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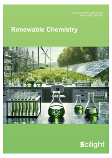

Review

Furfural as a Bio-Based Platform Molecule in Industry: Feedstocks and New Chemistries

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Abstract: Furfural is a versatile platform molecule, easily obtained in often very good yields from a variety of biomass and now being manufactured in several global locations. Several process innovations and extensive catalyst development work, largely disclosed in patents, have made manufacturing processes commercially viable and sustainable. Feedstock selection and strategies for furfural manufacture are examined, including biphasic systems, solid acid catalysis, deep eutectic solvents, microwave-assisted processes, and integrated biorefinery concepts designed to maximise overall biomass valorisation. The review explores the dominant reaction classes used to upgrade furfural—hydrogenation, oxidation, decarbonylation, and nitrogen-incorporation—emphasizing catalytic strategies and process architectures that enable selective, scalable, and industrially relevant transformations. Particular attention is given to furfuryl alcohol and its derivatives, emerging routes to cyclopentanone and 2-methylfuran, and oxidation pathways to furoic acid, maleic acid, and furan dicarboxylic acids. The growing importance of furfural as a precursor to polymer monomers, especially in routes to FDCA and polyethylene furanoate (PEF) as bio-based alternatives to PET, is analysed in detail. By integrating patent literature, industrial case studies, and recent academic advances, this review positions furfural as a central hub in future lignocellulosic biorefineries and highlights the innovations that are likely to define its next phase of commercial deployment. By integrating patent literature, industrial case studies, and recent academic advances, this review positions furfural as a central hub in future lignocellulosic biorefineries and highlights the innovations that are likely to define its next phase of commercial deployment.

Keywords: furfural; feedstock; furfuryl alcohol; polyethylenefuranoate (PEF); materials; chemicals

1. Introduction

Furfural is a colourless liquid that becomes yellow upon air exposure, with an almond-like aroma. It is soluble in most organic solvents and slightly soluble in water and alkanes. Notably reactive, furfural can decompose at high temperatures or react vigorously with strong acids and bases, posing fire and explosion risks. While its reactivity can pose problems in storage and transport, it also makes it an ideal platform molecule for downstream functionalisation. The presence of an aldehyde group and an aromatic furan ring in furfural makes it highly reactive, allowing it to undergo reactions of both the aromatic ring and the aldehyde functional group. It can be transformed to many high value-added compounds, directly or indirectly, through reactions including selective hydro-deoxygenation, decarbonylation, decarboxylation, hydrogenation, and hydrogenolysis [1]. Currently, industry uses furfural as a solvent in various industries, a precursor for other chemicals, and a component in resins, pharmaceuticals, and agrochemicals. It is also used as a flavoring agent, fungicide, and herbicide.

Furfural is easily derived from biomass, primarily agricultural residues, with increasing interest in its role as a sustainable platform chemical for biofuels, biochemicals and biopolymers. Part of its attraction is that it is typically made from the more amorphous and more easily hydrolysed hemicellulose component of many types of biomass, including agricultural wastes. This leaves the cellulose component from the biomass which is the starting material for many important chemical compounds including bio-ethanol. It has been ranked for some time as one of the top high-valued and marketable building blocks [2]. The global market value of furfural reached

US $520 million in 2021 and is growing at ca. 5–7% making it a significant component of the biorefining sector [3]. Other forecasts up to 2032 make similar predictions [4] driven by increasing demand for bio-based chemicals and sustainable solvents across several sectors as well as increasing applications in the manufacture of pharmaceuticals and agrochemicals alongside increasing legislation and policy favouring green and bio-based chemicals [5]. There is significant growth is in areas including fragrances and perfumes, food, chemical, and pharmaceutical industries. The market is expected to expand further due to the increased demand for furfural alcohol which is made from furfural.

This article reviews recent developments in furfural chemistry with a deliberate focus on industrial relevance, commercial practice, and patented innovation. Rather than providing an exhaustive academic survey, it highlights representative examples of feedstock utilisation, process technologies, and catalytic transformations that have demonstrated scalability or near-term applicability. Particular emphasis is placed on emerging manufacturing concepts that integrate furfural production into biorefinery frameworks, as well as on downstream upgrading routes that enable access to fuels, fine chemicals, and polymer precursors. By consolidating advances across feedstocks, processing strategies, and value-added derivatives, this review aims to clarify how furfural is evolving from a single-product commodity chemical into a central platform molecule within sustainable chemical manufacturing.

2. Discussion

2.1. Feedstocks for the Manufacture of Furfural

The commercial production of furfural usually involves the acid hydrolysis of non-food pentosan polysaccharides found in food crop leftovers and wood waste. Furfural is produced via dehydration processes of the pentoses (C5 sugars) (Figure 1):

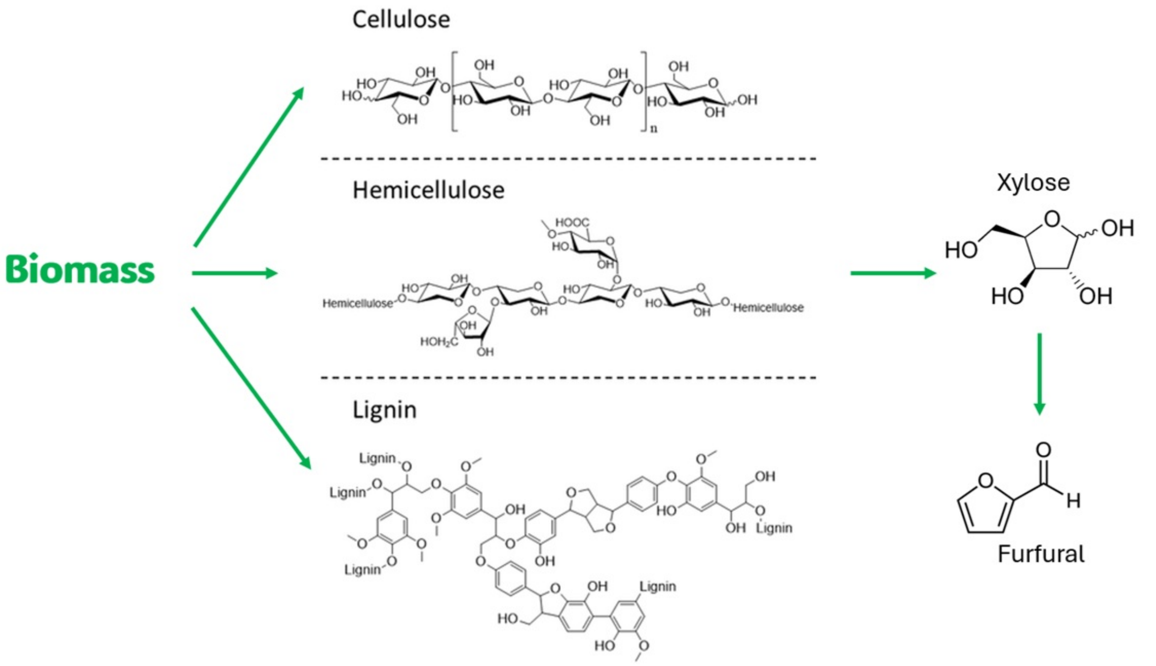

Figure 1. Furfural synthesis from biomass.

The production of furfural from fossil resources is not considered to be economically viable. Numerous biomass species, including bagasse, rice hulls, corn cobs, woody residues and water hyacinth have been investigated as potential feedstock for the manufacture of furfural [6]. The large available volumes of these feedstocks—over 0.5bn MT sugarcane bagasse and close to 1bn MT corn stover—makes them attractive for the manufacture of what is becoming a large volume platform chemical. There was little interest in the use of wheat crop residues for furfural production until the last few years presumably due to the poor solubility of such complex and heterogenous materials, Similar comments can be applied to rice-based crop residues despite the 1bn+ MT quantities available [7]. There are however, recent reports of the use of both of these large volume but awkward feedstocks for the manufacture of furfural as well as the use of woody feedstocks, for example as part of a proposed poplar wood biorefinery [8]. The use of biomass feedstocks does carry uncertainties with respect to seasonality and variable prices along with sustainability questions over issues such as land use. First isolated in a laboratory in 1831, the Quaker Oats Company began producing furfural industrially in 1921 using sugar cane bagasse, corn cobs, and oat hulls, but due to low demand and expensive production costs, it was not significantly used. The process is energy-intensive, time consuming and low yielding but more recently there has been a shift to continuous production with improvements in time efficiency but little change in product yields. The Rosenlew process which relies on in-situ acid production from the biomass decomposition, the development of which is hampered by high steam and production costs. Similar cost problems occur with the Biofine process which leads to improved furfural yields by maintaining the product in the vapour phase facilitating separation. Newer technologies that might lead to significant improvements are the use of biphasic solvent systems that continuously remove the reactive furfural from the acidic water (or other reactive extraction techniques), the use of microwave reactors or other types of process intensification (probably combined with reactive extraction) and the use of unconventional solvents such as ionic liquids and deep eutectic solvents (DES) [9]. Microwave-assisted heating combined with reactive extraction for example, has been shown to promote higher furfural yields [10].

Mineral acids (including sulfuric and phosphoric acids), solid acid catalysts (including zinc and aluminium chlorides and zeolitic materials), and bifunctional catalysts (i.e., titania-zirconia) have all been studied for their ability to catalyze the conversion of sugars into furfural [6,7]. While the original mineral acid-based process remains the benchmark, the problems with low yields (especially due to loss of product through further reactions), equipment corrosion and dealing with acid effluent streams make alternatives attractive. Temperature, residence duration, and feedstock concentration are variables impacting furfural synthesis efficiency. Rice husk, despite its complex structure, can yield a high percentage of furfural, approximately 90%, when using an acid hydrolysis process at temperatures ranging from 100 to 200 degrees [7]. The more commonly studied corn stover has been reported to give furfural yields as high as 97% using a mixture of iron chloride, THF and water [11]. Furfural was produced via catalytic flash pyrolysis at 400 °C using a Pd-PdO/$ZnSO_4$ catalyst, which enabled high yields of >70% (from cellulose), 96% (from C5 xylan) and up to 33% from biomass (e.g., corncob). Key challenges with the traditional manufacturing processes include: (i) corrosion of equipment; (ii) energy consumption for (iii) large volumes of waste (if not valorised); (iv) environmental concerns over waste streams including acid effluent streams.

New strategies to increase product yields include heterogeneous catalysts, ionic liquids, biphasic processes, heteropolyacids, and supercritical extraction although the work has included conversions of the intermediate monomeric sugars as well as directly from biomass [1,12]. Heterogeneous catalysts studied include zeolites and silicon-doped aluminophosphates although their small pores can lead to diffusional limitations. Acid-functionalised mesoporous silicas can alleviate diffusion limitations. Metal-based catalysts, carbon-based catalysts and ion-exchange resins have all been tried.

The production of furfural is intrinsically linked to the availability and efficient utilization of lignocellulosic biomass, which represents a vast, renewable, and underexploited resource for sustainable chemical manufacturing but hampered by the complex structure of lignocellulosic biomass [13]. Cellulose forms strong, crystalline microfibrils due to β-1,4-glycosidic bonds, while lignin provides rigidity and further resists hydrolysis through cross-linking with other components. Hemicellulose, the second major constituent, rich in pentose sugars like xylose and arabinose, is more easily hydrolyzed under acidic conditions [14–16]. Since hardwoods and softwoods differ in hemicellulose composition, biomass with higher hemicellulose content yields more furfural, making it crucial for commercial processes [17]. A wide range of agricultural residues and forestry by-products serve as the raw materials for furfural production. These include corn cobs, wheat straw, sugarcane bagasse, rice and oat hull, barley husks, sawdust, wood chips, bamboo, barley and wheat straw, cottonseed, pine grass, olive stones, eucalyptus and birch among others [18–22]. The availability, low cost, and non-competitive nature with food production is essential for industrial-scale deployment. Recent developments in furfural technology involve the valorization of both processed carbohydrates (such as purified xylose) [23] and virgin lignocellulosic biomass, allowing for more flexible and integrated biorefinery concepts. In other strategies, whole biomass is directly subjected to catalytic or thermochemical treatment, often in continuous or semi-continuous setups, to coproduce furfural along with other valuable products such as 5-hydroxymethylfurfural (5HMF), levulinic acid, bio-oils, and activated carbon. An important innovation in raw material processing is the use of deep eutectic solvents (DESs) [16] composed of components like choline chloride, Brønsted acids (e.g., oxalic acid), and Lewis acids (e.g., $CrCl_3·6H_2O$) These not only facilitate the solubilization and activation of xylose but also provide dual catalytic functionality. In combination with biphasic systems, involving a water phase and an organic solvent phase such as toluene (which extracts furfural in situ). These systems enhance furfural yield, selectivity, and catalyst recyclability. This strategy allows furfural to be continuously extracted from the reaction zone as it forms, suppressing degradation pathways and reducing humin formation. A variety of biomass sources have been processed successfully using these methods. For example, optimized systems have achieved furfural yields up to 87% from pure xylose and 79.8% from hemicellulose, under relatively mild conditions. Processes that avoid the use of corrosive liquid acids include autohydrolysis using super-hot compressed water to release pentose sugars without degrading cellulose or lignin. The resulting xylose-rich hydrolysate is then dehydrated using solid acid catalysts—such as sulfonated silica, or carbonbased sulfonic acid catalysts—within reactive distillation columns or continuous flow reactors [24]. Solid acid catalysts derived from renewable precursors are becoming popular and include catalysts based on covalent organic frameworks (COFs) functionalized with phenolic hydroxyl [15]. These COF catalysts exhibit excellent thermal stability, recyclability, and high surface area (>600 m^2/g), making them suitable for both batch and continuous systems. Similarly, phosphorus-doped carbon-based catalysts prepared from waste eucalyptus biomass have shown high conversion efficiencies in pure water, achieving furfural yields exceeding 74%. In addition to traditional sugar-rich biomass, other sources are being explored for integrated bioproduct recovery including bamboo powder, eucalyptus powder, corn bran, and even metalrich agricultural residues (i.e., rice straw containing Fe, Mn, or Cu) have been successfully converted into furfural using tailored catalysts and hydrothermal processes [24–26]. The incorporation of inherent metal ions or in-situ generated acids in these systems eliminates the need for additional chemical additives, simplifying process integration and reducing costs. Boronic acids or borates are also now popular for selective extraction and conversion of xylose into furfural [27]. These compounds form stable esters with xylose that can be transformed into furfural in a separate acidic phase. The biphasic nature of such systems enables high selectivity, efficient recycling of extractants, and the option for continuous processing.

Livestock and poultry manure also represents an emerging non-traditional feedstock for furfural production including a cyclic hydrolysis–autocatalysis process for manure-derived biomass which releases organic acids and furfural without requiring external acid catalysts [28]. This system valorizes waste streams while minimizing corrosion and simplifying downstream processing. Another novel feedstock class involves hydrogen-rich industrial organic solid waste including mixtures of rubber and plastics, co-pyrolyzed with waste wood fiber [29]. This synergistic combination yields both high-calorific pyrolysis carbon and chemical-rich pyrolysis oil containing furfural and levoglucosan. The process not only valorizes problematic wastes but also utilises its own gaseous byproducts to sustain pyrolysis without external energy input—an ideal solution for circular economy models.

Product yields of 70–88% have been reported with reduced energy consumption due to integrated heat recovery and solvent-free operation. Many systems now include provisions for co-producing value-added materials such as levulinic acid, formic acid, biofuels, and carbonbased materials. The diversity of raw materials and the innovations in biomass processing are driving significant advances in sustainable furfural production. From purified xylose to untreated agricultural waste, modern processes leverage tailored catalysts, biphasic solvent systems, and integrated valorization strategies to maximize yield, minimize waste, and enable scalable production.

2.2. Furfural in the Biorefinery

The production of furfural generally only represents partial valorisation of any biomass feedstock. Ultimately, any successful biomass-based industry will need to valorise a large fraction of the feedstock and learn from the long-term economic sustainability of petroleum refineries where little is wasted. Thus, the long-term viability of furfural production may depend on the concomitant valorisation of the other major biomass components. Its production within a biorefinery could complement the conversion of the C6 sugars from cellulose into commercial chemical products such as levoglucosenone and 5-hydroxymethylfurfural [30].

Global agricultural residues exceed 4 billion tonnes annually, with around 3.4 billion tonnes comprising fibrous materials like bagasse, straw, and cotton residues [31]. These residues typically contain 25–35% hemicellulose, making them suitable for furfural production. However, their seasonal nature and scattered distribution present logistical challenges for consistent industrial use. Wood-based feedstocks and residues are relatively uniform, making them easier to handle and process. With over 1.8 billion tonnes produced annually, they offer a stable and abundant supply due to their widespread use in industrial forestry and woodprocessing operations [32]. Grasses, with a high hemicellulose content of 35–45%, are wellsuited for furfural production [18]. Their composition makes them ideal feedstocks for lignocellulosic biorefineries, offering higher furfural yields compared to many other biomass sources. Municipal solid waste (MSW) contains 30–60% lignocellulosic material, including food, yard waste, paper, and plastics, making it a valuable resource for bio-based production. With over 2 billion tonnes generated globally in 2020 and projections reaching 3.4 billion tonnes by 2050, MSW is abundant, especially in urban areas [33]. Utilizing its lignocellulosic fraction can reduce landfill use and promote circular economy practices.

2.3. Furfural Derivatives and Upgrading

Furfural's unique structure, featuring both an aldehyde group and a furan ring, enables diverse chemical transformations, making it a valuable precursor in numerous industrial applications (Figure 2):

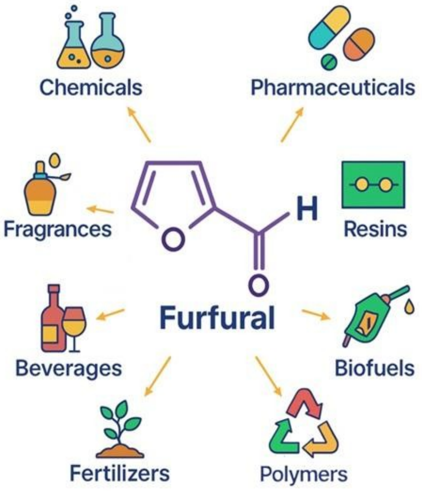

Figure 2. Key industrial and commercial applications of furfural.

The figure illustrates the wide-ranging uses of furfural across several sectors, including fine chemicals and pharmaceuticals, bio-based polymers and resins, biofuels and lubricants. Furfural also finds applications in fragrance and beverage formulations, as well as in agricultural and environmental technologies. It is a versatile platform molecule with increasing relevance in sustainable materials and green chemistry. Building on these applications, Figure 3 highlights representative value-added chemicals that can be produced from furfural through key transformation pathways such as hydrogenation, oxidation, amination, and decarbonylation:

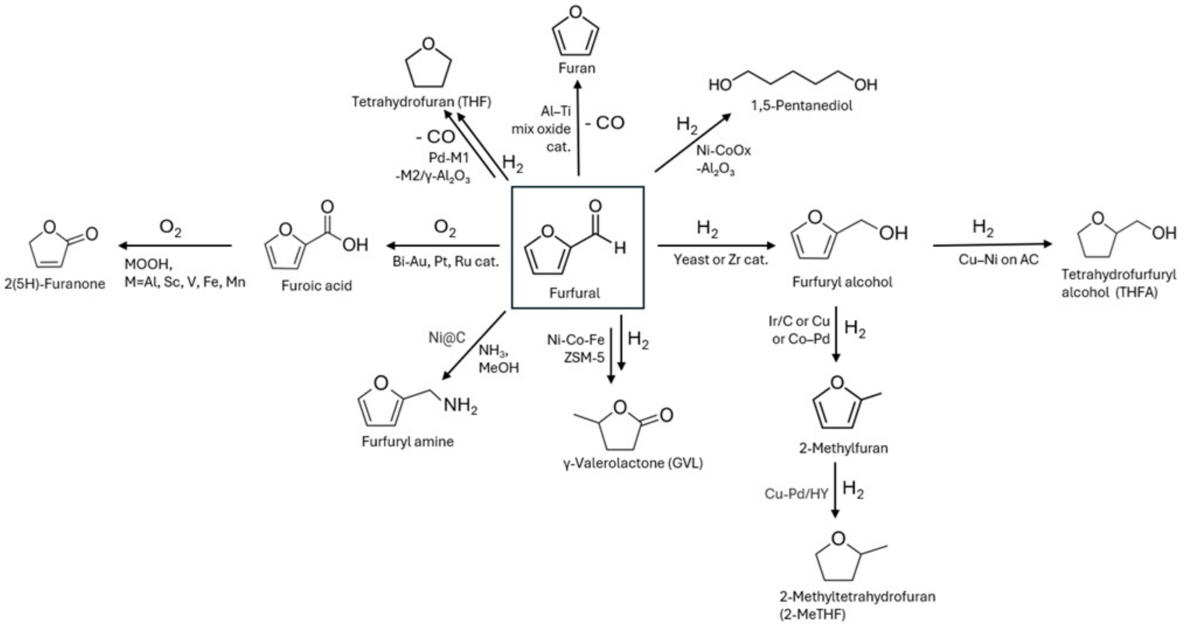

Figure 3. Representative value-added chemicals that can be produced from furfural.

2.3.1. Hydrogenation Products

The hydrogenation of furfural to furfuryl alcohol is probably the most valuable downstream process. Approaches to improve efficiency, selectivity, catalyst recyclability, and sustainability include microbial conversion and enzymatic systems as well as highly engineered metal-based heterogeneous catalysts. One biotechnological route employs the yeast *Kluyveromyces marxianus* to convert furfural into furfuryl alcohol under mild conditions [34]. A zirconium hydroxide catalyst supported on magnetite has exceptional performance [35] with both Lewis acid and base sites. Its magnetic nature allows for easy separation and recovery and it can be reused. The bifunctional zirconium-based catalyst can be used to selectively convert furfural to furfuryl alcohol and isopropyl furfuryl ether in isopropanol [36].

Pt nanoparticles anchored on FeO_x/SBA-15 [37] catalyse hydrogenation with 100% selectivity to furfuryl alcohol. A Cu–Al catalyst system [38] enables100% conversion and selectivity for furfuryl alcohol at low temperature and pressure, while its low-cost synthesis and benign environmental profile enhance its industrial attractiveness. An easily made core–shell catalyst composed primarily of SiO_2, copper and small amounts (<1%) of a noble metal component achieves near-quantitative yields under mild conditions [39].

Solvent-free systems are popular. A Pd–Ru nano-catalyst supported on carbon black is very effective under solvent-free hydrogenation conditions. Formic acid can be used as a hydrogen donor for the gas-phase hydrogenation of furfural derived from lignocellulosic biomass [40] using a Ni–Cu bimetallic catalyst supported on graphite. Among new catalyst supports, activated carbon composites play a major role [41]. A cobalt-based catalyst with reduced copper supported on multiple types of activated carbon gives very good selectivity under industrially relevant hydrogenation conditions.

Bioengineered enzymes include a mutant *E. coli* strain expressing the YahK-Y114W variant of alcohol dehydrogenase and show much improvement over a wild-type enzyme [42]. A dualenzyme system co-expressing YjgB and GDH Q252L in *E. coli* enables high-yield biosynthesis of furfuryl alcohol or 2,5-furandimethanol from furfural or HMF [43]. with excellent scalability and minimal environmental burden.

Furfuryl Alcohol Derivatives

Tetrahydrofurfuryl alcohol (THFA) can be made through further hydrogenation for example using a Cu–Ni catalyst supported on nitric acid-modified activated carbon derived from agricultural waste [44]. Furfural is converted simultaneously into 2-methyltetrahydrofuran and THFA using a Cu–Pd/HY catalyst [45].

A highly efficient Ni@C@CNT gave superior performance due to improved dispersion of active sites and the formation of a Ni_3C phase with Pt-like catalytic activity. Under optimal conditions the catalyst achieved almost quantitative furfural conversion and excellent tetrahydrofurfuryl alcohol yield, and maintained good reusability. This approach provides a simple and scalable route to producing efficient non-noble metal catalysts.

A one-pot strategy has been developed for converting furfural into the important product, γ-valerolactone (GVL) using a Ni-Co-Fe/ZSM-5 catalyst, addressing issues of over hydrogenation common with Ni or Co catalysts [46]. By alloying Ni and Co with Fe, the catalyst achieved better metal dispersion, easier reduction of metal oxides, more Lewis acidic sites, and enhanced C=O adsorption while suppressing hydrogenation of the furan ring.

Pentanediol is an important chemical used in plasticizers, cosmetics, and fungicides. A Ni– CoOx–Al_2O_3 mixed metal–metal oxide catalyst enables the one-pot direct conversion of furfural to 1,5-pentanediol [47]. Catalyst deactivation through Ni^0 oxidation can be reversed via H_2 treatment, highlighting the catalyst’s potential for cost-effective and sustainable 1,5-pentanediol production from biomass-derived furfural.

Photocatalytic and photoelectrocatalytic reforming of furfuryl alcohol under environmentally friendly conditions enables simultaneous hydrogen (H_2) evolution and partial oxidation to furfuraldehyde [48] using TiO_2-based photocatalysts.

2-Methylfuran

2-Methylfuran is being considered as a potential green fuel or gasoline additive It can be produced via hydrogenation of furfural, though current methods yield it only as a lowproductivity by-product during furfuryl alcohol synthesis with Cu catalysts. From extensive catalyst screening, Ir/C gave the highest 2-methylfuran yield. A hydrogen-free system uses a carbon-coated bimetallic catalyst in a cooperative reduction setup with isopropanol and CO as hydrogen donors. A Co–Pd catalyst with minimal Pd loading achieves quantitative conversion and high 2-methylfuran yield offering economic advantages due to low noble metal content [49]. Pushing selectivity to the limit, a doped tungstated zirconium catalyst (NiFe/WO_xZrOs) achieves 100% conversion and selectivity toward 2-methylfuran [50] but has a complex synthesis. Catalytic transfer hydrogenation, using a Cu–Co@Silicalite-1 catalyst with alcohols as hydrogen donors, enables a solvent-free route to 2-methylfuran, avoiding external hydrogen [51].

Hydrogenation of 2-methylfuran affords 2-methyltetrahydrofuran, co-produced with THFA [45], completing a comprehensive hydrogenation cascade from furfural. Through such diverse strategies—biological, chemical, and hybrid—furfural can be the platform for a family of highperformance alcohols, ethers, and biofuels. The continued development of selective, scalable, and environmentally responsible hydrogenation technologies is paving the way for furfuralbased value chains in future biorefineries.

Cyclopentanone

The production of the useful chemical cyclopentanone from renewable resources such as furfural and xylose represents a promising avenue in green chemistry. A one-pot process from xylose offers a streamlined route to cyclopentanone through in situ catalytic transformation [52] giving high conversion but only moderate product yields.

2.3.2. Oxidation Products

The oxidative transformation of furfural opens the door to a variety of valuable compounds including furoic acid, furanone derivatives, and maleic acid. These transformations are central to the sustainable production of many bio-based materials and intermediates.

Furoic Acid

Furoic acid is typically obtained via oxidation of the furfural aldehyde group while preserving the furan ring for example, using molecular oxygen in aqueous solution, catalyzed by a noble metal–bismuth supported catalyst [53]. The environmentally attractive process generally gives high conversions and selectivities and benefits from operational simplicity, making it highly attractive for scalable production. Furoic acid can be co-produced using furfural from xylosyl carbohydrates via a two-phase system combining a polar organic solvent and aqueous ammonium chloride [54].

Photocatalysis presents another avenue for selective oxidation, and recent advances using graphitic carbon nitride (g-C_3N_4) modified with precious metals demonstrate significant improvements in furoic acid synthesis [55]. These catalysts operate efficient light absorption and favorable electronic properties. Under oxygen flow at just 40 °C, high furfural conversion and furoic acid yields are achieved, showcasing the potential of photocatalysis for low temperature, energy-efficient oxidation of biomass-derived compounds.

Electrochemical oxidation further expands the possible uses of furfural and furoic acid can be produced electrochemically alongside adiponitrile, a high-value monomer [56].

Furoic Acid Derivatives

Selective oxidation of furfural or its derivatives can generate 2(5H)-furanone compounds— oxygenated heterocycles with broad application potential. A novel approach employs a composite photocatalyst based on several metal oxyhydroxides, for the mild, light-driven oxidation of furfural [57]. These semiconductors initiate oxidation under visible light without requiring additional oxidants or high temperatures. The process is designed to be clean, catalyst-recyclable, and highly selective, with practical implications for the sustainable synthesis of fine chemicals and specialty materials derived from lignocellulosic biomass.

Among the most valuable oxidation products derived from furfural are maleic acid and maleic anhydride which are traditionally produced from fossil fuels. One promising route involves photocatalytic oxidation using metal oxide–loaded inorganic semiconductors [58]. The proposed mechanism starts with oxidation of furfural to furoic acid or furanone intermediates, followed by further ROS-mediated transformations leading to ring opening. For example, with FeO_x/TiO_2 in water at 20 °C and with a 200 W xenon lamp, furfural was converted with high efficiency and selectivity toward maleic acid. In contrast, $CuOx/CeO_2$ in ethanol at 40 °C under 300 W xenon light converts furfural also with high conversion and selectivity to maleic anhydride.

2.3.3. Furan by Decarbonylation

The decarbonylation of furfural offers a selective route to furan, a valuable heterocyclic compound widely used in the synthesis of pharmaceuticals, agrochemicals, and polymers. When carried out under gas-phase conditions, this transformation becomes not only efficient but also suitable for continuous operation. Gas-phase continuous decarbonylation catalysts based on titanium-modified activated alumina, with platinum and palladium as the active metal sites are effective [59]. This catalyst delivers nearly complete conversion of furfural with a very good furan selectivity The system demonstrates excellent stability and reusability making it both durable and economically attractive for large-scale deployment.

Furan Derivatives

Furan can serve as a platform for further hydrogenation to more saturated cyclic ethers including tetrahydrofuran (THF) is a high-value solvent and intermediate with applications in polymer production and battery electrolytes. A sophisticated one-step continuous process has been developed to convert furfural directly into THF, integrating both the decarbonylation and hydrogenation steps in a single catalytic sequence. The furfural feedstock is vaporized and passed over a Pd-M1-M2/γ-Al_2O_3 multifunctional catalyst [60]. This tightly integrated system achieves complete conversion of furfural, with a THF yield of 75% and an additional 20% yield of 2-methyltetrahydrofuran another commercial product sometimes favoured as a solvent due to its greater stability to oxidative destruction. The catalyst exhibits remarkable robustness, making it highly suitable for continuous, industrial-scale use. The method combines efficiency with simplicity, eliminating the need for intermediate separation and significantly reducing energy input and process complexity.

Conventional THF synthesis relies on oil- or gas-linked raw materials, involves several reaction and separation processes, and requires high capital investment due to complex reactor systems, stringent safety requirements, and high energy consumption. In contrast, the one-step process described in the attached patent produces THF directly from biomass-derived furfural through integrated decarbonylation and hydrogenation in a single continuous reactor using a multifunctional Pd-based catalyst. The process achieves more than 99% furfural conversion, with approximately 75% selectivity to tetrahydrofuran and an additional ~20% selectivity to 2-methyltetrahydrofuran, resulting in a combined product yield of about 95%. The simplified one-step design significantly reduces process complexity, reactor count, and downstream separations, which in turn lowers capital and operating costs. The moderate operating conditions and demonstrated catalyst lifetime exceeding 2000 h further support favorable economics and reduced downtime. Overall, although the new process involves precious-metal catalysts and depends on the availability and price of furfural, its use of renewable feedstock, lower energy demand, and streamlined process flow provide a clear structural cost advantage over conventional fossil-based THF production. When co-product value from 2-methyltetrahydrofuran and potential carbon or sustainability incentives are considered, the one-step furfural route is well positioned to be commercially competitive and more sustainable than established petrochemical pathways.

2.3.4. Nitrogen-Functionalized Derivatives

Furfural is the starting point for many nitrogen-containing compounds with wide-ranging applications from fine chemicals and pharmaceuticals to polymer intermediates. The synthesis of these compounds relies on the electrophilic nature of furfural's aldehyde group, enabling direct amination, imination, or ammoximation under reductive or oxidative conditions. Recent innovations have pushed these reactions toward greater sustainability and industrial relevance through biocatalysis, continuous-flow chemistry, and the use of non-precious metal catalysts.

Furfuryl Amine

The formation of furfuryl amine is via a two-step pathway: nucleophilic attack by ammonia to form an imine, followed by hydrogenation to yield the amine. A modern green chemistry synthesis method combines biocatalysis with in-situ extraction to overcome the major hurdles of biological amination, including product inhibition and side reaction formation. Microbial fermentation is coupled with simultaneous extraction, enabling real-time removal of furfuryl amine from the broth [61]. An innovative route couples chemical catalysis with microbial bioconversion using a ternary deep eutectic solvent (TDES) system composed of choline chloride, formic acid, and acetic acid, which simultaneously acts as both catalyst and solvent. The furfural is then aminated biologically using *Galactomyces p.* CCZU11-1, yielding furfuryl amine [62]. The process is economical, avoids mineral acids, and represents a novel chemical–biological hybrid strategy for biomass-to-amine conversion. In a purely chemical route, furfural is subjected to reductive amination using a Ni@C catalyst in a methanol-ammonia solution under hydrogen pressure [63].

Furfuryl amine also serves as a key intermediate in the synthesis of more complex molecules including methyl pentanedicarbamate, a green alternative to pentamethylene diisocyanate (PDI) [64]. The process involves hydrogenolysis and amination of a furfurylmethyl carbamate ester, followed by the synthesis of the final dicarbamate compound. This route avoids toxic isocyanates.

Furan Nitrile

2-Furan nitrile (also known as 2-furonitrile) is synthesized via a two-step tandem reaction: ammoximation—where furfural reacts with ammonia and an oxidant to form furfural oxime—followed by dehydration of the oxime to yield the nitrile. A recently disclosed process achieves this transformation in two continuous flow reactors, offering high process efficiency and scalability [65]. In the first reactor, D-xylose is converted to furfural using a heteropolyacid catalyst in an organic solvent. In the second, furfural undergoes ammoximation with ammonia and an oxidant. This is followed by thermal dehydration to yield 2-furan nitrile. The process is specifically designed for industrial-scale, low-cost production of furan nitriles. This continuous process reflects a growing emphasis on flow chemistry and tandem catalysis, and highlights furfural's value as a platform molecule for nitrogen-containing building blocks, opening the door to sustainable routes for agrochemicals, pharmaceuticals, and specialty chemicals.

2.3.5. Monomers

Furfural, as a renewable platform molecule, can play an important role in the increasingly popular development of bio-based polymers and advanced materials. Its structural versatility enables a wide array of downstream derivatizations, creating monomers for resins, and functionalized polyesters. Innovations in catalysis and green chemistry have opened up new sustainable pathways for synthesizing furfural-derived building blocks.

2,5-Furandicarboxylic Acid (FDCA)

One of the most commercially promising furfural-derived monomers is 2,5-furandicarboxylic acid (FDCA)—a molecule structurally analogous to terephthalic acid (PTA), yet fully biobased. FDCA enables the production of polyethylene furanoate (PEF), a next-generation polyester with superior gas barrier and mechanical properties compared to PET and used in packaging, films, 3D printing, textiles and fibers, thermoelectric devices, electronic components and others [66]. The global PET market for PET exceeds 70 million tons annually, but it is difficult to make bio-based and is the subject of a major substitution program for many applications especially packaging. FDCA can be synthesized from furfural through several routes. One multi-step method begins with acetalization of furfural using an alcohol and an acidic ion-exchange resin, followed by acylation in an ionic liquid to yield 5-acylfurfural [67]. This intermediate is then oxidized with hydrogen peroxide giving high product yields and simplified product recovery (Figure 4):

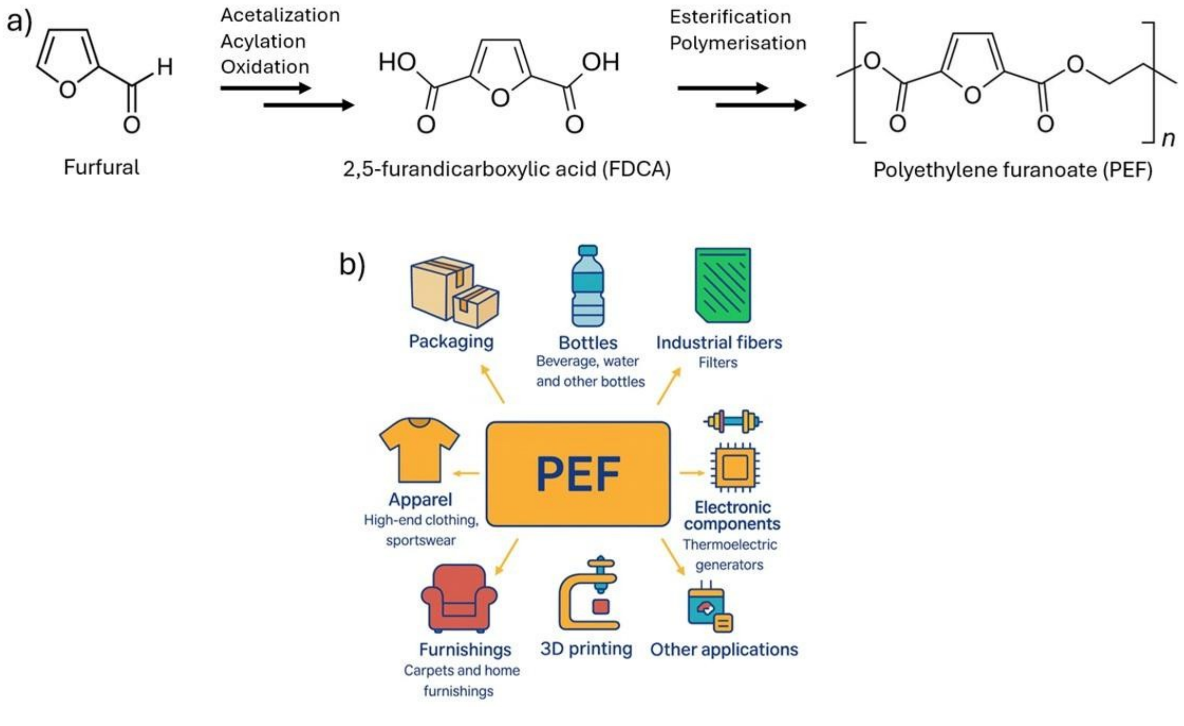

Figure 4. Polyethylene furanoate (PEF) synthesis from furfural (**a**) and applications (**b**).

A more direct method starts with 5-hydroxymethylfurfural (HMF)—produced from hexose sugars—which is oxidized to FDCA using a non-noble metal catalyst, such as mixed oxides [68]. This pathway avoids costly metals like Ru or Pt while maintaining high catalytic performance under aerobic conditions. It enables the cost-effective production of FDCA from glucose or crude HMF derived from cellulose. Biocatalysis can play a growing role. A two-enzyme cascade system, involving *Bacillus pumilus* laccase and alcohol oxidase, converts HMF to FDCA via hydroxymethylfuroic acid (HMFCA) and 5-formyl-2-furancarboxylic acid (FFCA) [69]. This mediator-free system offers high selectivity and avoids toxic reagents. Another notable approach uses CuO foam as an integrated catalyst in an alkaline aqueous system to oxidize pentahydroxymethylfurfural into FDCA [70]. One related solvent-free strategy employs ball milling and in situ oxidation of furfural to form furoate, followed by carboxylation and acidification to produce FDCA [71]. Other processes use mixed furanic feedstocks, including 5-methylfurfural and alkoxymethylfurfurals, which are oxidized in the presence of Co–Mn–Br catalysts in acetic acid, producing crude FDCA mixtures that are easily purified. These lead to high conversions and tolerate impurities in the feed [72]. From a carbohydrate starting point, fructose can be first dehydrated in biphasic systems to produce HMF, then oxidized via biocatalysis at low temperatures (20–50 °C) to produce FDCA with up to 100% yield [73]. FDCA synthesis has been expanded to hydroxylated furfural derivatives, produced via selective functionalization and oxidized using heterogeneous metal catalysts to yield high-value furan diacids suitable for polyester and copolyester production [74]. These innovations reinforce the role of furfural as a cornerstone molecule in the emerging circular bioeconomy.

2,2′-bifuran-5,5′-dicarboxylic acid (BFDCA)

While furfural itself contains only a single reactive aldehyde, researchers have developed novel derivatives such as 2,2′-bifuran-5,5′-dicarboxylic acid (BFDCA), which enables linear polyester formation through dicarboxylic acid functionality. BFDCA normally involves synthesis via palladium-catalyzed coupling, but newer methods introduce sulfur-bridged bifunctional monomers, connecting two furfural-derived units without the need for transition metals. These sulfur-bridged difuran polyesters are synthesized from a dicarboxylate and a diol component, producing materials with excellent UV-blocking and gas barrier properties, suitable for films, coatings, and packaging. Furthermore, these materials may be formulated into curable resin compositions, enabling crosslinked thermosets or flexible thermoplastics depending on formulation [75]. Such strategies expand the functional and environmental appeal of furfural-derived polymers, offering bio-based alternatives to PET and other fossil-derived polyesters, with the added benefit of inherent furan functionality that can be tuned for performance, degradability, or recyclability.

Other Monomers

A metal-modified hydroxyapatite catalyst (M1–M2·HAP) has been used to convert furfural intermediates into furan ethylene monomers, suitable for direct polymerization [76]. M1 is a transition metal like Cu, Ni, or Co, while M2 includes elements such as Ce, Fe, Zn, Ti, or Sn. The monomers exhibit capabilities for both self-polymerization and copolymerization, including with styrene, which improves surface properties of the resulting polystyrenes. This method employs a continuous fixed-bed reactor system, operating under mild, scalable conditions, thereby supporting industrial synthesis of biomass-based polymers.

Another approach utilizes a Cu-based acid–base bifunctional catalyst, structured as M·HAP/Z or M·HAP/$A_xB_yPO_4$, to catalyze the one-step hydrogenation–deoxygenation of furyl-3-butene2-ketone**,** obtained from the condensation of furfural and acetone [77]. These furan-based olefins are used to prepare reversibly curable liquid rubbers, which show dynamic bonding behavior and potential for self-healing or recyclable elastomeric materials. The strategy offers a renewable alternative to petroleum-based monomers for specialty rubbers and adhesives.

Another invention presents a novel synthetic route to a dianhydride monomer starting from furfural [78]. The process involves reduction and oxidation of furfural to produce diene and monoene intermediates, which are coupled via Diels–Alder reaction to form a precursor. This intermediate undergoes dehydration to phthalic anhydride, followed by halogenation and Suzuki coupling to generate the final halogenated dianhydride. These monomers are precursors to high-performance polyimides, known for their thermal stability and mechanical strength. The method operates under mild conditions, uses inexpensive bio-based feedstocks, and introduces a clean, scalable route to aromatic dianhydrides.

2.3.6. Polymers

Polyethylenefuranoate (PEF)

PEF is currently manufactured by Avantium and branded under the name Releaf^R with plans to scale up to 100kT. The overall market for PEF and its monomer FDCA is estimated at €200 billion (addressable market). New markets for PEF include biodegradable packaging. The success of PEF will also depend on the economics of the process and the selling price differential between PEF and its monomer feedstock. The favoured monomer for the manufacture of PEF is FDC. While the most advanced routes to FDCA are from HMF made from edible fructose, a serious alternative is to use a furfural-based route taking advantage of the more sustainable lignocellulosic feedstock and better yields. The conversion of FUR to FDCA requires both the addition of carbon (to convert C5 to C6) and oxidation chemistry. One possibility is to first oxidise furfural to a furoate salt which can then be reacted with carbon dioxide in a high temperature carboxylation step [79]. The initial oxidation of furfural (to furoic acid) has itself been well studied and the early basic conditions used for this have since been superseded by catalytic aerobic oxidation under neutral conditions [80]. Biocatalytic methods have also been applied to the furan to FDCA process [81].

Different routes from Furfural to FDCA have been compared [82]. FDCA production from furfural made from biomass hydolysate (i.e., from paper and pulp mills) has been explored by KSE Inc. [83]. Their modern reactive distillation technology enables the subsequent simultaneous reaction and separation of other important downstream chemicals like the solvent THF.

Other Polyesters

Innovations include sulfur-bridged difuran polyesters, which combine a dicarboxylate and a diol component derived from furfural [75]. These materials exhibit high oxygen barrier properties, in some cases better than PET, and UV-blocking capabilities up to approximately 350 nm. Poly(alkylene sulfonyldiylbisfuranoate**)** is made from dimethyl 5,5′-sulfonyldi(furan2-carboxylate). It has sulfone bridges (–SO_2–) rather than thioethers (–S–), giving it a higher glass transition temperature of 91 °C and a melting point of 240 °C. The sulfone linkages contribute to enhanced mechanical strength by stiffening the polymer chains. Poly(alkylene sulfinyldiylbisfuranoate) is based on dimethyl 5,5′-sulfinyldi(furan-2-carboxylate). It is expected to have intermediate properties between thioether and sulfone variants. Curable thermosetting resins can be synthesized using diglycidyl esters of sulfur-bridged difuran dicarboxylic acids and cured with anhydrides such as hexahydromethylphthalic anhydride (MHHPA). This gives rigid, cross-linked networks with glass transition temperatures around 120 °C. Such polymers can be tailored into films, coatings, and packaging materials with enhanced UV-blocking properties.

2.3.7. Resins

Furfural and its derivatives are well studied as renewable feedstocks for resin synthesis, particularly in wood adhesives and composite materials. Traditional phenol–formaldehyde resins dominate industrial applications but rely heavily on petrochemicals and release hazardous formaldehyde. A recent invention describes a furfural- and HMF-based bonding resin designed for widespread use in mineral wool insulation, wood panels, molding compounds, composites, among others. The resin formulation includes one or more of furfural and/or its derivatives [84]. These are crosslinked with curing agents and the resulting resins are highly adaptable and compatible with both thermosetting and thermoplastic systems, offering strong bonding properties. Another breakthrough involves a phenol- and formaldehyde-free phenolic resin synthesized from lignin and furfural, using a eutectic solvent system [85]. This process forms a neutral or weakly alkaline eutectic mixture based on choline chloride and urea or thiourea, into which lignin is dispersed and depolymerized. A weak base promotes crosslinking with furfural compounds, forming a high-performance, bio-based phenolic resin. This novel system is particularly attractive for wood product adhesives, providing a lowtoxicity, renewable alternative with broad application potential in areas including engineered wood and construction industries.

2.3.8. Lubricants

Furfural is used in the formulation of synthetic lubricants using aldol condensation, hydroxyalkylation, and hydrogenation chemistries to produce long-chain branched molecules suitable for biomass-based lubricants. One method employs the aldol condensation between 2,5,8-nonyltrione and furfural, followed by hydrogenation to produce a highly branched, lowviscosity base oil [86]. The entire process produces an effective lubricant and is renewable. Another pathway uses hydroxyalkylation of furan and furfural to form cyclic intermediates, which are then hydrogenated and hydrodeoxygenated to produce ether-based synthetic lubricants [87]. A third method involves the reaction of lauric acid with furfural in the presence of zirconium dioxide, using aldol condensation. The resulting compounds are hydrogenated to yield stable, high-yield low-viscosity oils. Together, these innovations establish furfural-based lubricants as viable alternatives to petroleum-based oils—meeting performance demands while enhancing sustainability and reducing environmental impact.

2.3.9. Biofuels and Energy Applications

Furfural is a key intermediate in the sustainable production of liquid fuels and energy carriers. A high-density biomass-derived liquid fuel has been developed through the condensation of furfural with isophorone [88]. This reaction forms C14–C19 compounds, and the resulting fuel can be used as a renewable aerospace fuel or blended with conventional jet fuels to enhance performance. When mixed in controlled ratios, it increases the combustion heat value and improves the cetane number of the final fuel blend, making it a promising candidate for highperformance aviation applications. A method for producing C8–C15 biofuel precursors from furfural and alcohols has been established by reacting furfural with a primary or secondary alcohol in the presence of a base catalyst, generating α,β-unsaturated aldehydes or ketones, or unsaturated alcohols [89]. The simplicity of the method, combined with short reaction times and high product yields, makes it suitable for industrial-scale production of mid-chain fuel precursors, which can later be hydrogenated to form diesel- or jet-fuel-range hydrocarbons.

The one-pot conversion of furfural to cyclopentanone and cyclopentanol uses in situ hydrogen generated from methanol reforming [90]. Furfural and a methanol-water mixture are reacted in the liquid phase using a Cu_x/Mg_3AlO_γ catalyst. Methanol reforming provides the necessary hydrogen without the need for external hydrogen input, while the hydrogenation of furfural proceeds simultaneously to produce the target cyclic compounds. From high-density aerospace fuel components to hydrogen-rich cyclic fuels and metal-free precursors for mid-range hydrocarbons, furfural-based systems offer a viable path toward cleaner, renewable, and more efficient energy solutions.

2.3.9. Pharmaceutical Intermediates

Furfural and its derivatives are increasingly being considered as renewable building blocks in pharmaceutical applications, enabling greener routes to complex molecules with therapeutic, aromatic, or biofunctional properties. Furfural is as a precursor for synthesizing entecavir, an antiviral medication using a Grignard, reaction followed by an asymmetric Piancatelli rearrangement catalyzed by a chiral Lewis acid [91]. The resulting intermediate undergoes Sharpless epoxidation, epoxide ring-opening with a boron reagent and Pd/C catalyst, and coupling with a purine compound in the presence of a phosphine catalyst. After a carbonyl olefination step and deprotection, entecavir is obtained. This streamlined sequence, using inexpensive starting materials and a limited number of steps, is efficient and scalable for industrial production. Another route involves the synthesis of 3-chloro-5-hydroxy-2pentanone, a useful pharmaceutical intermediate, through a continuous two-step fixed-bed catalytic process [92].

2.3.10. Flavors/Fragrances

Furfural also finds application in flavor and fragrance chemistry. In beverages, furfural is used to adjust sensory characteristics so as to create a beer-taste beverage with enhanced “sharpness” by maintaining a high furfural-to-color (EBC) ratio [93]. In alcoholic and non-alcoholic drinks, adjusting furfural levels in relation to color enhances the product’s perceived freshness. This can be achieved by directly adding furfural, making the method adaptable to various production scenarios without extensive formulation changes. For plant-based beverages, a method was developed to enhance the aroma of whole-grain milk using cereal grains such as rice, millet, oats, and soybeans. Through a sequence of thermal and mechanical treatments, aroma-active compounds including furfural, maltol, and pyrazines are generated. The result is a wellrounded, sweet, and roasted flavor profile with good mouthfeel and product stability [94].

In perfumery, furfural is used to synthesize 3-(2-furyl)-2-octyl acrylate via esterification with n-octanol and a solid acid catalyst [95]. This biomass-based fragrance intermediate, derived from furfural and malonic acid, supports low-carbon manufacturing and provides a sustainable pathway to high-value perfume components. Another method produces beta-(2-furan) ethyl propionate through a Horner–Wadsworth–Emmons reaction between furfural and triethyl phosphorylacetate, followed by hydrogenation over Pd/C and purification by flash evaporation [96]. In another example, furfural undergoes aldol condensation with acetone to produce furfurylidene acetone, a versatile intermediate with fragrance potential [97].

2.4. Catalytic Technology

Catalytic technology underpins virtually all modern advances in furfural production and upgrading, enabling higher selectivity, improved yields, reduced energy demand, and enhanced process robustness. Early industrial furfural manufacture relied heavily on homogeneous mineral acids, which remain effective but are associated with significant drawbacks including corrosion, difficult waste management, and limited control over side reactions.

As a result, extensive research and industrial development have focused on replacing or augmenting these legacy systems with heterogeneous, recyclable, and multifunctional catalysts. In furfural synthesis from lignocellulosic biomass, solid acid catalysts such as zeolites, heteropolyacids, sulfonated carbons, acid-functionalised mesoporous silicas, and metal oxides have been widely investigated. These catalysts provide tunable acidity, improved stability, and opportunities for continuous processing. Diffusion limitations associated with microporous materials have driven the development of mesoporous and hierarchical catalyst architectures, while carbon-based and biomass-derived solid acids offer additional advantages in terms of sustainability and cost. Bifunctional catalysts combining Lewis and Brønsted acid sites, as well as metal–acid combinations, have proven particularly effective in promoting pentose dehydration while suppressing humin formation. Catalysis also plays a decisive role in downstream furfural upgrading. Hydrogenation processes dominate industrial utilisation, with copper-, nickel-, cobalt-, and noble-metal-based catalysts enabling highly selective conversion to furfuryl alcohol, tetrahydrofurfuryl alcohol, 2-methylfuran, cyclopentanone, and related products. Advances in catalyst design—including core–shell structures, alloying strategies, tailored supports, and magnetic or structured catalysts—have improved activity, selectivity, and catalyst recovery. In parallel, biocatalytic and hybrid chemo-enzymatic systems have emerged as powerful alternatives, offering high selectivity under mild conditions with minimal by-product formation. Oxidation, decarbonylation, and nitrogen-incorporation reactions further demonstrate the central role of catalysis in expanding the furfural value chain. Heterogeneous aerobic oxidation catalysts, photocatalysts, electrocatalysts, and continuous-flow catalytic systems now enable the selective production of furoic acid, maleic acid, furan, furfurylamine, and nitriles under increasingly mild and controlled conditions. Collectively, these developments illustrate how catalytic innovation is transforming furfural from a single-product chemical into a versatile hub for sustainable chemical manufacturing.

2.5. Green Processes

Green process development has become a defining feature of modern furfural chemistry, driven by the need to improve environmental performance, economic viability, and regulatory compliance. Central to this evolution is the adoption of process strategies that minimise waste, reduce energy consumption, and maximise the valorisation of renewable feedstocks. Many of these advances are closely coupled to catalytic innovation but extend beyond catalyst choice to encompass solvent systems, reactor design, and overall process integration. A major trend in sustainable furfural production is the move toward biphasic and reactive extraction systems, which continuously remove furfural from the reactive aqueous phase as it forms. This approach suppresses secondary degradation reactions, increases selectivity, and reduces energy requirements for downstream separation. The use of unconventional solvents, including ionic liquids and deep eutectic solvents, has further enabled efficient biomass solubilisation and catalytic dehydration under milder conditions, while offering opportunities for solvent and catalyst recycling. Process intensification strategies such as microwave-assisted heating, continuous-flow reactors, reactive distillation, and gas-phase catalytic systems have significantly reduced reaction times and improved energy efficiency. Autohydrolysis and hydrothermal processing eliminate the need for added mineral acids, lowering corrosion risks and simplifying effluent treatment. The integration of furfural production with the co-generation of other value-added products, such as levulinic acid, biofuels, furan derivatives, and carbon materials, aligns furfural chemistry with modern biorefinery and circular economy concepts. Downstream, green processing principles are evident in the increasing use of solvent-free reactions, catalytic transfer hydrogenation, in situ hydrogen generation, photocatalysis, electrocatalysis, and biocatalysis. These approaches reduce reliance on external hydrogen, hazardous oxidants, or stoichiometric reagents, while enabling operation at lower temperatures and pressures. In polymer and materials applications, furfural-derived monomers and resins offer bio-based alternatives to fossil-derived counterparts, with reduced carbon footprints and enhanced recyclability. Together, these developments demonstrate that furfural chemistry is no longer defined solely by product scope, but by how efficiently and responsibly those products are made. The convergence of catalytic technology, green solvents, process intensification, and integrated valorisation strategies positions furfural as a key enabler of sustainable chemical manufacturing in the transition away from fossil resources.

3. Conclusions

Furfural is undergoing a resurgence as a foundational platform chemical in the global shift toward sustainable manufacturing, green chemistry, and circular economy principles. Derived primarily from the hemicellulose fraction of lignocellulosic biomass, furfural represents a compelling example of how renewable, non-food, and waste-based resources can be transformed into high-value chemicals, materials, and fuels.

Furfural production no longer relies on a single process or feedstock but instead encompasses a growing ecosystem of technologies, catalysts, and valorization strategies and a wide range of agricultural residues can be used. The diversification of biomass sources not only improves feedstock security and price stability but also enhances regional viability, allowing for localized furfural production in areas with abundant waste. Furfural's reactivity—owing to its furan ring and aldehyde group—makes it exceptionally versatile as a precursor to many valuable products. Furfuryl alcohol remains the most significant derivative and serves as a gateway to numerous industrial chemicals, resins, and thermosetting polymers. The conversion of furfural into FDCA and PEF is especially promising, offering renewable alternatives to PET with superior mechanical and barrier properties. Furfural-derived solvents like 2methyltetrahydrofuran and intermediates like furan, furoic acid, and furfuryl amine have wide applicability across sectors such as pharmaceuticals, agrochemicals, and energy.

Recent advances in catalytic technology have been central to this progress, enabling furfural production and upgrading with significantly improved efficiency, selectivity, and environmental performance. Modern heterogeneous and bifunctional catalysts, including solid acids, metal–oxide systems, and carbon-based catalysts, now routinely deliver furfural yields exceeding 80–90% from purified pentose streams and up to ~70–80% from untreated biomass under optimized biphasic or continuous-flow conditions, while greatly reducing corrosion and acidic waste generation. Green process innovations such as reactive extraction, deep eutectic solvents, solvent-free hydrogenation, catalytic transfer hydrogenation, photocatalysis, electrocatalysis, and biocatalysis have further lowered energy demand, minimized by-product formation, and enabled operation under milder conditions. Together, these catalytic and process advances are transforming furfural from a traditionally energy-intensive commodity into a cornerstone of low-carbon, scalable, and economically viable biorefinery systems.

Further developments underscore furfural's broad utility across pharmaceutical, fragrance, food, beverage, and other industries, supporting the transition toward renewable feedstocks, continuous flow manufacturing, and environmentally responsible production methods.

Author Contributions

J.H.C. and R.A.M. contributed equally to the design of this work, including the acquisition, analysis, and interpretation of data. R.A.M. used AI tools to create some of the images in this work. J.H.C. and R.A.M. have approved the submitted version. Both authors agree to be personally accountable for their own contributions to the study. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used the AI tools ChatGPT (DALL·E) to create Figures 2 and 4b. Following this use, the authors reviewed and edited the content as necessary and take full responsibility for the final publication.

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