–450 $kg/m^3$, and it was found that the adhesive-free insulation board made of bagasse showed higher mechanical properties, and the fracture modulus (MOR) was twice that of the coconut shell and met the requirements of the relevant standard thermal insulation application building materials [60].

Cotton straw is rich in lignocellulose and can be used to make insulating fiberboard and produce pulp [61]. The composite materials of a cotton straw with NaOH (5 g/L) and steam flash blast (3 MPa, 170 °C, 4 min) combined treatment (SFE-AT) have the highest mechanical properties and stability against water. This may be due to the fact that the cotton straw fibers prepared by the SFE-AT combined treatment contain the lowest non-cellulosic impurities and have the smallest diameter, resulting in optimal adhesion between the polypropylene (PP) matrix and the cotton straw fibers [62]. In addition, there are also scholars who studied corn stalks who produced a prototype weighing 80 $g/m^2$ by acid pre-impregnated SE (APSE)-treated (1.6 Mpa/5 min) corn stalks, and they found the explosion index of the handsheet was 0.99 kPa $m^2/g$, its strength index close to that of waste corrugated pulp [57].

### 4.2. Producing Glucose

SE deselects the straw structure from lignin and dissolves hemicellulose, an economical and convenient operation process that results in higher sugar yields [19]. The study found that the glucose yield from the SE pretreatment of rapeseed straw was 29.4%, which was 17.8% higher than the control, and glucose production was also increased by 200% [48]. Continuous SE pretreatment of wheat straw was carried out at different temperatures and residence times using a pressurized mechanical refining system, and the results show that under SE pretreatment (198 °C/6 min), the total glucose yield is 85.8% under the best conditions [63]. Betula pubescens steam blast pretreatment enables efficient enzymatic glycation, and when Betula pubescens is treated at 170–230 °C for 5–15 min, it is found that enzymatically released glucose increases with the severity of the pretreatment until 220 °C for 10 min, with a maximum dissolved glucose level of 97% [64].

The use of catalysts enhances the hydrolysis of cellulose, thereby increasing sugar recovery. The straw remains at 160–190 °C for 2–10 min with 1–8% $H_2SO_4$ as the catalyst, and there will be a 73% saccharification rate [65]. The glucose conversion rate of maize straw under SE (200 °C/5 min) treatment was as high as 91.5%, and compared with the shredding storage method, the shredding decreased the sugar conversion rate but increased the sugar yield [66]. Bagasse was extracted with solvent after SE (220 °C/5 min) treatment, and the yield of reducing sugar was as high as 89.0–95.1% [67]. When sunflower stems stay under steam treatment at 180–230 °C for 5 min without recommending any catalyst, 16.7 g of glucose is obtained, while most of the hemicellulose-derived sugars released are in the oligomeric form [68]. As one of the fruit crops widely grown in the tropical subtropics, bananas produce a large amount of waste after harvesting, namely rachis and pseudo-stems. The pretreatment of rachis by SE (177 °C/5 min) and with 2.2% $H_2SO_4$ results in a total glucose yield as high as 91.0%. A pseudo-stem steam blasting pretreatment (198 °C/5 min) with 1.5% $H_2SO_4$ results in a total glucose production of 87.1% [69]. The efficiency of enzymatic hydrolysis can be improved by dilute acid pretreatment, the most commonly used method for obtaining high sugar yields from lignocellulosic biomass. Therefore, acid pretreatment combined with steam blasting can result in higher sugar yields [70].

### 4.3. Methane Production

If straw biomass is burned in the traditional way, it may cause environmental problems [71]. Straw is considered to be one of the suitable substrates for biogas production. One of the most important methods of treating straw waste is anaerobic digestion (AD) [72]. However, because straw has a rigid structure and a high C/N ratio, it cannot be completely biodegraded during AD [73].

However, as straw biomass has a complex and stable three-dimensional structure and contains a large amount of lignin [74], it protects cellulose and hemicellulose, making its degradation by microorganisms difficult [75]. In addition to the lignin protection effect, an important factor limiting microbial degradation of straw is the percentage of carbon to nitrogen [76,77]. Previous research has shown that anaerobic microorganisms consume carbon faster than nitrogen, and the optimal C/N ratio for anaerobic digestion systems is typically in the range of 20 to 30 (*w/w*) [78]. When the C/N ratio is not in the optimal range of the C/N ratio for anaerobic digestion, biogas production and straw biodegradability will be negatively affected. As a renewable gas, biogas is mainly composed of methane ($CH_4$), which can be used to produce heat or electricity [73].

In recent years, for the improvement of the anaerobic digestion efficiency of lignocellulose, the biodegradability of cellulose has been the limitation stage. In order to destroy the structure of straw waste, researchers used various experimental methods, mainly the SE method [79], the photocatalytic degradation, the acid-base method [80], the acid-base method [81], and microbiology [82]. These methods can improve the degradability of lignocellulose to varying degrees. Studies have found that SE pretreatment may increase the cellulose content in the straw. However, the hemicellulose content in the straw samples appears to have little effect on SE treatment. This result may be due to the hydrolysis of hemicellulose at the SE temperature (155 °C). According to previous studies, this happens at temperatures between 150 and 230 °C [83], which shows that the SE helped to adjust the C/N ratio during the reaction, and therefore increased the methane production [73].

### 4.4. Bio-Oil and Biofuel Productions

Renewable energy sources, including bioenergy, are getting a lot of attention because they are likely to become substitutes for traditional fuels or as a supplement to energy shortages in the future. Bioenergy is one of the renewable energy sources that are becoming increasingly popular worldwide because it can produce fuels that function similarly to crude oil while being better than traditional fuels in terms of the effects of pollution [84]. Biomass energy is a clean and abundant fuel that has been used to fulfil energy needs since ancient times [85]. Crop straw has the advantages of abundant resources, low cost, and environmental friendliness, so it has a broad application prospect in biofuel production. In particular, lignocellulosic biomass, straw biomass, is a renewable carbon neutral resource which can be used to produce green fuel and other products [85]. Therefore, looking for low-cost and high efficiency conversion technologies to deal with crop residues in biofuel production is very important [86].

Biofuels can be derived from biomass by thermal chemical or biochemical transformations [87]. The main products of fast pyrolysis mainly include bio-oil, whose calorific value is the same as that of biomass raw materials, but its energy density is higher than that of biomass raw materials when compared with conventional fuels, such as biological oil, so it is more convenient for transportation, which is more suitable for mass production [88]. Bio-oils are all sorts of organic liquid mixtures, which include cellulose or hemicellulose-derived sugar monomers, sugar oligomers, and sugar derivatives such as carboxylic acids [87,89].

SE can modulate the biomass morphology, composition, and properties to accommodate multiple transformation processes for subsequent biofuel production [90]. The pretreatment of SE (450 °C) using maple, switchgrass, and corn stalks as raw materials found that the bio-oil yield reached 56%, 46%, and 51 wt%, respectively [91]. The lignin left behind during the production of bioethanol can be converted into bio-oil by rapid pyrolysis. The SE pretreatment (500 °C) of wheat straw and the addition of rapid cracking using water-insoluble solids (WIS) yielded a 31.9% by weight bio-oil [92]. In order to increase the yield of bio-oil, some scholars use acid-catalyzed vapor pretreatment, and some authors have performed a 450 °C steam explosion after pretreating pine wood with 1% $H_2SO_4$ and observed a bio-oil yield of up to 63%. SE has been shown to be an effective way to maximize bio-oil quality and energy, and studies have found that wheat straw has increased its bio-oil quality and chemical energy yield by steam blasting 1.9-fold and 1.7-fold, respectively [92].

### *4.5. For Ethanol Production*

Due to the low cost of agricultural biomass and the emissions of greenhouse gases from the burning of biomass being relatively low, bioethanol production from agricultural biomass is one of the options with the most potential for economic growth and environmental improvement [93,94]. Interestingly, bio-oil and ethanol can be continuously obtained during the biomass conversion process (Figure 4). That is, the residues after ethanol production can be rapidly pyrolyzed to obtain bio-oil, and the main components of these residues are crude protein, crude fiber, and crude fat [92,95]. Under the background of carbon emission reduction and new energy development, more advanced strategies promoting the conversion of straw biomass from lignocellulosic raw materials to bioethanol production are urgently needed [52,96].

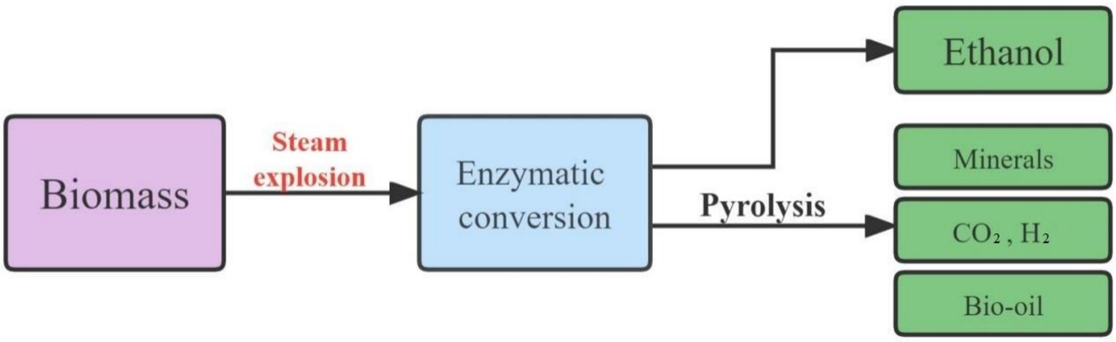


**Figure 4.** Steam explosion coupling bioconversion process for continuous production of ethanol and bio-oil.

Straw is a potential source of bioethanol and other value-added products such as oligosaccharides and lignin, unlike other industries [97]. After SE pretreatment, two forms of substances are obtained: solid and liquid, which can be filtered and separated. The solid part contains mainly cellulose and lignin, which can be used to produce biofuels such as bioethanol [92] or butanol [98]. Biomass digestibility depends on different chemical, physical, composition, and structure-related parameters [99–101].

It is hoped that technological advances will reduce the cost of saccharification of cellulosic materials and make ethanol production profitable. Since the many sources of raw materials are one of the reasons for the low cost of ethanol production, genetic studies aimed at improving the productivity of plants as potential energy substrates are essential [102]. The removal of hemicellulose and the conversion of lignin during SE pretreatment contributes to the improved digestibility of biomass to enzymes. For example, the SE pretreatment of straw before enzymatic saccharification showed that the enzymatic saccharification and alcoholic fermentation of straw were effectively promoted under the treatment of 3.53 MPa for 2 min. By adding chemicals or water impregnation, the biomass is hydrolyzed to a greater extent [103]. The authors found that wheat straw was treated with dilute acid $H_2SO_4$ (0.9%) for SE at different temperatures (160–200 °C) and dwell times (5, 10, and 20 min). The authors found that acid-impregnated biomass at 180 °C for 10 min provides the highest raw ethanol yield (140 L/t wheat straw) [104]. Switchgrass and bagasse were pretreated with 3% $SO_2$ impregnated with SE, and it was found that ethanol yield increased by 18–28% under the catalysis of $SO_2$ [105].

### 4.6. Potential Application in Soil Quality Improvement

In recent years, the excessive and irrational application of chemical fertilizers and land aging have attracted widespread attention. A huge amount of crop straws are generated per year [106]. Today, more than 60% of straw is returned to the fields, and this number will gradually increase [107]. Therefore, straw return is an effective strategy for the utilization of straw resources to replace chemical fertilizers. However, due to the high lignocellulose content of crop straw, it is difficult to degrade after returning it to the field, which affects the full utilization and short-term fertilizer effect of straw resources.

Straw contains a lot of trace elements, which can be used as a beneficial fertilizer for crop growth. SE can further promote the dispersion of the straw fiber, destroy the covalent bond between hemicellulose and lignin, and release effective nutrients [108]. Studies have shown that returning straw to the field is beneficial to the improvement of soil properties, thereby increasing crop yields. [109,110]. The rapid degradation of straw is particularly important. According to [111], the physicochemical properties of straw pretreated with SE were significantly adjusted. In addition, the degradation rate of cellulose and hemicellulose in the straw was significantly increased compared to the control. The SE pretreatment results in 92.7% hemicellulose solubilization and 81.3% lignin solubilization at 200 °C [112]. It is reported that SE pretreatment reduces 47–95% of hemicellulose and 5–16% cellulose of crop straw [113]. In contrast with the untreated straw, the contact angle of the straw after SE treatment was significantly reduced, the hydrophobicity of the straw was weakened, and the surface wettability of the straw was improved, indicating that the straw treated by SE had a certain water retention capacity after being added to the soil. In addition, the acidity of the straw after SE treatment increased, implying that SE straw returning has better potential for improving soil pH [47]. Moreover, the SE pretreatment can greatly reduce the pathogenic microorganism. Hence, SE-treated straws may be more suitable for crop straw return to the field.

## 5. Conclusions and Perspectives

Straw cellulosic biomass is a tough feedstock due to the compact binding of its constituents (i.e., cellulose, hemicellulose, and lignin). SE pretreatment can effectively improve the wettability of straw, reduce silicon content, improve the adhesiveness between straw particles and water-soluble adhesives, and improve fiber quality; effectively destroy the structure of straw lignocellulose, dissolve hemicellulose, and improve the digestibility of straw biomass, saccharification rate, and ethanol yield; adjust the carbon-nitrogen ratio of straw to increase methane production; and finally, adjust the structure of biomass, increasing a specific surface area and porosity, which is beneficial to the production of bio-oil. In addition, after SE pretreatment, the improvement of straw wettability, porosity, surface area, lignocellulosic structure, and other physical and chemical properties is beneficial to the release of straw nutrients, and the soil structure and water holding capacity are improved. SE has been shown to be a versatile and efficient method for the pretreatment of straw lignocellulosic biomass. SE-pretreated straw is also a very promising soil amendment.

SE pretreatment of waste straw to produce biofuel and chemical value-added products is a technology that has entered the commercialization stage. However, there is still a lot of room for improvement. For example, the main disadvantage encountered during SE is the partial degradation of hemicellulose and lignin, resulting in the formation of inhibitory compounds that negatively affect enzymes and microorganisms; therefore, future research should pay more attention to the degradation of these inhibitory compounds. Some acids in catalytic-SE technology may lead to the dissolution of cellulose and hemicellulose, resulting in the loss of dry matter as well as reduced product quality and yield, and for this reason future research should focus on the inhibition of cellulose dissolution. It is difficult to further utilize these residues by drying treatment before recycling of SE treated straw biomass, and these residues may be utilized by hydrothermal technology. SE treatment requires higher temperatures and more expensive reactor materials for better biomass treatment, and SE process parameter optimization research should be carried out in the future. In addition, there is a lack of research on the SE pretreatment of straw waste to improve soil. Research should be carried out to verify its soil improvement performance and comprehensively consider the related economic benefits.

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