sustainability

Review

High-Value Utilization of Corn Straw: From Waste to Wealth

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Abstract: As a renewable lignocellulosic biomass resource, corn straw has great potential for waste utilization in agriculture and sustainable development. In recent years, considerable attention has been given to the research on repurposing organic acids, saccharides, and other active substances extracted from corn straw. This review is focused on the progress in the preparative techniques and product development of organic acids and saccharides, realizing the high-value utilization of corn straw. This review also discusses the potential applications of corn straw in the food and biopharmaceutical industries, and sheds light on the current challenges and future directions in the efficient utilization of straw resources.

Keywords: corn straw; resource benefits; product innovation; sustainability

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1. Introduction

Over the past few decades, the high-value utilization of corn straw is gradually becoming a hotspot. In order to make the most use of straw resources and minimize pollution, a series of studies have been performed to produce biobased products from corn straw [1,2]. It is generally known that corn straw contains multiple bioactive substances, among which organic acids and saccharides are the main components [3,4]. Up until now, both chemical synthesis and microbial fermentation were applied in the extraction and purification of these active substances. Furthermore, the industrialized production of biobased products from corn straw was progressively achieved via process optimization and economic benefit assessment [5–7]. Based on the continuous efforts and research works, a series of achievements including advanced materials, chemical products, and functional food have been obtained recently, contributing to the sustainability of agriculture from waste to wealth in regard to corn straw [8,9].

As a common agricultural byproduct, corn straw is treated mainly by open burning in developing countries, resulting in serious environmental pollution and resource waste. Many developed countries and regions are actively exploring effective ways to transform and utilize the straw resource [10,11]. Corn straw commonly refers to the remaining part of corn after harvest, and primarily consists of the roots, stems, and leaves. The stems include the outer stem rind, inner stem pith, and stem nodes, while the leaves consist of leaves and leaf sheaths. Among them, the stem rind of corn straw is rich in wax, cellulose, and lignin. Similarly, the dry-weight portion of corn straw is also rich in cellulose, hemicellulose, and lignin. At present, research on the utilization and conversion of corn straw focuses on the straw-returning treatments, fermented straw feed, and energy chemical industry.

The traditional methods for straw returning are primarily mechanical pulverization followed by plowing and covering treatments. However, these treatments may cause a series of problems, such as those related to the negative impacts of agricultural production due to a long period of straw degradation. Additionally, the straw-returning treatments require watering and fertilization management, leading to an increase in the costs of agricultural production. Notably, the direct straw-returning treatments raise a high standard for the soil depth, as otherwise the processes of seeding and budding will be impeded in the subsequent cultivation cycle. Consequently, farmers often choose not to use these processing methods for corn straw. Despite all this, the soil aggregate stability can be significantly improved when the removal rates of corn straw are less than 50%. Hence, the straw-returning treatments are of great significance to soil health for sustainable agricultural development [12,13].

In recent years, corn straw has been used as a feed additive after treatments using proper physical, chemical, or biological processes. However, corn straw is not suitable for directly feeding livestock and poultry, due to its high crude fiber content, relatively low nutritional value, as well as low levels of crude proteins and fat. Therefore, in practical applications, additional nutritional supplements must be added to the straw feeds. Furthermore, as one of the organic substrates, corn straw can also provide a nutrient source for edible fungi growth [14].

The British Petroleum Statistical Review of World Energy 2022 reported that coal was still the primary fuel for energy consumption on a global scale. In 2021, China ranked first in coal consumption, followed by India. During the past decades, the growth rates of energy consumption for India and China were 4.6% and 0.8%, respectively. It is worth noting that the demand of natural gas in 2021 exceeded 4 trillion m^3 in the whole world, with a growth rate per annum of 4.8% in the past decades. In particular, the Chinese natural gas supply and demand gap reached 167.3 billion m^3 per year [15]. At present, the non-renewable energy source is still the main energy structure of developing countries. Since these conventional energies cause environmental pollution, the utilization and development of biomass resources may help to alleviate the energy crisis and environmental issues.

Numerous studies have focused on the utilization of biomass resources by anaerobic digestion in order to improve the waste management and recovery of renewable energy [16]. There are three utilization technologies of corn straw as a raw material resource for energy. Briefly, the first category involves the solidification and shaping of corn straw, making it serve as a new type of solid fuel in industrial production [17]. It should be noted that the direct use of corn straw as fuel is not suitable due to its low heating value. Therefore, the special technological treatments are required in order to improve the heating values. The second category encompasses the liquefaction of corn straw, where it is hydrolyzed into small molecules such as xylose and glucose [18]. Subsequently, ethanol can be obtained from these sugar compounds through fermentation and separation processes. The third category involves the gasification of corn straw [19], which converts the corn straw into clean combustible gases such as CO, H_2, and CH_4 through gasification and oxidation. In the comprehensive utilization of corn straw through liquefaction and gasification, digestion processes involve various microorganisms, including fermentative bacteria, hydrogen-producing bacteria, acid-producing bacteria, and methanogenic archaea (Figure 1).

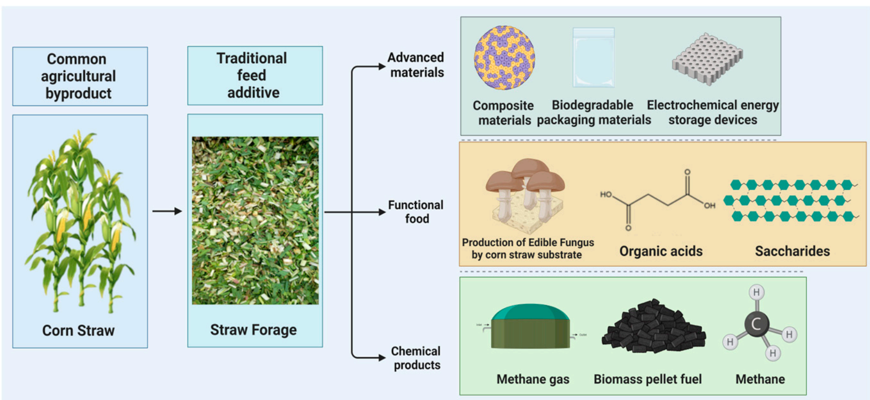

Figure 1. Current status of corn straw in research and application.

Renewable energy in the form of combustible gas has been produced from corn straw by anaerobic digestion, where the organic matter can be transformed into CH_4 and CO_2 through microbial actions under anaerobic conditions [20]. These processes include hydrolysis and acidogenesis stages. Firstly, the organic matter is hydrolyzed into small organic compounds, and then these compounds are further converted into simpler volatile fatty acids, alcohols, and other substances during the acidogenesis stage. Four fermentation types can be distinguished based on their predominant end products, namely ethanol fermentation, butyric acid fermentation, mixed acid fermentation, and propionic acid fermentation. It is worth noting that the hydrolysis and acidogenesis stages are accompanied by the production of hydrogen gas during the whole process of anaerobic digestion of corn straw [21]. There are various factors that might affect the production of combustible gases during the digestion processes, including pre-treatment methods [22,23], temperature, pH, catalysts [24], microbial species [25], and hydraulic retention time. It has been reported that up to 33% of the electron energy can be converted into the electron energy in the substrate of corn straw. In order to further improve the overall energy recovery efficiency and substrate conversion rate, a series of studies were performed to utilize the byproducts of hydrogen production for the generation of other energy products such as methane and diesel [26].

With the increasing popularity of renewable energy, a significant amount of research has focused on the industrial applications of biomass resources in the fields of energy storage devices, such as lithium-ion batteries, solid-state batteries, and redox flow batteries [11]. The corn straw also has a promising potential to be used as the main part of electrochemical energy storage devices, such as electrodes, binders, electrolytes, and membranes [27]. Although some of the proposed technologies in these studies are currently still at the laboratory-scale stage, the prospects of developing batteries by employing corn straw facilitate the resource recycling of agriculture wastes.

Currently, there are a series of comprehensive reports on the utilization of corn straw for energy production and battery manufacturing. Due to its relatively high cellulose content and biodegradability, corn straw has been considered as a valuable industrial raw material. Corn straw can be used both for papermaking and for biodegradable packaging materials as a substitute for wood [28]. Furthermore, as a raw material, the corn straw combined with polymers such as colloids can be used to produce composite materials, including fiberboard and wood-plastic composites [29]. However, a comprehensive summary of the research progress regarding the conversion of corn straw into high-value products for the food and biopharmaceutical industries is still warranted. Hence, this review aimed to explore the potential of corn straw as a feedstock for related industrial applications, via summarizing its active ingredients including organic acids and saccharides (Figure 2).

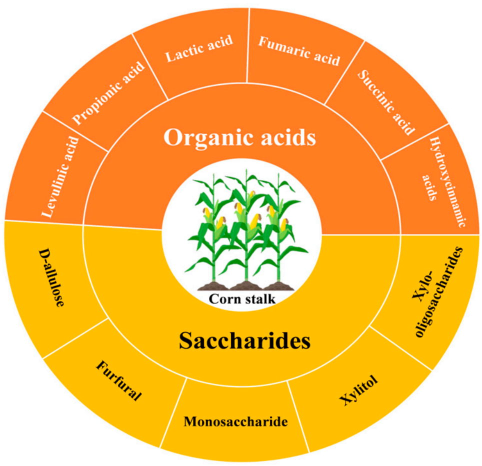

Figure 2. The main active ingredients of corn straw.

2. The Main Active Ingredients of Corn Straw

2.1. Organic Acids

2.1.1. Lactic Acid

Lactic acid is an essential natural organic acid with a long history of utility in the food, pharmaceutical cosmetic, leather, textile, and other food chemistry fields [30–32]. The commercial application of lactic acid has attracted considerable attention, owing to its promising potential in the production of biodegradable polymers [33]. Given food-related and environmental concerns, the utilization of corn straw via chemical synthesis and fermentation has been useful as it is an intriguing raw material with inherent benefits of accessibility, sustainability, and renewability [34]. To date, the large-scale production of corn straw is limited by environmentally unfriendly pretreatment, components, and other challenges. To solve these obstacles, different pretreatment technologies, such as mechanical, zymolytic and thermochemical processes, have been performed to degrade complex carbohydrates, enhance the enzymolysis effect, and finally maximize treatment efficiency to improve lactic acid production.

As listed in Table 1, microbial consortia DUT47 was enriched and selected from the hydrolysate of H_2SO_4-pretreated corn straw without detoxification. Under the enrichment temperature of 47 °C, the predominant families of DUT47 belonged to *Enterococcus* (97.62%), which exhibited strong anti-inhibitor resistance, thermophilic growth properties, and the concurrent usage of glucose and xylose. Thus, this innovative enrichment strategy was proven to be an efficient way to produce lignocellulose-derived lactic acid [35]. To facilitate the manufacture of L-lactic acid at a high titer, Liu et al. (2015) obtained the engineered *Pediococcus acidilactici* TY112 from a corn straw-based biorefinery process. Both experimental and techno-economic results showed that the optimal prototype had not only a high L-lactic acid titer and overall yield from cellulose in corn straw, but also a commercial potential in industrial application [36]. To gain a high-yield and high-titer lactic acid-producing bacterium from lignocellulosic biomass, Hu et al. (2016) established a feasible process for lignocellulosic lactic acid production using *Lacillus pentosus* strain FL0421 with 30 FPU/g straw and 10 g·dm^{-3} yeast extract from NaOH-pretreated and washed agro straws through fed-batch simultaneous saccharification and fermentation (SSFR) [37].

Table 1. Methodology and yield of the main active ingredients from corn straw.

Products	Operating Condition	Output/Yield	Reference
L- and D-lactic acid	Batch SSF with microbial consortium DUT47 at 47 °C and pH 5.5	43.73 g·dm^{-3} in lactic acid concentration, 0.50 g/g-corn straw in yield, 0.32 g/(L.h) in productivity	[35]
	Engineered strain *P. acidilactici* TY112 from dry milling biorefinery processed corn straw	104.5 g·dm^{-3} in L-lactic acid titer, 71.5% in overall yield.	[36]
	NaOH-pretreated and washed corn straw with *Lb. pentosus* FL0421 at 37 °C and pH 6.0 with cellulase activity of 30 FPU/g straw and yeast extract of 10 g·dm^{-3}	92.30 g·dm^{-3} in lactic acid titer, 0.66 g/g straw in yield, 1.92 g·dm^{-3} h^{-1} in productivity	[37]
	SSF of NaOH-treated corn straw with mixed cultures of *Lactobacillus rhamnosus* and *L. brevis*	0.70 g/g in lactic acid yield	[38]
	SSF at 25% (*w*/*w*) solid content with dry dilute-acid-pretreated and biodetoxified corn straw	77.66 g·dm^{-3} L-lactic acid from *P. acidilactici* TY112, 76.76 g·dm^{-3} D-lactic acid from *P. acidilactici* ZP26	[39]
Fumaric acid	Corn straw pretreated with dilute acid to grow fungal biomass and then digested with enzyme to obtain a glucose-rich liquid for fumaric acid production	Up to 27.79 g·dm^{-3} in production, 0.35 g/g in yield, 0.33 g·dm^{-3} h^{-1} in productivity	[40]

Table 1. *Cont.*

Products	Operating Condition	Output/Yield	Reference
Propionic acid	Anaerobic production from *P. acidipropionici* in corn straw via DDAPH fed-batch HCD fermentation	Titer in 64.7 g·dm^{-3} with productivity of 2.35 g·dm^{-3} h at the batch stage and 0.77 g·dm^{-3} h^{-1} in the overall process	[41]
	P. freudenreichii CICC 10,019 fermentation combined with expanded bed adsorption bioreactor (EBAB) of liquid hot-water-pretreated corn stalk hydrolysates	47.6 mg dm^{-3} vitamin B12 and 91.4 g dm^{-3} propionic acid at 258 h, with yields of 0.37 mg/g and 0.75 g/g, respectively	[42]
Succinic acid	SSF at 38 °C for 48 h, diluted alkaline-pretreated corn straw as substrate at 70 g dm^{-3}, load of 20 FPU cellulase, and 10 U cellobiase per gram of substrate	47.4 g dm^{-3} in maximal concentration, 0.72 g/g-substrate in yield	[43]
	Anaerobic fermentation of corn stalk hydrolysate with AFP111	21.1 g dm^{-3} in yield with corresponding yield of 76%	[44]
Levulinic acid	SIRE–BE for glucose conversion to fructose (yield > 88%) and transferred fructose to low-pH aqueous medium. Dehydration of fructose to HMF and conversion of HMF to LA at high yield (>60%)	Significant load of 6.4 wt% converted from fructose at high yield (63 mol%) and facile reaction conditions	[45]
	230 °C and 10 min with 0.5 mol/L catalyst ($FeCl_3$) with corn stalk as biomass substrate	Highest yield at 48.73%	[46]
	180 °C, 40 min with 0.5 mol/L $FeCl_3$	Maximum concentration of 16.14 g dm^{-3}, or yield of 48.89%	[47]
Hydroxycinnamic acids	Mild alkaline pretreatment of corn straw with sodium hydroxide, ethanol, and water	Coumaric acid and ferulic acid yields of 20 wt% and 9.5 wt%, respectively, on a lignin basis, total hydroxycinnamic acid yield of 33.5%	[48]
Glucose, cellobiose and xylose	Steam explosion and alkaline peroxide treatment to remove hemicellulose and lignin	220, 175, 22 and 20 g dm^{-3} reducing sugar, glucose, cellobiose, and xylose, respectively	[49]
Glucose and xylose	Removal of lignin at 90 °C, 20 min, 9/1 (*v*/*v*) dioxane–water including a 1.0 wt% HCl solution; treatment at 120 °C and 40 min in 1.0 wt% dilute hydrochloric acid	Total yields of glucose and xylose at 91.5% and 79.7%, respectively	[50]
Glucose and xylose	Ozonolysis for 90 min followed by planetary ball milling for 8 min with cellulase loading of 15 FPU/g straw	Glucose yield (407.76 mg/g- straw), nearly highest xylose yield (101.87 mg/g- straw)	[51]
xylo-oligosaccharides	Extraction of xylan with 10% NaOH, and enzymatic hydrolysis	Maximum yield of 1115 ± 32—1908 ± 26	[52]
	purification and separation of oligosaccharides in hydrolysates according to molecular masses using gel filtration chromatography	4 g dm^{-3} monosaccharides and acetic acid	[53]
Xylitol	Hydrolysate from the steam explosion pretreated Candida tropicalis CCTCC M2012462	Maximal xylitol concentration of 35.6 g dm^{-3}, productivity of 0.94 g l^{-1} h^{-1}, xylose yield of 0.71 g g^{-1}	[54]
Furfural	45 mg of SC-CaCt-700, 150 mg of corn straw and 7 mL of solvent mixed under magnetic stirring and heated in a preheated oil bath at 200 °C for 100 min	Yield of 93% in γ-valerolactone and 51.5% in water	[55]
D-allulose	*Escherichia coli* whole-cell catalyst-based microfluidic device to produce D-allulose from corn stalk hydrolysate.	Increase in D-allulose titer by 8.61 times to 8.78 g dm^{-3}	[56]

Different from the single-bacterium fermentation strategy, Cui et al. (2011) investigated the combination of *Lactobacillus rhamnosus* and *L. brevis* for producing lactic acid from NaOH-pretreated corn straw, and significantly improved the yield of lactic acid to 0.70 g/g [38]. With the same level of robust tolerance against inhibitors, two *L. acidilactici* strains were engineered from the wild-type *L. acidilactici* DQ2 using *ldhD* or *ldh* gene disruption. In SSFR, *P. acidilactici* TY112 and *P.* acidilactici ZP26 produced L- and D-lactic acid, respectively, which validated the feasibility of producing high-titer L- and D-lactic acid from corn straw [39].

2.1.2. Fumaric Acid

Fumaric acid, a four-carbon unsaturated dicarboxylic acid, is extensively used in the food, chemical, and medical fields [57,58]. As xylose and glucose are the main components of corn straw, Xu et al. (2010) implemented a two-stage method to efficiently utilize lignocellulosic biomass for fumaric acid production using *Rhizopus oryzae*. In practice, fumaric acid was generated in the hydrolysates from the enzymatic hydrolysis of corn straw residues after acid hydrolysis. The fumaric acid production was maximized to 27.79 g dm^{-3} under ideal conditions. The yield and productivity of fumaric acid were estimated to be 0.35 g/g and 0.33 g dm^{-3} h^{-1}, respectively [40].

2.1.3. Propionic Acid

Propionic acid, an aliphatic 3-carboxylic acid, has significant promise as a desirable organic substance that may be derived from lignocellulosic carbohydrates [59,60]. It potentially functions as a fundamental component for the synthesis of diverse C3-based substances. So far, the numerous efforts for propionic acid generation have focused on biological production using *Propionibacterium* (e.g., *P. acidipropionici*, *P. freudenreichii*, and *P. shermanii*), which can metabolize an enormous spread of carbon sources and produce propionic acid under anaerobic conditions.

Wang et al. (2017) systematically investigated the use of *P. acidipropionici* to improve the industrial viability and integration into propionic acid production of corn straw, which is the largest biomass system in the agricultural sector. After experimental improvement, the propionic acid titer and productivity were increased from 32.1 g dm^{-3} and 0.31 g dm^{-3} h^{-1} in DDAPH batch fermentation to 64.7 g dm^{-3} and 0.77 g dm^{-3} h^{-1}, respectively, in DDAPH fed-batch HCD fermentation, which both roughly doubled by changing process conditions [41]. Wang et al. (2020) applied crop stalk hydrolysates prepared using a liquid hot water method to optimize an economical process for the simultaneous production of propionic acid and vitamin B12. For higher fermentation outcomes, fed-batch fermentation with *P. freudenreichii* CICC 10,019 was performed in an expanded bed adsorption bioreactor (EBAB), and generated 47.6 m g dm^{-3} vitamin B12 and 91.4 g dm^{-3} propionic acid after 258 h, which correspond to yields of 0.37 mg/g and 0.75 g/g, respectively [42].

2.1.4. Succinic Acid

Succinic acid, a C4-dicarboxylic acid, is widely applied as the precursor of different essential chemicals in the agricultural, nutritional, and pharmaceutical industries [61,62]. From the perspectives of industrial application and commercialization, continuous strain improvement and purification simplification are attracting much attention. Zheng et al. (2010) applied the SSF technique for succinic acid production from corn straw using *Actinobacillus succinogenes* CGMCC1593. Under optimal conditions, the concentration and yield of succinic acid reached 47.4 g dm^{-3} and 0.72 g/g substrate, respectively, which suggest a potential for succinic acid industrial production from SSF using cheap biomass materials [43]. Jiang et al. (2014) investigated the mutation of AFP111 using ARTP combined with ME, and examined xylose consumption, succinic acid production, and the ATP of a typical *E. coli* mutant. Under anaerobic fermentation with nearly 80% xylose from corn stalk hydrolysate, 21.1 g dm^{-3} succinic acid was obtained, with a corresponding yield of 76% [44].

2.1.5. Levulinic Acid

Levulinic acid is a short-chain fatty acid containing a ketone group and a carboxylic acid group [63–65]. Because of these two functional groups, levulinic acid becomes a potentially versatile building block for synthesizing various organic compounds (e.g., levulinate esters) and can be used to produce food flavor, tobacco flavor, and fuel additives. Therefore, levulinic acid can be seen as an attractive chemical intermediate to synthesize liquid fuels and useful chemicals. To obtain more levulinic acid, an increasing number of scientists have conducted experiments with corn stalk.

Siamak Alipour and Hamid Omidvarborna proposed a new method for producing high-concentration levulinic acid from acid-pretreated corn straw [45]. In detail, a simultaneous isomerization, reactive extraction, and back-extraction method was used to convert glucose from a biomass hydrolysate solution to fructose at high yield (88%), and then to transfer fructose to an acidic aqueous reaction medium. In this medium, fructose was converted at a high yield (63 mol%) under facile reaction conditions to levulinic acid (yield up to 6.4 wt%) at the end of the process. In summary, this process also benefits from low energy input, recyclable streams, and catalysts. Lu et al. used $FeCl_3$, a more common inorganic salt, to catalyze glucan hydrolysis to produce levulinic acid with corn stalk as the substrate. The highest levulinic acid yield was obtained at 48.73% at 230 °C after 10 min in a 0.5 mol/L catalyst solution [46]. With the same catalyst (0.1–0.5 mol/L $FeCl_3$), Lu et al. (2017) investigated the optimal conditions of extracting levulinic acid from corn stalk at 160–200 °C for 0–60 min in a stainless-steel batch reactor. A maximum levulinic acid concentration of 16.14 g dm^{-3} was obtained at 180 °C and 40 min with 0.5 mol/L $FeCl_3$ [47].

2.1.6. Hydroxycinnamic Acids

Hydroxycinnamic acids exist mainly in plants, herbs, and fruits and have garnered attention recently owing to their potential health-promoting properties [66]. Recent studies manifest that corn straw may potentially contain up to 6 wt% hydroxycinnamic acids, and therefore several million tons of hydroxycinnamic acids can be yielded from corn straw for cellulosic ethanol production. Patrick A. Johnston et al. (2020) presented gentle alkaline pretreatment of corn straw hydrolysis for the direct extraction of hydroxycinnamic acids. The coumaric acid and ferulic acid yields on a lignin basis were 20 wt% and 9.5 wt%, respectively, with a total hydroxycinnamic acid yield of 33.5%. Even for enzyme loading at only 10% of the recommended level for enzymatic hydrolysis, the glucose yields reached 83.3 wt% at about 48 h and 85.3 wt% at 96 h [48].

2.2. Saccharides

The carbohydrates in biomass can be hydrolyzed into mono-saccharides, which are then transformed to yield an assortment of bio-fuels and chemicals. Nevertheless, the effective use of lignocellulose is impeded by its inherent structural complexity. The chief goals of the commonly reported pretreatment before hydrolysis are to lessen the contents of hemicelluloses and lignin, enhance porosity and surface area, and minimize crystallinity and fiber size. Despite the beneficial effects of the pretreatment procedures for lignocellulosic hydrolysis, achieving the optimal usage of lignocellulosic materials remains a challenge.

2.2.1. Monosaccharide

A higher level of sugars will be advantageous for subsequent fermentation, particularly in the fed-batch fermentation approach. To produce fermentable sugars in a high concentration, Yang combined steam explosion and alkaline peroxide to eliminate hemicellulose and lignin. Under the optimal conditions, the concentrations of reducing sugar, glucose, cellobiose, and xylose reached 220, 175, 22, and 20 g dm^{-3}, respectively. The fed-batch approach achieved a final total biomass conversion rate of 60%, which highlights the importance of pretreatment and the fed-batch process in sugar production [49].

Compared with one-stage pretreatment, two-stage pretreatment was developed to destroy the compact structure of lignocelluloses by removing lignin and hemicelluloses, which allowed cellulose to be more accessible to cellulase and thereby increased glucose recovery with a low enzyme dosage. An developed a two-stage pretreatment method to mitigate the adverse impacts of hemicelluloses on enzymatic hydrolysis and enhance the yields of glucose and xylose. With an enzyme dosage of 3 FPU/g substrate, the yields of glucose and xylose reached 91.5% and 79.7%, respectively, after the removal of lignin and hemicelluloses. The yield improvement was mainly attributed to the enlarged specific surface area and pore volume of enzymes to the cellulose [50].

Shi et al. applied two clean pretreatment processes, including 90 min of ozonolysis and 8 min of planetary ball milling, to improve the enzymatic hydrolysis of corn straw. Such a combination resulted in the highest glucose yield (407.76 mg/g straw) and almost the highest xylose yield (101.87 mg/g straw), which indicate the combination is a promising technique for preprocessing lignocellulosic biomass. Meanwhile, the cellulase loading for corn straw hydrolysate significantly decreased after ozonolysis and/or planetary ball milling pretreatment [51].

2.2.2. Xylo-Oligosaccharides

As functional sugars, xylo-oligosaccharides consist of 2–7 xylose units linked by β-1,4-glycosidic bonds, and demonstrate several bioactive properties. More interestingly, xylo-oligosaccharides present many technological advantages, such as high pH stability and thermal stability, which make them great candidates to be used in the food, health care, chemical, animal husbandry, and pharmaceutical industries. Zhang et al. systematically investigated the desorption of oligo-saccharides during ethanol elution to improve the quality and anti-oxidant activity of xylo-oligosaccharides extracted from corn stalk. The maximum purity of xylo-oligosaccharides reached 98.12% from 30% ethanol eluate. Furthermore, an assessment of antioxidant activity revealed that 3 mg/mL xylo-oligosaccharides extracted from 70% ethanol eluate exhibited the highest radical scavenging activity [52]. Patrícia Moniz et al. assessed the bifidogenic potential of substituted xylo-oligosaccharides from corn straw through non-isothermal auto-hydrolysis. Two fractions with the polymerization degrees 4–6 and 9–21 of refined xylo-oligosaccharides, respectively, were separated via gel filtration chromatography. Compared with commercial oligosaccharides, all the substrates were utilized by the microbiota, and fermentation increased bifidobacterial populations. Moreover, the production profile of short-chain fatty acids for xylo-oligosaccharides samples [53] is similar to that of commercial oligosaccharides.

2.2.3. Xylitol

Xylitol is particularly appealing in the food sector owing to its lack of an aldehyde or ketone functional group, which cannot induce a Maillard browning reaction when utilized in baked foods. Traditionally, the complex chemical route, complicated pretreatment, and high production cost limit the utilization of xylitol in the food industry. Nevertheless, the relatively easy and environmentally friendly microbial conversion of xylose to xylitol has attracted attention worldwide. With the aim to obtain both high xylose recovery and a high saccharification efficiency of glucan, the hydrolysate was obtained initially from the steam explosion pretreatment of corn straw. The maximal xylitol concentration, xylose productivity, and xylose yield were achieved at 35.6 g dm^{-3}, 0.94 g dm^{-3} h^{-1}, and 0.71 g/g, respectively, without detoxification, and after 38 h of fermentation using *Candida tropicalis* CCTCC M2012462. These findings potentially contribute to an exceedingly economical procedure for producing xylitol from xylan in corn straw [54].

2.2.4. Furfural

Because of its flexibility in producing various valuable substances (e.g., tetrahydrofurfuryl alcohol, 2-methlfuran, and valerolactone), furfural is regarded as a crucial platform component. Li et al. proposed a potential approach to enhance the direct conversion of raw corn straw into furfural using SC-CaCt-700, a brand-new and potent heterogeneous acid catalyst. With an improved furfural yield of 93% from 150 mg of raw corn straw at 200 °C for 100 min treatment in γ-valerolactone and a 51.5% yield in water, SC-CaCt-700 was extremely capable of directly converting raw corn straw into furfural owing to its large surface area and SO_3H density. On the whole, this technique devised to simultaneously turn hemicellulose and cellulose into furfural offers a possible means of fully using raw biomass, which is of great industrial interest [55].

2.2.5. D-allulose

D-allulose has been certified as generally recognized as safe (GRAS) by the FDA as it is a high-value rare sugar with multiple beneficial health effects. However, as a rare sugar and a good sugar substitute, D-allulose is seldom discovered in the natural world. Therefore, Jia et al. obtained a high-efficiency *Escherichia coli* engineered catalyst by combining biomolecular methods to manufacture D-allulose from D-glucose. Then, with a whole-cell catalyst immobilized microfluidic system, the corn stalk hydrolysate was converted into D-allulose, which was provided to verify the feasibility of producing D-allulose from non-food corn stalk [56].

3. Technology Readiness Assessment and Processing Challenges

To date, corn straw has received significant attention as an ideal source for producing various active substances. It is widely known that the composition of corn straw directly influences the process economy by raising or decreasing the end product yield, thus pretreatment (e.g., physicochemical, chemical, and biological methods) is the most crucial step that hinders bioactive compound production from corn straw, and is recognized as one of the most expensive processing steps [67,68]. After detoxification, corn straw is converted by enzymatic and biochemical approaches; the latter is considered to be more sustainable, owing to its selective conversion under mild conditions using microorganisms [69]. To address the current state-of-the-art of different approaches for corn straw conversion to bioactive compounds, many reviews are focused on the technological perspective of newly developed methods, such as ionic liquids (Figure 2). Nevertheless, growing concerns about the techno-economic basis in the production of corn straw-based active substances have remained questionable and have limited commercial applications [70]. The existing research has focused on maximizing the extraction efficiency, but ignores factors such as environmental impact and supply chain logistics. These steps not only contribute to the lack of cost-effective conversion technologies, and limited scale-up of product-specific technologies, but also lower competitiveness in the market compared to their counterparts.

Aiming at developing efficient technologies, it is crucial to quantify the technical and economic requirements, from the corn straw to the bioactive product. At the global scale, the National Aeronautics and Space Administration (NASA) proposed a qualitative method, technology readiness level (TRL), to characterize the maturity of a technology on a scale score from one to nine [71,72]. A higher scored technology can be employed on a commercial scale. As the numeric indication for comparing different biorefinery concepts and their potential, TRL 1–3 is identified as the laboratory scale, TRL 4–6 as the pilot scale, and TRL 7–9 as the commercial scale [73,74]. However, the techno-economic perspectives of corn straw-based bioproduction have remained questionable as the high-value utilization of corn straw is a complicated process involving multiple steps with different technologies [75]. With high efficiency, the absence of inhibitor production, and low environmental risks, mechanical milling has been used for biomass pretreatment at the pilot scale, and is evaluated to be at TRL 5–6. As a crucial step in many industries, the enzyme pretreatment of corn straw is identified at a TRL of 7–8. However, the high cost of enzymes limits its wide full-scale application. Other biological methods such as aerobic and anaerobic pretreatment are still at the laboratory scale, and their TRLs are 4–6. Although the technology has almost reached the highest level of the scale, some challenges still need to be overcome at the bench scale to reach higher production rates at the industrial scale of operation. Based on the assessment, the main issues that need further investigation are the proposal of kinetic mechanisms, the development of low-cost upgrading techniques, and pilot plant tests (Figure 3).

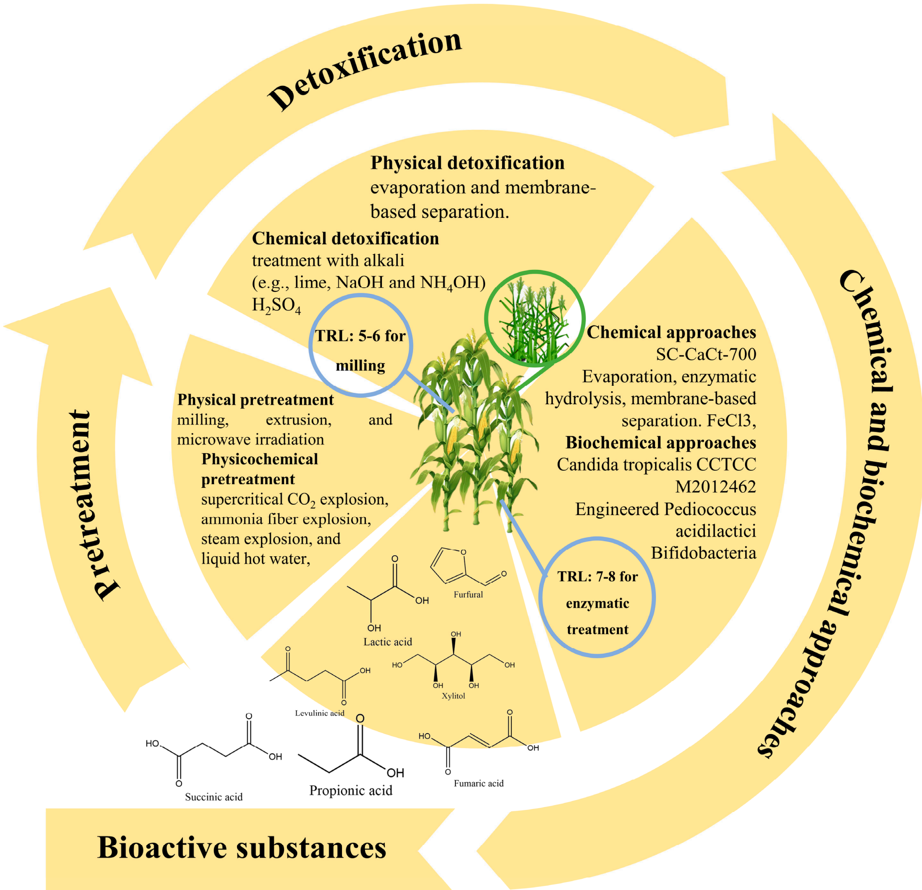

Figure 3. Summary of the process technology and TRL of the main active substance production from corn straw.

4. Conclusions

As a renewable resource, corn straw has great potential for waste utilization in agriculture and sustainable development. It is well known that soil fertility can be improved after straw incorporation. In addition to the application of clean energy production, the suitability of corn straw for the food and biopharmaceutical industries also deserves attention. Apart from technological advancement, the primary concern for farmers is whether the benefits outweigh the costs when deciding on the utilization of the straw resource. In developing countries, farmers tend to prefer direct burning rather than “turning waste into treasure”, which may be due to the dual constraints of technical limitations for straw utilization and the absence of mature markets. As a result, farmers find it challenging to identify convenient and economically beneficial ways to deal with their straw waste. In recent decades, the corn straw was widely used in the development of green energy, and its active ingredients, including organic acids and saccharides, were also exploited for application in the food and biopharmaceutical industries. Therefore, the core challenges for the utilization of straw resources lie in addressing the technical bottlenecks, breaking through the market barriers, and increasing government investment, thereby enabling farmers to achieve significant economic benefits with minimal time investment and reduced labor costs. In summary, the additional value of corn straw can be significantly improved by accelerating the technological innovation of straw utilization and the commercial circulation of its high value-added products.

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