Review article

Furfural as a low-volume, high-value asset from agricultural residues: A review on production, agricultural applications and environmental sustainability

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ABSTRACT

This comprehensive review explores furfural production from agricultural residues, focusing on its significance as a low-volume, high-value asset crucial for environmental sustainability. It covers diverse production technologies, recent advancements, and applications in agriculture, evaluating furfural's potential to enhance crop resilience and yield. Showing its role in a circular economy, the review discusses how furfural can replace conventional petrochemical processes, thereby reducing environmental impact. Case studies, such as successful implementations with cotton biomass byproducts, illustrate furfural's practical applications and environmental benefits. The study underscores the need for ongoing research, supportive policies, and furfural's growing role in sustainable agriculture and industry. It is focused on furfural's essential contribution to promoting environmental stewardship and sustainable practices. By examining furfural's role as a value-added product from agricultural residues, this review provides insights into its economic viability and potential challenges.

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1. Introduction

In recent years, there has been a renewed interest in using agricultural waste to make useful compounds. This is because of the focus on sustainable practices and the search for alternative, eco-friendly materials [1]. One such compound is furfural, which has garnered significant attention due to its wide applications and economic potential. Furfural production was first industrialized in 1922 by Quaker Oats company, marking the beginning of large-scale production using corn cobs and sugarcane bagasse as raw materials [2,3]. This breakthrough highlighted the viability of converting agricultural waste into valuable chemicals and set the stage for furfural's broad industrial applications. Furfural is in high demand across diverse industries such as oil refining, plastics, pharmaceuticals,
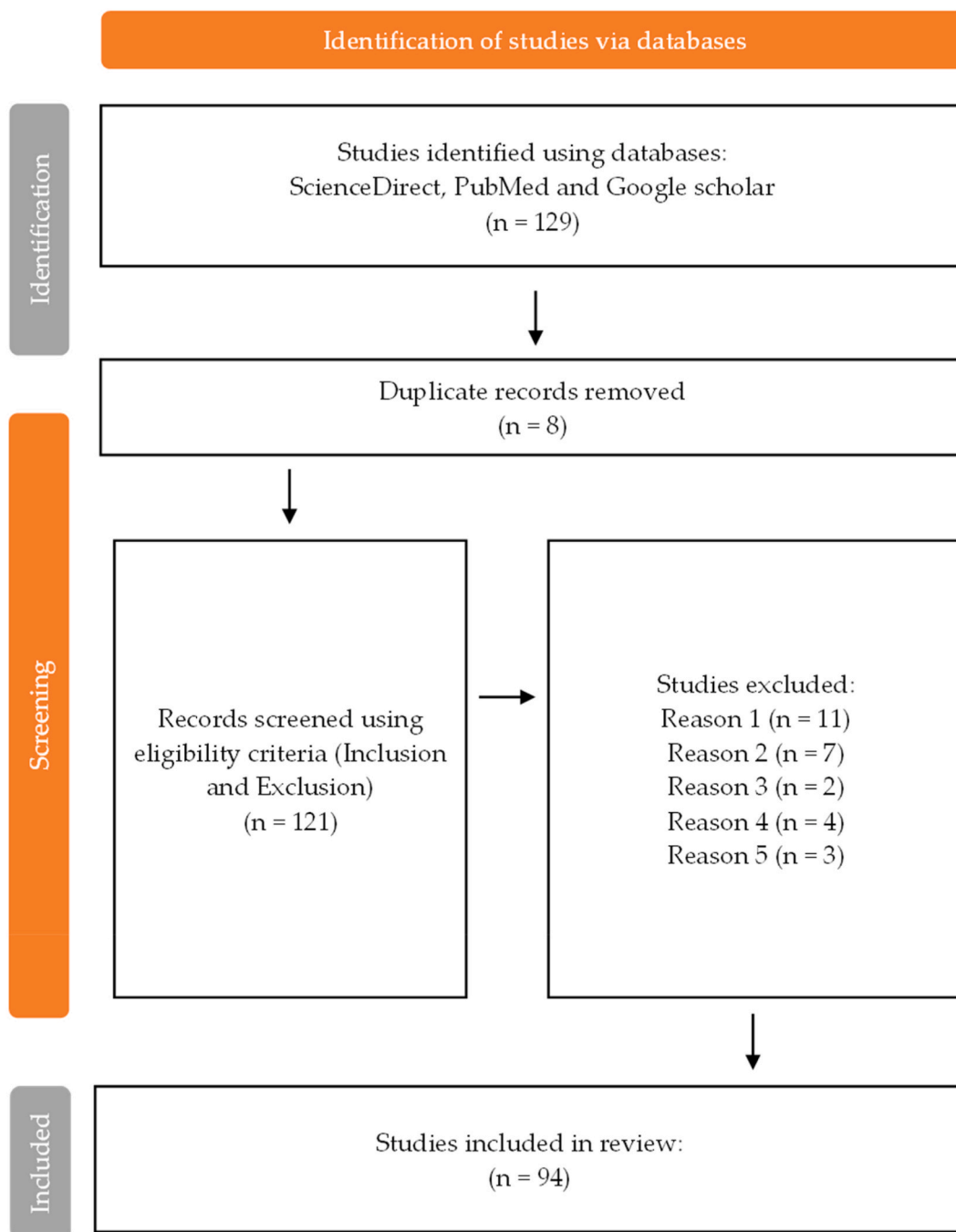

Fig. 1. Flow diagram for the criteria employed for selection of publications in review where database such as ScienceDirect, PubMed and Google scholar is used to search articles and were screened using eligibility criteria mentioned in section 2 and total of 74 studies were selected for review.

agrochemicals, and food. Companies like KRBL Limited (India), Central Romana Corporation (Dominican Republic), Pennakem (US), Hongye Holding Group Corporation Limited (China), Illovo Sugar (South Africa), Lenzing AG (Austria) and Merck KGaA (Germany) are some of the prominent companies in furfural market [4]. The production of furfural relies exclusively on the dehydration of sugars sourced from hemicelluloses, emphasizing the unique process and the absence of synthetic routes in the chemical industry. This bio-based chemical is primarily derived from lignocellulosic materials like corncobs, rice husks, and sugarcane [5,6]. The versatility of furfural extends to various applications: it is used in the chemical industry to produce resins and adhesives, in pharmaceuticals for potential therapeutic agents, and in the manufacturing of polymers and plastics. The shift towards renewable resources and environmental goals positions furfural as a key component in the bio-based economy. It is recognized as one of top thirty most valuable bio-based chemicals, underscoring its importance, the ongoing research into its production processes [5]. Industrial production of furfural typically involves the use of mineral acid solutions, such as phosphoric acid (H_3PO_4) or sulfuric acid (H_2SO_4), under pressure with biomass. However, this method is energy-intensive, inefficient, and generates significant pollution. For instance**,** Peleteiro and coworkers [4] have pointed out that this production process uses a lot of energy, and it is not very efficient. It is not practical or cost-effective to make furfural straight from lignocellulosic biomass that has not been treated. This is because the part that is being studied, hemicellulose, only makes up a small part of the whole lignocellulosic biomass [7–9]. Recent focus has shifted to biomass pre-treatment as a crucial step for efficiently recovering individual polymers and other compounds from lignocellulosic biomass [10, 11]. Catalysts play a critical role in biomass conversion, with research efforts concentrated on homogeneous and heterogeneous catalysts. Heterogeneous catalysts are particularly noteworthy due to their ease of post-separation and recyclability [7]. Additionally, the choice of solvent systems, including ionic liquids, organic solvents, and deep eutectic solvents, significantly influences furfural yield and process sustainability. Biphasic solvent systems for online extraction have demonstrated effective inhibitory effects with least side reactions [6,9]. The comprehensive investigation of heterogeneous acid catalysts in a study [5] provided an overview of their utility in producing furfural, 5-hydroxymethylfurfural (5-HMF). The flexibility in production and application of furfural makes it leading industrial chemical derived from biomass. Furthermore, it serves as a precursor for various furan-based chemicals, finds extensive use in producing decolorizing agents, nematicides, resins, fungicides, and bioplastics. Furthermore, furfural enhances flavors in food and beverages and has unique applications in infrastructure repair, wood modification, and book preservation [12]. Different from currently available literature reviews, the present **s**tudy distinguishes itself by providing novel insights into furfural production technologies, emphasizing innovative approaches to maximize furfural yield from agricultural biomass. By analyzing recent research findings, the review offers a inclusive overview of furfural's potential in sustainable farming practices, particularly its role in weed control, pest management, and soil enhancement. The review incorporates case studies and real-world applications, highlighting the practical implications and potential environmental and economic benefits of furfural production technologies. Additionally, we explore furfural's contribution to circular economy principles, showcasing its role in reducing agricultural waste, mitigating greenhouse gas emissions, and improving air and soil quality. Overall, our article not only presents novel insights and findings but also provides an up-to-date overview of furfural's diverse applications and its implications for environmental sustainability and circular economy practices.

2. Methodology

This review outlined inclusion and exclusion criteria to guide the selection of articles. Specifically, peer-reviewed journals were targeted to ensure the inclusion of high-quality sources, focusing on papers discussing production, agricultural applications, and environmental sustainability of furfural (Fig. 1). The search was conducted using various databases, including Web of Science, Scopus, Google Scholar, Science Direct with language restriction to English where ScienceDirect yielded most relevant studies. Keywords such as "Furfural production", "Agricultural biomass", "Cotton biomass", "Agricultural waste utilization", "Sustainable agriculture", "Environmental impact", "Pyrolysis", "Hydrothermal treatment", "Circular economy", "Petrochemical replacement", and "Crop yield enhancement" were used to identify relevant manuscripts. The search strategy followed the PRISMA guidelines, and initial searches were performed up to January 30, 2024, covering publications from 2007 to 2024 [13]. A total of 121 nonduplicate manuscripts were initially identified. These papers were further analyzed and 27 of them were taken out per our exclusion judgments (i. e., Reason 1: non-peer-reviewed articles, conference abstracts, and unpublished data; Reason 2: studies not directly related to furfural production, applications, or sustainability; Reason 3: articles discussing unrelated topics or applications outside the scope of furfural; Reason 4: studies lacking sufficient detail on methodologies, results, or implications; Reason 5: research papers published in languages other than English, unless an English translation is available). The left 94 publications met the inclusion criteria: peer-reviewed journal articles - research, reviews, and meta-analyses on furfural (furfural synthesis, environmental impact, economic feasibility, and practical applications of furfural; circular economy and furfural's role in replacing petrochemicals; furfural's potential in soil quality, crop yields, and agricultural sustainability; historical development). In addition to the 94 core papers, there were other 55 citations which are helpful for in-depth discussion on the historic development, emerging trends, raw materials background information, relevant processing procedure, and/or justifications. The review process involved analyzing titles, abstracts, and full-text manuscripts, with consensus reached through discussion in case of disagreement. Finally, some information and data in these included manuscripts were synthesized and analyzed multiple times to ensure accuracy and relevance.

3. Furfural production technologies

The production of furfural, a valuable and versatile chemical compound, involves various technological approaches that influence efficiency, yield, and environmental impact. Two-phase systems play a crucial role in the synthesis of furfural, offering a viable

solution to the challenges faced in single-phase systems. In single-phase systems, the furfural formed during the reaction is constant contact with substrate and catalyst. This interaction results into series of parallel reactions that produce unwanted by-products, reducing the yield and purity of the desired furfural product [14]. In contrast, two-phase systems provide a more controlled environment that mitigates these issues. These systems typically consist of an aqueous phase and an organic phase. The aqueous phase contains the substrate and catalyst, where the dehydration reaction occurs [15]. The organic phase, which is immiscible with the aqueous phase, acts as an extraction medium for the furfural. Nie and colleagues optimized conversion of xylose into furfural using various metal salts and ionic liquids. A single-phase system with $SnCl_4$ and 1-ethyl-3-methylimidazolium bromide (EMIMBr) achieved a 71.1 % yield at 20 wt% xylose concentration. A catalyst mixture of $SnCl_4$ (5 mol%) and $MgCl_2$ (5 mol%) yielded 68.8 %, similar to $SnCl_4$ (10 mol%) alone. Biphasic water-organic solvent systems further improved yields. The EMIMBr/$SnCl_4$ system, with water addition, efficiently converted xylan and corn stalk into furfural, yielding 57.3 % and 54.5 %, respectively [14]. Two-phase systems offer significant advantages in the synthesis of furfural, including selective extraction, enhanced yield and purity, and improved catalyst stability. Furfural's higher solubility in the organic phase facilitates its rapid partitioning away from the aqueous phase, reducing contact with the catalyst and minimizing side reactions [16]. This partitioning shifts the reaction equilibrium towards furfural formation, increasing both yield and purity by preventing the formation of by-products. Additionally, limiting the catalyst's exposure to reactive furfural and other intermediates helps maintain its stability and prolong its activity, thereby enhancing the overall process efficiency [17]. Several studies have highlighted the efficacy of biphasic systems, such as those using water and organic solvents like toluene or methyl isobutyl ketone, in significantly improving furfural yield and selectivity [18]. Consequently, implementing two-phase systems is a crucial strategy for the efficient and sustainable production of furfural, and future research should aim to optimize organic solvent selection and phase separation techniques to further refine this process.

3.1. Lignocellulosic biomass: composition and significance

Lignocellulosic biomass consist of three key components: cellulose, lignin and hemicellulose [19]. Hemicellulose and cellulose can be hydrolysed into fermentable sugars, essential for furfural production, while lignin is a complex aromatic polymer [20]. These components are crucial for plant cell wall structure and functionality, making them valuable for producing bio-based chemicals like furfural. Cellulose, making up 30–50 % of lignocellulosic biomass, is linear polymer of β-D-glucose units linked by β-1,4-glycosidic bonds, forming crystalline microfibrils [21]. This structure provides mechanical strength but resists enzymatic hydrolysis [22]. Effective pre-treatment methods were necessary for break down cellulose's crystalline structure, enhancing hydrolysis into fermentable sugars. Hemicellulose, accounting for 20–35 % of lignocellulosic biomass, is a branched, amorphous polysaccharide matrix that surrounds cellulose microfibrils. It consists of various sugar monomers like xylose, mannose, glucose, galactose, and arabinose [23]. As compared to cellulose, hemicellulose is less resistant to hydrolysis and can be more easily converted into
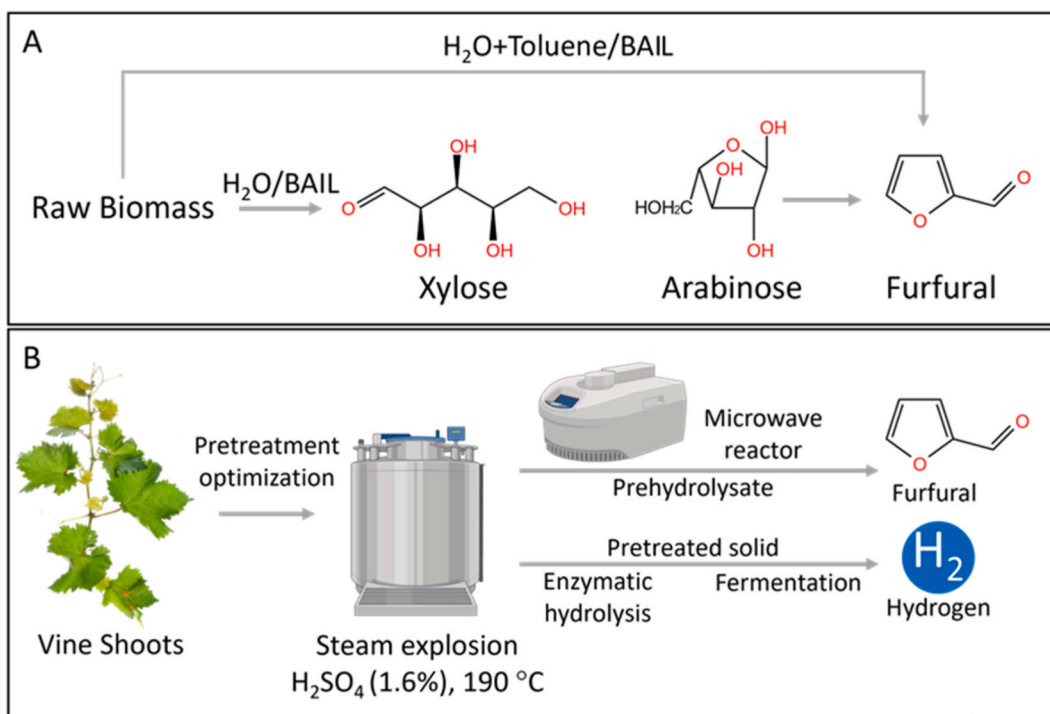

Fig. 2. A) Converting raw biomass into C5 sugars and furfural through a one-pot methodology by utilizing Brønsted acidic ionic liquids (BAILs) as catalyst (Adopted from [42]); B) Furfural production from vine shoots using steam explosion method (Adopted from [30]).

fermentable sugars, crucial intermediates in furfural production through acid-catalyzed dehydration [14]. Lignin, constituting 15–30 % of lignocellulosic biomass, is a complex aromatic polymer providing rigidity and resistance to microbial attack [24]. Composed of phenylpropanoid units linked by various bonds, lignin is difficult to break down and can hinder the hydrolysis of cellulose and hemicellulose [25]. However, lignin can be converted to high-value materials enhancing the economic viability of biomass processing. Effective separation and utilization of lignin can improve efficiency, profitability of furfural production. Understanding composition of lignocellulosic biomass and employing appropriate fractionation and pre-treatment techniques are crucial for optimizing furfural production, contributing to the sustainable use of renewable biomass resources.

3.2. Fractionation and pre-treatment technologies

3.2.1. Steam explosion

Various fractionation and pre-treatment methods are employed to process lignocellulosic biomass, making it more amenable to conversion into furfural. Steam explosion involves exposing biomass to high-pressure steam, resulting in the swelling of the cellulose and hemicellulose components [26]. This is followed by rapid decompression, which breaks down the cell walls and releases soluble sugars [27]. The physical disruption from steam explosion significantly enhances the digestibility of the biomass and enables efficient conversion of hemicellulose into furfural. Additionally, the integration of steam explosion into biorefinery concepts allows for the valorization of multiple biomass components, further enhancing resource efficiency [28]. Although not directly utilized to aid furfural production, the breakdown of hemicellulose through steam explosion sets the stage for subsequent furfural synthesis. In the preliminary study, Ghoreishi and colleagues employed large pilot-scale steam explosion for lignocellulosic feedstock breakdown, extracting valuable compounds such as furfural. Major components, including furfural of about 1.0 g/kg dry input biomass and acetic acid 0.5 g/kg was identified by quantitative analytical NMR spectroscopy. The addition of SO_2 was found to enhance furfural yields by promoting hemicellulose hydrolysis under acidic conditions, suggesting the potential for process optimization to increase profitability. Filtrate samples constitute 5-HMF having highest concentrations of 5.7–6.0 g/kg found in spruce filtrates. Feedstock type and explosion temperature significantly influenced total compound yield and showcasing potential profit margin enhancements, as exemplified in the ArbaOne pellets plant [29]. Study by Castro and colleagues [30] shows a comprehensive strategy for the valorization of vine shoots, an agricultural waste, involving steam explosion pretreatment and subsequent biological and chemical conversions (Fig. 2B). This integrated approach yielded significant recovery of sugars and furfural from vine shoots, demonstrating the potential for sustainable resource utilization and the production of bio-hydrogen and valuable chemicals. The optimized conditions yielded significant recovery of sugars, with hemicellulose sugars (68.2 %) and glucose (18.2 %) in the prehydrolysate. Enzymatic hydrolysis of the pretreated solid resulted in 45.3 % glucose, utilized by *Clostridium butyricum* for bio-hydrogen fermentation. Additionally, chemical conversion of xylose to furfural achieved noteworthy manufacture of 15 g/L with a 73 % yield. These results collectively highlight the potential of vine shoots as sustainable feedstock for production of bio-hydrogen and valuable chemicals, showcasing the efficiency of the proposed process strategy in maximizing resource recovery from this agricultural residue [30]. Tareen and his team investigated various catalysts for converting steam-exploded hydrolyzate from oil palm trunks into furfural. Their study demonstrated that the type of catalyst and the reaction conditions significantly affect furfural production efficiency. The different catalyst combinations resulted in varying degrees of xylose conversion and furfural yield, emphasizing the importance of selecting and optimizing catalysts in hybrid production processes. Under optimal conditions, a combination of sulfuric acid and dimethyl furamide achieved 100 % xylose conversion and a 66.43 % furfural yield at 170 °C over 2 h. Amberlyst-15 exhibited the highest xylose conversion at 77.05 %, a furfural yield of 35.74 %, and selectivity of 46.9 % at 130 °C for 3 h. Additionally, the combination of hydrotalcite and Amberlyst-15 produced notable results, achieving an 88.1 % xylose conversion, a 40.9 % furfural yield, and 46.4 % selectivity at 110 °C for 3 h. These findings highlight the significant impact of catalyst type and reaction conditions on the efficiency of furfural production from oil palm trunk hydrolyzate [31].

3.2.2. Enzymatic hydrolysis

Operating under milder reaction conditions compared to traditional acid-catalyzed methods, enzyme-assisted processes reduce energy consumption and minimize environmental impact. In enzymatic-assisted furfural production processes, enzymatic hydrolysis plays a pivotal role in breaking down hemicellulose into sugars, including xylose [6]. However, it's essential to note that while enzymatic hydrolysis primarily aims to produce sugars, conversion of xylose into furfural often occurs through subsequent acid catalysis. Acid catalysis offers a selective and efficient pathway for dehydration of xylose into furfural under optimized conditions, ensuring high product yields while minimizing unwanted side reactions. This sequential approach, starting with enzymatic hydrolysis followed by acid-catalyzed conversion, allows for precise control over reaction pathways and facilitates the efficient utilization of biomass resources for furfural production [32]. By integrating enzymatic and acid catalysis processes, enzymatic-assisted methods contribute to the advancement of green technologies in furfural synthesis, offering a more sustainable and environmentally friendly approach to biomass utilization. Moreover, the selectivity of enzymes enables precise control over reaction pathways, leading to higher product yields and fewer byproducts [33,34]. The mechanism involves the enzymatic hydrolysis of glycosidic bonds in cellulose and hemicellulose, releasing sugars that can be subsequently converted into furfural [35]. Through their sustainability and efficiency, enzyme-assisted processes contribute to the advancement of green technologies in furfural production. The study of He and coworkers [36] The study demonstrated the potential of one-pot synthesis for producing furfuralcohol (FOL) from corncob-derived xylose using efficient tandem catalysis with solid acid catalysts and *Escherichia coli* CCZU-T15 whole-cells. This method achieved high furfural yields and successfully converted furfural into furfuralcohol, showcasing the versatility and effectiveness of chemo-enzymatic catalysis for biomass utilization. Using SO_4^{2-}/SnO^{2-} kaoline as a catalyst at 3.5 wt%, a furfural yield of 74.3 % was achieved in a toluene-water

mixture (1:2, v) with OP-10 (p-octyl polyethylene glycol phenyl ether) at 170 °C for 30 min, demonstrating promising efficiency. Additionally, *E. coli* CCZU-T15 whole-cells transformed furfural (50.5 mM) into furfuralcohol at a 13.0 % yield from the starting corncob material when combined with corncob hydrolysate residue, produced by enzymatic hydrolysis (Spezyme CP cellulase, β-glucosidase) of oxalic acid-pretreated corncob. The overall one-pot synthesis strategy showcased notable potential for the effective utilization of corncob, particularly in achieving high FOL yields through chemo-enzymatic catalysis [36]. Cornejo and coworkers reported flexible two-step biorefinery for glucose and furfural production from various feedstocks exemplified the versatility and efficiency of tailored pretreatment conditions. By optimizing the process, the biorefinery showcased the potential to produce significant quantities of glucose and furfural from diverse biomass sources, underscoring its applicability in biomass conversion and valorization. Tailored pretreatment conditions enable 100 % glucose yields or efficient furfural transformation, showcasing versatility in biomass utilization, having the potential to produce 12.6 kg glucose and materials, along with 2.5 kg furfural, from 50 kg of biomass [37]. Sun and coworkers' developed highly efficient biorefinery process for Eucalyptus demonstrated the effectiveness of a biphasic system with specific catalysts for furfural production. By achieving high furfural yields and enzymatic hydrolysis efficiency, the study highlighted the potential for solvent-based biphasic systems to enhance cellulose conversion and biomass utilization, offering insights into process optimization and scalability. The researchers developed an efficient biorefinery process for Eucalyptus using a biphasic system of choline chloride/lactic acid and 2-methyltetrahydrofuran, with $Al_2(SO_4)_3$ and H_2SO_4 as catalysts. Optimized conditions (150 °C, 30 min, 0.2 M $Al_2(SO_4)_3$, 0.075 M H_2SO_4) resulted in a 54.7 % furfural yield and a 97.0 % enzymatic hydrolysis efficiency. This process effectively removed lignin (91.0 %) and hemicelluloses (100.0 %), enhancing cellulose conversion by disrupting the cell wall structure and increasing cellulose accessibility. Confocal Raman and atomic force microscope analyses confirmed the transformation, demonstrating the effectiveness of this solvent-based biphasic system [38]. However, it's important to note that while this study focuses on enzyme-assisted processes primarily for glucose production, enzymatic hydrolysis of hemicellulose can also assist in furfural production by releasing sugars that can be subsequently converted into furfural [35]. However, despite these promising advancements, further research is imperative to fine-tune process parameters, evaluate scalability, and address challenges related to cost-effectiveness and environmental impact. By overcoming these problems, enzyme-assisted furfural production technologies can be integrated into industrial settings, paving way for more sustainable and environmentally friendly approach to biomass utilization.

3.2.3. Acid-catalyzed hydrolysis

Acid-catalyzed hydrolysis, a method for furfural production, demonstrates significant environmental advantages by efficiently breaking down hemicellulose into furfural, this process maximizes the utilization of agricultural waste while minimizing the generation of residual biomass (Fig. 2) [39]. The mechanism involves protonation of glycosidic bonds in hemicellulose by the acid catalyst, facilitating hydrolysis and leading to the formation of xylose [40]. With optimized reaction conditions, acid-catalyzed hydrolysis offers high furfural yields from various biomass sources, contributing to resource efficiency and waste reduction in agricultural industries [41].

A critical challenge in acid hydrolysis for furfural production is the instability of furfural under typical operating conditions, leading to its decomposition into humins, which significantly reduces yield. Optimizing reaction conditions, employing biphasic systems, and using selective catalysts or stabilizing agents can mitigate this issue and improve furfural yield. Lyu and Botte studied the hydrolysis of hemicellulose, oxidation of corncobs and xylose, and humin formation using metal chloride catalysts to identify factors inhibiting furfural production at 90 °C and 170 °C. They found that hemicellulose hydrolysis was complete at 170 °C but incomplete at 90 °C. Both corncobs and xylose were oxidized to CO_2 and CO by certain metal chlorides at both temperatures, inhibiting furfural production. Additionally, no humins formed at 90 °C, while humin formation occurred with all metal chloride catalysts at 170 °C, significantly inhibiting furfural production at higher temperatures [43]. Xu and coworkers [44] addressed challenges in furfural synthesis from biomass, specifically the traditional acid-catalyzed dehydration of xylose and hemicellulose, known for poor activity and equipment corrosion. Utilizing pyridinium hydrogensulfate [Hpy][HSO_4] as a catalyst under optimal conditions, furfural yields of 75.4 % (from xylose) and 80.4 % (from hemicellulose) were achieved, surpassing most reported ionic liquids. Further, Kinetic equations were employed to calculate reaction constants and activation energies, revealing [Hpy][HSO_4]'s high efficiency, recyclability, and cost-effectiveness, positioning it for potential large-scale fu6rfural synthesis applications [44]. Homogeneous acids, such as sulfuric and hydrochloric acid, uniformly mix with the biomass, leading to efficient hydrolysis. However, they present challenges including corrosiveness, separation difficulties, and environmental hazards. Despite these drawbacks, they are widely used due to their high efficiency. For example, Yemis and Mazza [5] explored microwave-assisted acid-catalyzed conversion to furfural from xylose and xylan. They optimized condition at 180 °C with a solid-to-liquid ratio of 1:200, a time of 20 min, and pH 1.12. Hydrochloric acid emerged as the most efficient catalyst, yielding 72.1 %, 48.4 %, 45.7 %, furfural from flax shives, wheat straw, triticale straw respectively. Another study [45] investigates UAAH for converting various lignocellulosic materials to furfural using HNO_3 (4 mol L^{-1}) as acid. Using 0.1 g of grass, the study achieved the highest yield (72.4 ± 4.3 mg g^{-1}) under sonication conditions of 30 °C, 50 % amplitude, and a 60-min reaction time. Parameters such as ultrasound amplitude ranged from 20 % to 70 %, and the reaction time varied from 30 to 120 min, highlighting their influence on the yield. Compared to mechanical stirring, UAAH proved more effective, highlighting its potential as a single-step, lignin-removal-free method for biomass conversion to furfural. Soetedjo and coworkers investigated temperatures (140–170 °C) and sulfuric acid concentrations (0.1–0.5 M) with reaction times up to 120 min in solvent system of 70.0 w% ethanol in water. Results showed that higher temperatures and acid concentrations in the ethanol-water solvent led to shorter reaction times for maximum furfural yield. The study demonstrated significant improvement, achieving the highest furfural yield of 70.0–72.0 mol % after a 15-min reaction at 170 °C with 0.2–0.5 M sulfuric acid concentrations [45]. Heterogeneous acids, including solid acid catalysts like ion-exchange resins and sulfonated carbon materials, offer advantages such as ease of separation from the reaction mixture, reduced environmental impact, and reusability. However, they may require longer reaction times or higher

temperatures. Gomes and coworkers proposed a sustainable method using glycine-based ionic liquid, water-2-methyltetrahydrofuran biphasic system to produce furfural from sugarcane bagasse acid hydrolysates, demonstrating high yields and minimal lignin interference. Employing [GlyIm][HSO₄] and water-2-methyltetrahydrofuran (2-MeTHF) biphasic system, the authors optimize furfural yields while mitigating side reactions. The process begins with acid hydrolysis of SCB, extracting 85 % of hemicellulose, predominantly as xylose, under optimized conditions (150 °C, 30 min, 4 % v/v H2SO4). Furfural production from xylose achieves an 87 % yield using 10 equivalents of the ionic liquid at 180 °C for 10 min. Applying these conditions to SCB hydrolysates yields a remarkable 90 % furfural, demonstrating the efficacy of this green approach with negligible lignin interference [46]. Summarized details about furfural production technologies, detailing methods, feedstock sources, catalysts, and operating conditions are given in Table 1.

A promising area for future research that could revolutionize furfural production is the development of advanced catalysts tailored for efficient and selective furfural synthesis from diverse biomass feedstocks. A study utilized a heterogeneous catalyst, Pd–PdO/ZnSO₄ (1.1 mol% Pd), for furfural production via flash pyrolysis of lignocelluloses at 400 °C. This catalyst achieved high furfural yields: 74–82 mol% from both dry and wet C6 cellulose and its monomers, 96 mol% from C5 xylan, and 23–33 wt% from sugarcane bagasse and corncob. The catalyst features a structured design with bifunctional properties: ZnSO₄ supports glucose dehydration and isomerization, while a core-shell configuration of metallic Pd0 encapsulated by a PdO layer catalyzes Grob fragmentation of formaldehyde (HCHO) and subsequent steam reforming into synthesis gas (H2 and CO). This innovative catalyst promises efficient furfural synthesis, highlighting its reusability and potential for advancing sustainable biofuel production [47]. Current processes often rely on heterogeneous catalysts such as solid acids or acidic ionic liquids, which can have limitations in terms of activity, selectivity, and stability [48]. Research focusing on designing novel catalysts with enhanced performance could significantly improve furfural production efficiency. Additionally, catalysts that are more resistant to deactivation and can operate under milder conditions (lower temperature and pressure) would reduce energy consumption and environmental footprint [49].

3.3. Case study: preparation of furfural from crop residues

Cotton plant (*Gossypium hirsutum* L.) is grown mainly as a fiber source for textile industry. During the field growth and post-harvest processing, a vast quantity of cotton biomass materials other than fiber is produced. Those biomass byproducts include but are not limited to leaves, burs, sticks/stems/stalk, gin trash (waste), cottonseed hull [50–52]. Currently, common methods for the disposal of cotton byproducts include landfilling, incineration, and composting for soil amendment; however, they are not economical and efficient in considering the requirement of sizable land and suitability of climatic conditions [53]. Thus, valorization of those cotton byproducts as industrial raw materials is an important research challenge in cotton biomass research to increase the values of these byproducts [54–56]. The specific effort on production of furfural chemicals from cotton biomass materials is highlighted in the case study.

As per the data collected in 1975, Mansilla and coworkers [57] reported that there are 27 % of pentosan in cotton husk. However, the furfural yield in industrial operation is only 8–9% based on dry basis by the typical two-step procedure [57]. Abadir [58] applied the one-step process to make furfural from cotton stalks by hydrolysis in HCl solution. This work proposed an optimal condition of furfural production as hydrolysis time = 3.5 h, acid concentration = 11.5 % (w/s) and liquid/solid ratio = 30:1, tested at fixed temperature of 140 °C. At the optimal conditions, ZnO, CaO, And TiO could further promote the yield through the catalytic functions.

Lv and colleagues [59] investigated a method for the homogeneous degradation of cotton cellulose into furan derivatives by integrating reaction and extraction technologies. They dissolved cotton cellulose in concentrated ZnCl2 solution to enhance yields of 5-HMF, 1-(furan-2-yl)-2-hydroxyethanone, and furfural. Various organic solvents (such as TBP, n-OcOH, and n-BuOH) were used as extraction phases, with DMSO acting as an accelerator. However, the addition of DMSO inhibited the production of the key product, 5-HMF. Alternatively, using solid acid catalysts under hydrothermal conditions offers an environmentally friendly chemical process where products can be easily separated via filtration, allowing for catalyst reuse. They employed sulfated metal oxides (e.g., SO_4^{2-}/Fe₂O₃, SO_4^{2-}/ZrO₂ and SO_4^{2-}/TiO₂) for the direct catalytic degradation of cotton cellulose under mild hydrothermal conditions [60]. Applied to such superacid, selective conversion of cotton cellulose to glucose and 5-hydroxymethyl furfural was achieved while suppressing undesired side-products. Under optimal conditions, the cellulose conversion ratio reached 50.1 %, with a corresponding yield of 11.0 % and a selectivity of 22.0 % for 5-hydroxymethyl furfural, and a yield of 26.8 % with a selectivity of 53.4 % for glucose, respectively. While furfural and its derivatives are high-value chemicals in bio-oil produced by torrefaction or pyrolysis [61,62]. Cotton stalk pyrolysis was conducted in fixed bed reactor with purpose of chemical production of furfural and acetic acid [63]. The researchers found that both furfural, acetic acid concentrations in pyrolysis oil increased in presence of MgCl2 as a catalyst in the tested temperature range of 493–553 K. It has been reported that in water-free pyrolysis oil, the contents of furfural and acetic acid are 54 % and 28 %, respectively, at a pyrolysis heat of 553 K. Analysis of solid residues showed 85 % hemicellulose is decomposed, while cellulose, lignin remained reasonably stable. Similarly, Mo and coworkers [64] studied the catalytic degradation of the cotton stalk with solid super-acid (SO_4^{2-}/ZrO₂). They reported the optimized experimental conditions as temperature 503 K, time 75 min and catalyst dosage 30 % (mass fraction) with a maximal yield of 27.2 % for 5-HMF. Chen and coworkers [65] comparatively investigated the formation of furfural from three biomass byproducts (i.e., corncob, wheat straw and cotton stalk) by catalytic fast pyrolysis. They observed the highest furfural yield with corncob while the yield of wheat straw and cotton stalk are at the comparable level under the tested conditions. On the other hand, wheat straw shows better furfural selectivity than corncob and cotton stalk. Cottonseed hull, the byproduct of cotton processing, is rich in short cotton cellulose on its surface. Thus, utilization of cottonseed hull has also attracted the attention of furfural researchers. From cottonseed hull one-pot direct synthesis of 5-HMF was explored by Wang and coworkers The reported yield of 5-HMF reached up to 51 % using 1-butyl-3-methylimidazolium chloride ([Bmim]Cl) catalyzed by chromium (III) chloride at 130 °C for 2 h. However, reactant contained a lot of impurities because the fiber cellulose could not completely separate

Table 1

Overview of technologies used for furfural production.

Technology	Feedstock	Catalyst	Operating Conditions	Yield	Reference
Microwave-assisted acid-catalyzed conversion	Xylose, Xylan	Hydrochloric Acid (HCl)	Temperature: 180 °C Solid to liquid ratio: 1:200 Time: 20 min pH: 1.12	Furfural yield from Wheat Straw: 48.4 % Triticale Straw: 45.7 % Flax Shives: 72.1 %	[5]
Green method with ionic liquid	Sugarcane Bagasse	[GlyIm][HSO$_4$] (Glycine-based Ionic Liquid)	Furfural Production: Temperature: 180 °C Time: 10 min 10 eq. of Ionic Liquid	Furfural: 90 %	[46]
Ethanol-based furfural production	Xylose	H$_2$SO$_4$	Temperature: 140–170 °C Acid Concentration: 0.1–0.5M Reaction Time: Up to 120 min	Furfural: 70.0–72.0 mol%	[45]
Enzymatic hydrolysis	Corncob	Spezyme CP cellulase β-glucosidase	Enzyme loading-Spezyme CP cellulase: 15 FPU/g substrate Antibiotic: Tetracycline Temperature: 50 °C Rotation speed: 180 rpm Hydrolysis Duration: 95 h β-glucosidase: 30 CBU/g substrate	–	[36]
	Corncob-derived xylose	SO$_4^{2-}$/SnO2-kaoline	Temperature: 170 °C Time: 30 min Solvent: Toluene-water (1:2, v:v) with 10 mM OP-10	Yield of furfural: 74.3 %	
		E. coli CCZU-T15 whole-cells	Solvent: Toluene-water (1:3) with 12.5 mM OP-10 Temperature: 30 °C Furfural: 1.6 mol glucose/mol pH: 6.5	FOL yield: 100 %	
Enzymatic hydrolysis	Poplar Pine Whear straw	Enzyme: Cellic® CTec2	Biomass pretreatment-Temperature: 164–192 °C Residence time: 5 min Sulfuric acid (98 %)/Feedstock ratio (wt%): 0-4 Enzyme hydrolysis-Temperature: 50 °C Total Solids Content: 10 % pH: 5 with readjustment after 24 h Stirring: 180 rpm Hydrolysis duration: 72 h Enzyme dosage: 60 g/kg ODM (oven dry mass)	Microwave irradiation: Pine chips: 77 % Wheat straw: 45 % Poplar chips: 59 % Conventional heating: Poplar chips: 76 % Pine chips: 90 % Wheat straw: 58 %	[37]
Enzyme hydrolysis	*Eucalyptus grandis*	Al$_2$(SO$_4$)$_3$ H$_2$SO$_4$	DES-based biphasic systems utilize choline chloride/lactic acid (ChCl/LA) along with 2-methyltetrahydrofuran (2-MTHF). Pretreatment condition-Temperature: 150 °C Time: 30 min Catalyst Concentrations: 0.2 M Al$_2$(SO$_4$)$_3$, 0.075 M H$_2$SO$_4$ Enzyme: Cellulase	Furfural: 54.7 % Enzymatic hydrolysis efficacy: 97.0 %	[38]
Steam Explosion Pretreatment	Vine Shoots	–	Temperature: 190 °C Solvent: H$_2$SO$_4$ Impregnation: 1.6 %	Hemicellulose recovery: 68.2 % Glucose recovery: 18.2 %	[30]
Enzymatic Hydrolysis	Pretreated Vine Shoots	–	–	Glucose Recovery: 45.3 %	
Biological Conversion (Fermentation)	Pretreated Vine Shoots Slurry	–	–	Biohydrogen Production: 830.7 mL/L Yield: 3550 mL/100 g raw vine shoots	
Furfural Production (Microwave Reactor)	Hemicellulose in Prehydrolysate	–	Temperature: 202 °C Catalyst: 0.195 M FeCl$_3$	Furfural Production: 15 g/L (Yield: 73 %)	
Steam explosion pretreatment followed by acid hydrolysis	Oil palm trunk	–	Steam explosion-Temperature: 210 °C Time: 4 min Pressure: 0.68–7.0 MPa Acid hydrolysis-Temperature: 121 °C Time: 1 h Solvent: 3 % H$_2$S0$_4$	–	[31]

Table 1 (*continued*)

Technology	Feedstock	Catalyst	Operating Conditions	Yield	Reference
Furfural production from hydrolyzate	Oil palm trunk hydrolyzate	–	Temperature: 170 °C Time: 120 min Solvent: H_2SO_4, Dimethyl furamide ($C_9H_{13}NO_2$) Pressure: 0.68–7.0 MPa	Xylose conversion: 100 % Furfural yield: 66.4 %	
Furfural production with cosolvents	Oil palm trunk hydrolyzate	Amberlyst-15	Temperature: 130 °C Time: 3 h Pressure: 0.68–7.0 MPa	Xylose conversion: 77.1 % Furfural yield: 35.74 % Selectivity: 46.9 %	
Furfural production with solid/base catalysts	Oil palm trunk hydrolyzate	Hydrotalcite Amberlyst-15	Temperature: 110 °C Time: 3 h Pressure: 0.68–7.0 MPa	Furfural Yield: 40.9 % Xylose conversion: 88.1 %	

from the shell. Thus, Ge and coworkers [66] adopted alkali dissolution and acid dissolution methods to prepare cellulose from cotton hull first. 5-Hydroxymethyl furfural was then produced from the purified cottonseed hull cellulose. The authors reported a yield of the furfural product around 40 % under the catalysis of $H_4[Si(W_3O_{10})_4]$ and $CuCl_2$. For cotton farming sustainability, Subramani and coworkers [67] examined a biorefinery process for the conversion of cotton gin trash to multiple high value products. In the process, the cellulose-rich fraction of gin trash was converted to 39 mol% (with 80 % purity) of 5-chloromethylfurfural, a solid fuel possessing a higher heating value of 20 MJ kg^{-1}. The case studies outlined in the review highlighted the innovative utilization of cotton biomass byproducts for furfural production, their significant environmental impact and practical applications. By repurposing agricultural residues into valuable chemicals, these studies exemplify the potential for sustainable resource utilization and waste reduction in the agricultural sector. For instance, Mansilla and coworkers [57] highlighted the considerable pentosan content in cotton husk, indicating the potential for furfural production from this agricultural waste. This study underscores the environmental impact of repurposing cotton husk, a byproduct of the textile industry, into a valuable chemical feedstock, thereby reducing waste and resource depletion. Abadir's work [58] on the one-step furfural production process from cotton stalks using hydrolysis in HCl solution demonstrates a practical approach to converting agricultural residues into high-value chemicals. By optimizing hydrolysis conditions and exploring catalytic enhancements. Lv and coworkers' research [59] cotton cellulose homogeneous degradation into furan derivatives presents an innovative technique for maximizing product yields while minimizing the generation of undesirable by-products. This approach not only enhances the environmental sustainability of furfural production but also offers practical advantages in terms of product purity and efficiency. Moreover, the utilization of solid acid catalysts in hydrothermal conditions, as demonstrated by various studies, offers a green alternative for furfural synthesis from cotton cellulose. By leveraging environmentally friendly catalysts and mild reaction conditions, these methods minimize energy consumption and waste generation, contributing to the overall sustainability of furfural production processes. Additionally, the exploration of cottonseed hulls and cotton gin trash for furfural synthesis underscores the importance of valorizing agricultural waste streams. By converting these biomass byproducts into valuable chemicals, such as furfural and its derivatives, these studies demonstrate the potential for creating economic value while simultaneously reducing environmental impact through waste reduction and resource utilization (Fig. 3). Overall, these case studies showed the environmental benefits and practical applications of furfural production from cotton biomass byproducts. By utilizing agricultural waste into valuable chemicals, such as furfural, these studies contribute to the transition towards a more sustainable and circular economy, where waste is minimized, and resources are utilized efficiently.
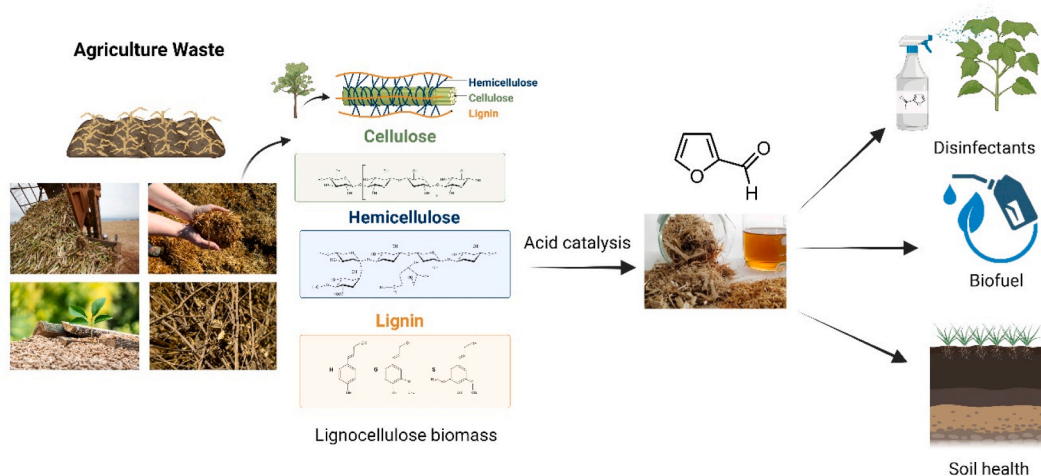

Fig. 3. Production of furfural through agriculture waste.

Corn cobs, which contain approximately 29.98 % hemicellulose, can be effectively used for the preparation of furfural [68]. In a study by Du et al. (2015), one-pot method used for furfural production by corn cobs catalyzed by the solid acid ZSM-5. The study found that various reaction conditions significantly impact the yield of furfural. As the reaction heat increased up to 473 K, yield of furfural rose from 45.9 %. However, temperatures above this threshold led to a decrease in yield, likely due to degradation or condensation of reaction intermediates on higher temperature [69]. The dosage of the solid catalyst also influenced the yield; increasing the catalyst amount from 20 % to 30 % resulted in increase of furfural yield 35.6 %–39.1 %. Notably, xylose conversion was nearly 100 %. However, increasing catalyst loading further resulted in reduction in furfural yield, possibly due to enhanced secondary reactions. These reactions include the dehydration of xylose to other products like formaldehyde and the degradation of furfural [70]. Additionally, the study observed increase in xylose conversion and furfural yield with longer residence times, conversions rising from 37.0 % to 92.2 % and yields 13.8 %–45.9 %. Maximum furfural yield is observed at 473 K after 2 h. Beyond this point, more reaction time resulted in decreased yield and selectivity. The type of solvent used also affected the yield. For example, furfural yields were 25.4 % in an isobutanol/water system, 13.4 % in THF/water, and 28.9 % in DMSO/water. The conversion of xylose ranked as follows: DMSO > Toluene > THF > Isobutanol. Furfural can undergo further reactions in the aqueous phase in the presence of catalysts, but immediate extraction into the organic phase can prevent secondary reactions, as the catalyst is only active in the aqueous phase [71]. Castro et al. explored production of furfural from xylose and corn cob biomass using p-sulfonic acid calix [4]arene (CX_4SO_3H) in a biphasic system comprising butyl acetate and a saturated aqueous NaCl solution, employing a microwave-assisted technique. The study achieved a 77.0 % yield of furfural from xylose under microwave irradiation at 160 °C for 10 min using 1.0 mol% CX_4SO_3H (5 wt%). Also, arabinose yielded 40.5 % furfural under similar conditions. For corn cob biomass, furfural was obtained with a 56 % yield after 60 min at 160 °C with 12.5 wt% CX_4SO_3H. This approach not only provides satisfactory yields but also offers advantages such as the direct conversion of renewable feedstocks, high carbon efficiency with water as the sole by-product, short reaction times, and the use of a recyclable catalytic system (CX_4SO_3H and saturated aqueous NaCl solution) [72]. Another study explored a green and efficient method to produce furfural from corn cob using γ-valerolactone as the solvent and H-ZSM-5 as the catalyst under mild temperatures (170–210 °C). The results demonstrated a high furfural yield of 71.68 % at 190 °C for 60 min using 35 g/L H-ZSM-5 (1.4 g H-ZSM-5/g corn cob). Additionally, the study reported an activation energy of 67.67 kJ/mol for furfural production from corn cob via a modified Arrhenius equation, offering significant insights into the production process employing H-ZSM-5 zeolite in γ-valerolactone [73].

Rice husks, a lignocellulosic by-product of rice cultivation, serve as a significant source of biomass [74,75]. Currently, furfural is produced industrially from corncobs and sugarcane bagasse using acid hydrolysis with sulfuric or hydrochloric acid. These traditional methods usually attain yields between 35 % and 50 % of theoretical maximum, depending on pentosan content in the biomass [76,77]. A research investigation focused on furfural production from rice husks via acid hydrolysis, exploring various reaction parameters with temperature ranging from 180 to 230 °C, sulfuric acid (0.05 % and 3 % (w/w)), and reaction durations from 1 to 105 min. The optimal conditions were identified at 200 °C, 0.10 % (w/w) acid concentration, and a 40-min reaction period. Under these conditions, furfural

Table 2

Agriculture applications of furfural.

Source/region	Application	Key finding	Reference
Corncobs (Mumbai, India)	Reduction in agriculture waste	Conditions: Hydrolysis, HCl (1.5 M), 80–110 °C, 2–12 h; Pentosan (32 %) rich corncob yield 11.027 % furfural	[85]
Bagasse		Conditions: H_2SO_4, NaCl, 40 min, 170–190 °C	[118]
Rice husks, sorghum husks, corn cobs (Ilorin, Nigeria)		Conditions: H_2SO_4, 200 °C, 4 h; Significant increase in plant growth and decrease in nematode population	[86]
Bagasse and rice husk		Conditions: 453–493 K, 15 psi, 30 h, sulfuric acid (0–1.5 %); Maximum yield of furfural was obtained from baggase (11.5 %) as compared to rice husk due to higher hexosan and pentosan contents	[119]
Vegetable matter		Conditions: Acidic medium, 20–110 °C, 4–12 h; Yield of the furfural obtained was 10–13 %	[120]
Bamboo		Yield of the furfural obtained was 68.37–85.69 mol%	[121]
Corn cob and oat hulls		Conditions: HCl, 180 °C, 30 min; Yield of furfural obtained was 1–1.5 %	[84]
Corn cobs		Conditions: HCL, 180–185 °C, 30–45 min; Yield of furfural was obtained approximately 7.75 %	[84]
Camellia oleifera fruit shell		Yield of the furfural obtained was 67.54 %	[122]
Furfural (Furfural factory, Zhangye)	Soil quality	Increase in TN, TK, TP, Av-N, Av-K, Av-P and enzyme activities	[115]
Furfural and its biochar (China)		Furfural is more effective in lowering pH and enhancing phosphorus availability, while biochar increases soil organic carbon	[114]
Furfural residue (China)		Increase in plant height and yield, enhancement in cation exchange capacity, and percentage of water-stable aggregates	[123]
Furfural residue (China)		Reduction in soil pH (P < 0.05), increase in total nitrogen content, total phosphate, wheat shoot biomass, and root biomass	[124]
Furfural oxidation intermediates	Air quality	Oxidation intermediate reacts slowly with O_2, unlikely to result in ozone formation	[116]
Furfural		Adsorbed furfural imparts photochemical properties to surfaces, enhancing nitrous acid formation, influencing indoor oxidation capacity	[117]
Furfural and furfural residue	Carbon neutrality and reduction in greenhouse emission	Utilization of agro waste results in the reduction in the utilization of fossil fuels leading to carbon neutrality and decrease in greenhouse gas emission	[103, 104]

production achieved 6.0 % (w/w) of the oven-dried rice husk weight, corresponding to 55 % of the theoretical yield, with a solid yield of 60 %. This process illustrates efficient furfural production from rice husks, generating valuable by-products and energy from solid fraction, while also improving characteristics of resulting ash. Valorizing rice husks before combustion enables furfural production, alongside yielding a solid residue suitable for combustion, potentially mitigating environmental impacts. Furthermore, study achieved furfural yields exceeding typical industrial levels (35–50 % of theoretical yield). Additionally, the process generated other compounds including hydroxymethylfurfural, acetic acid, formic acid, and levulinic acid. The innovation of obtaining a solid residue suitable for power generation underscores efficacy of this valorization-pre-combustion approach [74].

4. Environmental sustainability

4.1. Reduction of agricultural waste

The global underutilization of waste generated from agricultural biomass is a pressing concern [78]. For example, China alone produces approximately annually 1.04 billion tons of waste from agriculture, 1/3rd of global yield [79]. Conventional methods often fall short in terms of economic viability. However, advanced processes such as hydrolysis and pyrolysis, especially under acidic conditions, have proven to be more optimal for production of furfural [80]. Furfural plays a major role in conversion of agricultural waste aligning with the principles of sustainable and circular economies [81,82]; via series of chemical processes particularly leveraging the rich hemicellulose content found in biomass such as corncobs, bagasse, and rice husks. However, the concept of agricultural waste management for ecological agriculture and sustainable development has gained considerable attention from policymakers [83]. Various lignocellulosic-rich agro-biomasses have emerged as focal points in recent years. Notably, corncobs were utilized as early as 1921 by Forge for furfural synthesis through acid hydrolysis, exhibiting the historical significance of this process [84]. Recent studies have expanded the scope of furfural production to include diverse biomasses such as bamboo, sorghum husks, and rice husks. For instance, a study using pentosan-rich agro-waste, including corn cobs, demonstrated a maximum furfural yield of 11 % under specific conditions [85] (Table 2). Furfural derived from rice husks, sorghum husks, and corn cobs, using sulfuric acid, exhibited promising results in reducing nematode populations in soil and roots, consequently increasing crop yield (Table 2) [86]. Overall, the findings from various studies underscore the potential of different lignocellulosic-rich agro-waste sources for furfural production. The need for further exploration into additional biomass sources, including hardwoods, softwoods, and various agricultural wastes, is emphasized to maximize the utilization of available resources [87]. In conclusion, utilization of agro-wastes for furfural production aligns seamlessly with broader concept of sustainable agriculture and results in reduction of waste produced from agriculture. This approach encourages viewing by-products as valuable resources, contributing not only to waste reduction but also fostering a more efficient and responsible use of agricultural resources. Thus, conversion of agricultural waste into furfural emerges as a pivotal strategy, promoting sustainability and creating a more circular economy within the agricultural and chemical industries. Furfural production shares common environmental benefits with lignocellulosic biorefinery processes, particularly in terms of reducing agricultural waste and achieving carbon neutrality [41]. The utilization of agricultural biomass for furfural production contributes to waste reduction and resource efficiency, aligning with the principles of sustainable and circular economies [88]. Similarly, lignocellulosic biorefinery processes aim to valorize biomass resources and minimize waste generation by converting lignocellulosic materials into valuable products [89]. Both approaches offer opportunities to utilize agricultural residues effectively, thereby reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Furfural production holds significant potential for small-scale farmers in developing countries by transforming agricultural residues into valuable commodities. This process not only generates additional income through the valorization of biomass wastes like rice husks and sugarcane bagasse but also enhances technological skills and resource efficiency on farms [90]. By providing access to new markets and stable income opportunities, furfural production empowers farmers with improved livelihoods and resilience against economic uncertainties [91]. Moreover, adopting furfural technologies promotes sustainable agricultural practices by reducing biomass burning, thereby mitigating environmental impacts and aligning with global sustainability goals [92]. Overall, furfural production represents a promising avenue for fostering economic development and environmental stewardship among small-scale farmers in developing nations.

4.2. Carbon neutrality and greenhouse gas emission reduction

The combustion of fossil fuels is a source of greenhouse gas emissions, posing a significant threat to the environment and consequently contributing to global climate changes [93,94]. In the context of sustainability, fuels and materials derived from organic or plant wastes offer a solution to overcome this drawback, addressing the challenges associated with the fossil resource crisis and ultimately decreases the emission of greenhouse gas and carbon neutrality [95,96]. In the early 19th century, Henry Ford proposed implementation of bio-based economy, considering rational and essential choice for advancement of civilization [97]. This advancement has sparked exploration into alternative methods for creating sustainable polymers from renewable natural resources. The goal is to reduce dependence on fossil fuels and achieve a balance between CO_2 production and consumption rates [98,99]. Biomass and materials derived from biomass have emerged as some of the most promising alternatives in this pursuit of sustainable industrial practices [100,101]. In particular, lignocellulosic biomass, the most abundant and renewable biomass on Earth [102], holds critical importance. Numerous studies highlight its significant potential as a plentiful, carbon-neutral renewable source that can help reduce CO2 emissions and atmospheric pollution, emphasizing its abundance and global availability [103,104].

From economic standpoint, lignocellulosic biomass can be produced more rapidly and at a lower cost than other major agricultural biofuel feedstocks such as soybeans, corn starch, and sugarcane [99]. In terms of sustainable and carbon-neutral economy, biomass

refining has garnered significant interest in recent years. Biomass represents largest natural carbon source that can be utilized without negatively impacting carbon balance of ecosystems [8,105].

In view of this, aforementioned earlier, furfural is used as a source of chemical intermediates, solvent in petrochemical refining, agricultural uses, lubricant and fuel additives, pharmaceuticals, battery technologies, polymer production, metal extraction, and biofuels/bio-based chemicals [106,107]. Furthermore, 2-furoic acid its oxidation product valuable feedstock in organic synthesis and serves as a crucial intermediate for production of medicines and perfumes [108]. The electrocatalytic oxidation of furfural holds significant promise as a cost-effective and energy-efficient strategy, contributing to the broader goals of sustainability and the reduction of greenhouse gas emissions in industrial processes [108]. Therefore, utilization of agro-wastes for furfural production not only aids in carbon neutralization but also addresses environmental concerns. Traditional biomass decomposition processes release carbon into the atmosphere, while the conversion of biomass into furfural effectively sequesters carbon in a chemical form. This dual benefit not only contributes to the reduction of greenhouse gas emissions but aligns with the broader objective of achieving environmental sustainability.

4.3. Impact on air and soil quality

Biochar has recently garnered increased attention as a potential solution for enhancing carbon Biochar has recently gained attention as a potential solution for improving carbon balance and soil quality in degraded soils [109,110]. However, there remains limited understanding of biochar's specific effects on ameliorating sandy saline soils. In contrast, organic materials such as furfural residue are believed to enhance chemical and physical properties of saline soils with low fertility [111–113]. To investigate this, a 56-day experiment conducted to study impact of furfural and its biochar counterpart on soil properties [114]. The findings demonstrated that both furfural (corncob) and biochar had a notable impact on soil properties, resulting in decrease in soil pH, an increase in soil organic carbon content, and enhancements in cation exchange capacity as well as levels of available phosphorus. Specifically, furfural was more potent than biochar in reducing soil pH; application of 5 % furfural led to a pH reduction of 0.5–0.8 units (initial range of 8.3–8.6), whereas same concentration of biochar resulted in a decrease of 0.25–0.4 units due to acidity losses during pyrolysis. Furthermore, furfural significantly boosted available phosphorus content by 4–6 times, compared to a 2 to 5 times increase observed with biochar. In terms of reducing soil exchangeable sodium percentage (ESP), biochar showed a slight advantage over furfural; specifically, soil ESP declined by 51 % with 5 % furfural and by 43 % with 5 % biochar [114]. In conclusion, furfural was more effective in increasing available phosphorus and decreasing pH, while biochar results in increasing soil organic carbon and reducing ESP in saline soil. Similarly, recycling furfural residues for enhancing soil organic content and nutrient levels has shown promise in calcareous soils, leading to increased soil organic matter, nitrogen, phosphorus, potassium, and enzyme activities. However, furfural residue application resulted in a more significant decrease in soil pH compared to biogas residue application, indicating the need for careful consideration of application rates and soil conditions. The results indicated that introducing furfural residues to calcareous soils resulted in elevated levels of soil organic matter, total nitrogen, phosphorus, potassium, available potassium (Av-K), available phosphorus (Av-P), available nitrogen (Av-N) and enzyme activities. However, it led to a decrease in pH in comparison with unfertilized control. Generally, when concentration of residue compounds with chemical fertilizer increased, most soil properties also improved significantly. Furfural residue application resulted in a greater increase in soil organic matter, total phosphorus, Av-P, Av-K, and cation exchange capacity (CEC), but it also led to a more significant decrease in pH compared to biogas residue application. Notably, enzyme activities showed a more pronounced response to the application of furfural residue, leading to higher dehydrogenase, invertase, and catalase activities. Furthermore, the application resulted in a decrease in zinc and an increase in other heavy metals. In conclusion, higher rates of furfural residue application lead to satisfactory maize production by enhancing soil physical and chemical properties in semi-arid and arid calcareous soil [115]. Residues of furfural not only offer potential as organic resources to moderately replace chemical fertilizers but also demonstrate promise as soil conditioners, improving soil pH, bulk density, and compactness.

As previously mentioned, furfural is emitted into the atmosphere as an intermediate during industrial processes, biomass burning, and the production of alkane fuels from biomass [12,92]. To comprehensively understand impact of furfural on the atmosphere and air quality, a study was conducted to investigate kinetic and mechanistic aspects of furfural chemistry. The study demonstrated that furfural undergoes oxidation, involving reactions with OH radicals, leading to formation of intermediate radicals and then production of specific compounds. The primary oxidation products include 2,5-furandione, 2-oxo-3-pentene-1,5-dialdehyde, 5-hydroxy-2 (5H)-furanone and 4-oxo-2-butenoic acid. According to kinetic analysis, intermediate radicals formed during oxidation of furfural react slowly with O_2 under atmospheric conditions. This is due to addition of O_2 to these radicals is highly reversible and slightly exothermic. Instead, these radicals tend to react directly with NO_2, O_3, and/or RO_2/HO_2. The findings indicate that atmospheric oxidation of furfural is unlikely to contribute significantly to ozone formation. While furfural emissions contribute to the atmospheric composition, the specific compounds formed during its oxidation are not predicted to significantly impact ozone levels. However, the overall effect on air quality also depends on the concentration of furfural released and the presence of other pollutants in the atmosphere [116]. Results revealed by Depoorter and coworkers [117], for indoor environments were contrary to these findings. Their study highlighted that furniture surfaces with special coatings emitted volatile organic compounds (VOCs) when subjected to UV irradiation. Irradiated films containing furfural, as well as a combination of furfural and nitrate anions, led to notable emissions of volatile organic compounds (VOCs), with 2-Butenedial and 2(5H)-furanone being prominent. This process resulted in formation of maleic anhydride after UV irradiation. Furthermore, incorporation of potassium nitrate into film generated NOx and HONO concentrations that reached up to 10 ppb, which is approximately 4 ppb in typical indoor settings. Importantly, HONO interacts with indoor pollutants, producing carcinogenic compounds and generating OH radicals through photolytic reactions. The presence of these

indoor OH radicals, in turn, contributes to formation of irritating and toxic substances, thereby impacting indoor air quality [117]. In summary, the utilization of furfural and its residues in soil remediation and agriculture shows promise for enhancing soil quality and crop productivity. However, careful consideration of application rates and environmental impacts is necessary to ensure sustainable practices and mitigate potential risks to soil and air quality.

Furfural production offers several unique features and advantages that distinguish it from other lignocellulosic biorefinery processes. One notable aspect is the versatility of furfural as a high-value chemical intermediate with diverse industrial applications. Furfural serves as a precursor for various downstream products, including solvents, resins, plastics, pharmaceuticals, and biofuels, contributing to its wide-ranging utility across multiple industries [125,126]. Additionally, furfural production typically involves mild reaction conditions and straightforward process steps, making it relatively cost-effective and energy-efficient compared to some other lignocellulosic conversion methods [127]. Furthermore, furfural production from agricultural biomass offers a sustainable and renewable alternative to petrochemical-derived chemicals, aligning with global efforts for decrease dependence on fossil resources and ease environmental impact [128,129]. Moreover, the byproducts generated during production of furfural, for instance furfural residue and biochar, can be utilized beneficially in soil remediation and agricultural applications, further enhancing the sustainability profile of furfural production. Overall, the special features of furfural production include its versatility, cost-effectiveness, sustainability, and potential for value-added utilization of byproducts, positioning it as a promising pathway for lignocellulosic biomass valorization and industrial biorefinery.

4.4. Contribution to circular economy

Furfural, derived from renewable biomass like corncobs and sugarcane bagasse, is a reliable source for sustainability in the circular economy. Its synthesis from agricultural residues aligns with circular principles, minimizing waste and maximizing resource efficiency [130–132]. As an essential in biorefineries, furfural plays a pivotal role, unlocking multiple high-value products from a single renewable resource and exemplifying closed-loop systems [133,134]. The significance of furfural extends to the production of value-added chemicals, notably furfuryl alcohol, a key ingredient in sustainable resins and polymers (Fig. 4) [135,136]. This dual functionality as both a precursor and renewable feedstock underscores its ability to drive circular economy practices. In biofuel production, furfural offers an eco-friendly alternative to traditional fossil fuels, aligning with circular goals to reduce dependency on non-renewable resources and promote sustainable energy solutions [137,138]. Waste valorization takes center stage as furfural transforms agricultural crop residues into valuable products, addressing waste issues and aligning with circular principles of closing material loops. Its role in synthesizing biodegradable polymers contributes to mitigating plastic waste challenges, emphasizing the potential of furfural to drive sustainability in the materials industry. Moreover, its usefulness extends to climate change mitigation through potential integration into carbon capture and utilization processes [139,140]. This showcases its role in a broader strategy to address environmental challenges and promote a circular approach to managing carbon resources. From its renewable biomass origins to applications in biorefineries, chemicals, biofuels, and waste valorization. Its utilization exemplifies principles of the circular economy, contributing significantly to the shift towards a sustainable and regenerative industrial approach. This shift towards not only
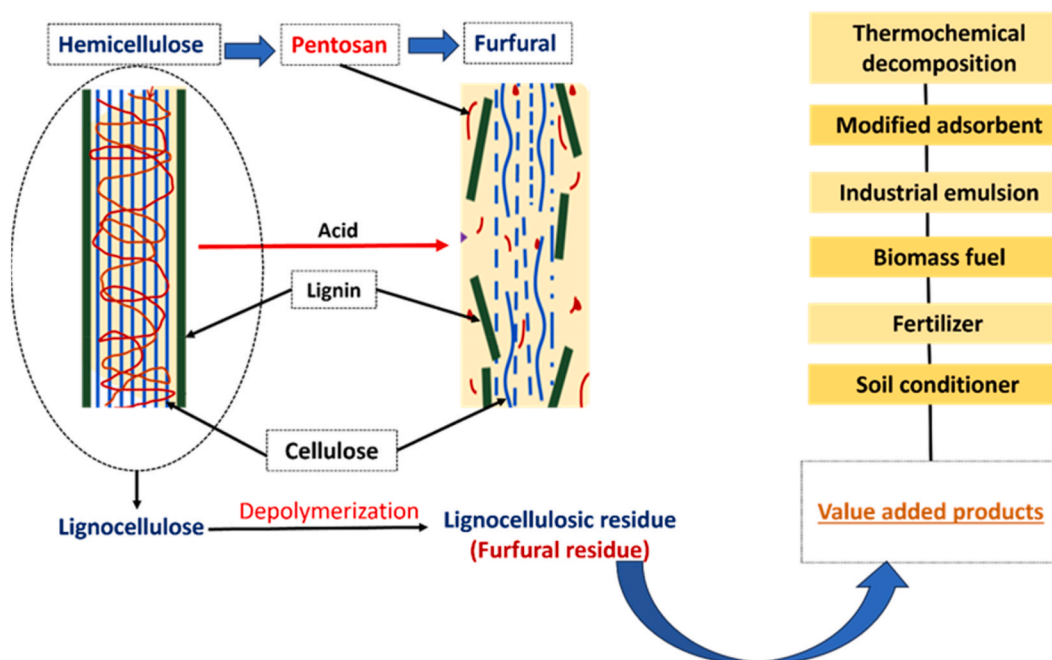

Fig. 4. Overview of conversion of lignocellulosic biomass to furfural and transformation into value-added products (modified from [81]).

contributes to lowering carbon emissions but also helps in diversifying feedstock base for chemical production, enhancing supply chain resilience, and reducing dependence on finite resources. Additionally, furfural and its derivatives can serve as drop-in replacements for petrochemical intermediates in various industrial applications, ranging from plastics and resins to pharmaceuticals and solvents [2]. Furthermore, the recent advancements in furfural production from agricultural waste hold significant promise for advancing the principles of the circular economy and reducing dependence on conventional petrochemical processes. Studies such as those conducted by Yemis and Mazza [5] and Gomes and coworkers [46] have elucidated the efficacy of converting diverse biomass residues, including wheat straw and sugarcane bagasse, into furfural using acid-catalyzed hydrolysis and sustainable ionic liquid-based methods. These methods provide a sustainable way to utilize biomass waste while also enhancing resource efficiency and promoting environmental sustainability by lowering greenhouse gas emissions and addressing waste disposal issues. Ntimbani and colleagues' research on furfural and ethanol production simultaneously from sugarcane bagasse and harvest residues demonstrated economic benefits of integrated biorefineries over single-product processes. Various scenarios were explored, including furfural-only, ethanol-only, and combined furfural-ethanol co-production under different operating conditions. Steam explosion pretreatment at 205 °C replaced industrial furfural process conditions (180 °C) in the ethanol-only scenario, demonstrating the versatility and potential of steam explosion technology in enhancing furfural production efficiency. Various scenarios were evaluated for autocatalytic furfural production at temperatures of 170 °C, 185 °C, and 200 °C, alongside furfural production using 0.5 wt% H_2SO_4 at 170 °C and 185 °C [26]. The economic analysis, determined by internal rate of return (IRR), furfural-only biorefinery (Scenario 1) emerged as most profitable option, achieving an IRR of 12.92 %. This was primarily due to its lower initial capital investment of 272 million USD and a 51 % bypass. Moreover, integrated biorefinery (Scenario 5) combining furfural and ethanol demonstrated superior performance compared to ethanol-only production (Scenario 2), yielding an IRR of 12.78 %. These findings underscore economic benefits associated with co-production strategies [26]. Wiranarongkorn and coworkers explored integrated biorefinery processes for efficient furfural production from bagasse, with a focus on converting furfural residue utilizing the entire bagasse with 50 % sugar recycling for 5-HMF production. Heat integration improved biorefinery efficiency, achieving a 71 % energy recovery potential and maximum profit at an 11 % internal rate of return. Among scenarios, scenario 2 involves utilizing the entire bagasse in biorefinery plant. Within this framework, 50 % of the waste generated during 5-HMF production is recycled to recover unreacted sugar. This approach emerged as the most promising, achieving a maximum biochemical product of 1064 kg h^{-1} furfural compared to other scenarios. These included processes without sugar recycling (S1), with 80 percent biomass bypassed to the biorefinery (S3), 60 % biomass bypassed (S4), and a system combining power and heat separately (S5). Their study demonstrates the potential for maximizing energy recovery and furfural production efficiency through heat integration and biomass utilization strategies, offering insights into sustainable furfural production from biomass feedstocks [141]. Another case study investigated the challenges associated with furfural production by optimizing processes and intensifying synthesis. The study focused on assessing different distillation and pretreatment techniques, using total annual cost and eco-indicator 99 as key criteria. Findings indicate that integrating dilute acid pretreatment with a thermally coupled process offers best balance of cost-effectiveness and environmental sustainability across all feedstocks. Specifically, optimal furfural production from wheat straw, employing this approach alongside thermally coupled distillation, yielded a total annual cost of $13,092,504 and an environmental impact of 4,536,512 eco-points annually [90]. Study by Ng and coworkers reported a gate-to-gate life cycle assessment (LCA) to evaluate furfural and glucose co-production from lignocellulosic empty fruit bunch (EFB) biomass. Results indicate environmental impacts, including 4846.85 kg CO2 eq./ton EFB for global warming potential (GWP), 7.24 kg SO2 eq./ton EFB for acidification (ADP), 1.52 kg PO4 eq./ton EFB for eutrophication (EP), and 2.62E-05 kg 1,4-DB eq./ton EFB for human toxicity (HT). Overall, findings suggest economic viability and environmental sustainability, potentially influencing Malaysia's palm oil industry [142]. Moreover, recent technological innovations, exemplified by the work of Xu and coworkers [44] and Castro and coworkers [30], have enhanced process efficiency and minimized environmental impact through the development of advanced catalysts and integrated biorefinery approaches. The transition towards furfural and other bio-based chemicals is further supported by favorable market conditions and regulatory incentives aimed at promoting sustainable alternatives to fossil-based products. Despite challenges related to scalability and market competitiveness, ongoing research efforts, as highlighted in studies by Tareen and coworkers [31], Wang and coworkers [143] and Soetedjo and coworkers [45] continue to drive progress in maximizing the potential of furfural to advance the circular economy agenda. By facilitating the efficient utilization of agricultural waste streams and reducing reliance on finite fossil resources, furfural production represents a critical pathway towards achieving a more sustainable and resource-efficient future in the chemical industry. Furthermore, the integration of furfural production with agricultural practices offers additional benefits, including improved soil health and crop yields. Studies such as those by Lv and coworkers [59], Subramani and coworkers [67], and Ghoreishi and coworkers [29] demonstrate how furfural residues can be utilized as soil conditioners, enriching soil organic content and nutrient levels, thereby enhancing crop resilience and agricultural productivity. Additionally, the furfural production processes, as highlighted by the findings of Wu and coworkers [114], can be recycled as a soil amendment, further promoting soil fertility and carbon sequestration. These synergistic effects underscore the potential of furfural production to create a closed-loop system where agricultural waste is transformed into value-added products, benefiting both the environment and agricultural sustainability.

4.5. Environmental synergies between furfural production and lignocellulosic biorefineries

It is worth pointing out that furfural production and lignocellulosic biorefinery processes share several environmental benefits that contribute to sustainable resource utilization and waste reduction [19]. Both processes involves transformation of biomass materials into high-value products, reducing reliance on fossil fuels and mitigating environmental impacts linked to traditional chemical synthesis [129]. For example, studies on furfural production from agricultural residues such as corncobs and rice husks have demonstrated significant reductions in agriculture waste, highlighting the potential for converting underutilized biomass into high-value chemicals

(e.g., corncobs in Mumbai, India; rice husks, sorghum husks, and corn cobs in Ilorin, Nigeria) [85,86]. Similarly, lignocellulosic biorefinery processes, such as the hydrolysis of bagasse and rice husk using sulfuric acid, have been shown to effectively valorize agricultural residues while generating bio-based products (e.g., furfural) [46]. These processes not only contribute to waste reduction but also offer opportunities for bioenergy production and carbon sequestration, thereby mitigating greenhouse gas emissions and promoting climate resilience (e.g., bagasse and rice husk studies) [46,119]. Furthermore, both furfural production and lignocellulosic biorefinery processes have implications for soil quality and agricultural sustainability. For instance, the application of furfural residue to soil has been linked to increases in total nitrogen, phosphorus, and potassium levels, as well as improvements in enzyme activities and crop yields [123,124]. Similarly, studies on biochar derived from lignocellulosic biomass have shown enhanced soil organic carbon content and nutrient availability, contributing to improved soil health and crop productivity [114]. Overall, by harnessing renewable biomass resources and adopting environmentally friendly production methods, furfural production and lignocellulosic biorefinery processes offer promising pathways towards achieving environmental sustainability goals and transitioning towards a bio-based circular economy. However, furfural production from agricultural residues presents environmental risks primarily associated with its production processes and waste management. The production of furfural involves acid hydrolysis and dehydration, which can release volatile organic compounds (VOCs) such as furfural itself, along with other emissions like sulfur dioxide (SO_2) and particulate matter if not controlled effectively [144,145]. These emissions contribute to air pollution and can have health implications for nearby communities [146]. Moreover, the energy-intensive nature of furfural production, particularly during the distillation and separation stages, can result in significant greenhouse gas emissions if the energy sources are not renewable or efficiently utilized [147]. Agricultural residue sourcing also raises concerns about potential land use change impacts, deforestation, and habitat loss if not managed sustainably. Furthermore, the treatment and disposal of wastewater and solid wastes generated during furfural production require careful consideration to prevent environmental contamination and ensure resource recovery [82]. Addressing these challenges through technological innovations and rigorous environmental management practices is essential to enhance the overall sustainability of furfural production.

5. Conclusion and future perspectives

This study on furfural reveals its remarkable versatility and significance as a bio-renewable chemical with applications spanning plastics, pharmaceuticals, agrochemicals etc. The implications for agriculture and environmental sustainability are important, as furfural's use as fungicide and nematicide aligns with sustainable pest management, and its presence in transportation fuels and bioplastics contributes to eco-friendly practices. There is a need for further research to optimize production processes, explore new applications, and assess environmental impact, while future perspectives involve innovations in catalysis and biomass utilization. For this effort, agricultural biomass-derived heterogeneous catalysts have been emerging recently as greener and sustainable alternatives for those metal/metal oxide catalysts in the production of furfural products. Further attempts in research should also address extraction methods, scalability, and broader ecological impacts. In addition to the scientific challenges, policy recommendations should incentivize research and development, including for those innovations that leverage furfural for improved pest management and reduced reliance on traditional pesticides. Furthermore, promoting furfural's expansion into novel sectors, such as energy and materials, can contribute to economic diversification and sustainability. Ultimately, integration of scientific advancements and supportive policies aims to provide a sustainable and eco-conscious future.

Data availability statement

All data required to support this study is already mentioned in the manuscript.

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CRediT authorship contribution statement

Ashok Pundir: Writing – original draft, Investigation. **Mohindra Singh Thakur:** Investigation, Conceptualization. **Suraj Prakash:** Writing – original draft, Investigation. **Neeraj Kumari:** Writing – original draft, Investigation. **Niharika Sharma:** Writing – original draft, Investigation. **Zhongqi He:** Writing – review & editing, Investigation. **Sunghyun Nam:** Writing – review & editing, Investigation. **Sangram Dhumal:** Writing – review & editing, Investigation. **Kanika Sharma:** Writing – review & editing, Investigation. **Sujata Saxena:** Supervision, Investigation. **Sunil Kumar:** Supervision, Investigation. **Sheetal Vishal Deshmukh:** Writing – original draft, Investigation. **Manoj Kumar:** Writing – original draft, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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