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Combined conversion of lignocellulosic biomass into high-value products with ultrasonic cavitation and photocatalytic produced reactive oxygen species - A review

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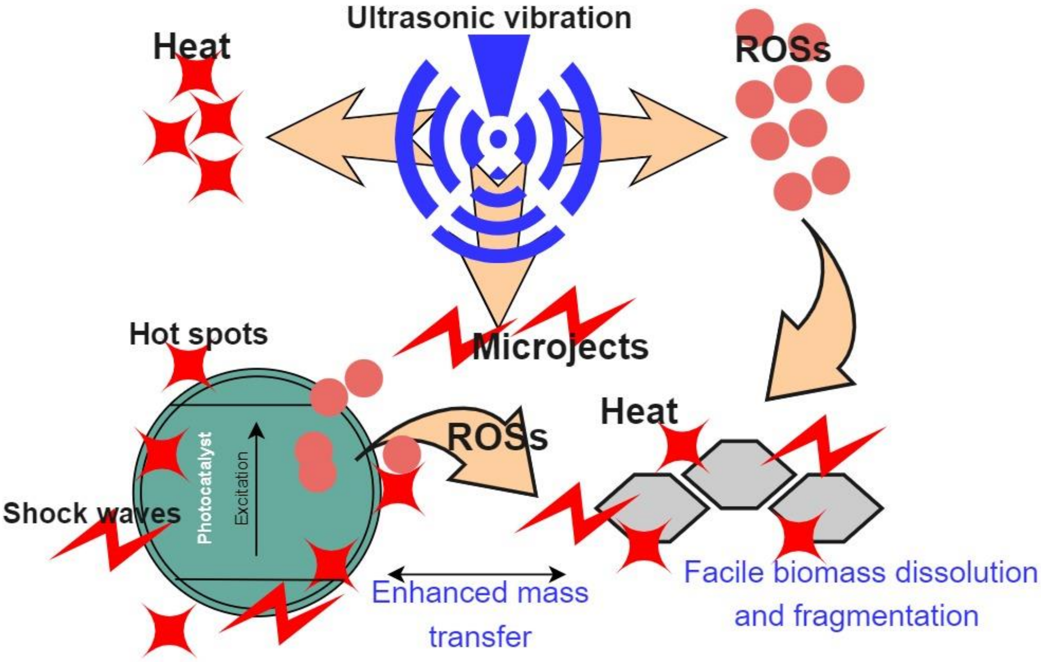
Abstract:	The production of high-value products from lignocellulosic biomass is carried out through the selective scission of crosslinked C–C/C–O bonds. Photocatalytic technology has been proven to be a valuable tool for valorizing biomass at mild conditions. The photoproduced reactive oxygen species (ROSs) can initiate the scission of crosslinked bonds and form radical intermediates. However, the low mass transfer of the photocatalytic process could limit the production of a high yield of products. The incorporation of ultrasonic cavitation in the photocatalytic system provides an exceptional condition to boost the fragmentation and transformation of biomass into the desired products within a lesser reaction time. This review critically discusses the main factors governing the application of photocatalysis for biomass valorization and tricks to boost the selectivity for enhancing the yield of desired products.

Graphical abstract



Highlights (for review)

Highlights

- Mechanisms of photoproduced ROSs to cleave crosslinked C–C/C–O in biomass
- Photocatalytic materials design and operating factors for biomass conversion
- Impact of ultrasonic vibration on the mass transfer and biomass valorization
- Synergistic effects of sonophotocatalysis to boost the yield of high value products
- Future directions for the optimization of sonophotocatalytic biomass conversion

Combined conversion of lignocellulosic biomass into high-value products with ultrasonic cavitation and photocatalytic produced reactive oxygen species - A review

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Abstract

The production of high-value products from lignocellulosic biomass is carried out through the selective scission of crosslinked C–C/C–O bonds. Several techniques are applied nowadays to optimize biomass conversion into desired products with high yields. Photocatalytic technology has been proven to be a valuable tool for valorizing biomass at mild conditions. The photoproduced reactive oxygen species (ROSs) can initiate the scission of crosslinked bonds and form radical intermediates. However, the low mass transfer of the photocatalytic process could limit the production of a high yield of products. The incorporation of ultrasonic cavitation in the photocatalytic system provides an exceptional condition to boost the fragmentation and transformation of biomass into the desired products within a lesser reaction time. This review critically discusses the main factors governing the application of photocatalysis for biomass valorization and tricks to boost the selectivity for enhancing the yield of desired products. Synergistic effects obtained through the combination of sonolysis and photocatalysis were discussed in depth. Under ultrasonic vibration, hot spots could be produced on the surface of the photocatalysts, improving the mass transfer through the jet phenomenon. In addition, shack waves can assist the dissolution and mixing of biomass particles.

Keywords: Biomass valorization; Selective scission of C–C/C–O; Photocatalysis; ultrasonic vibration; High value products; Circular bioeconomy.

1. Introduction

The large-scale conversion of biomass materials/wastes started during the mid of 19th century towards the generation of several chemicals, including cellulose esters and oils. However, since that time, the industrial conversion of biomass materials into high-value products has been ignored because of the low competition with less economical routes, such as the catalytic conversion of hydrocarbons into different chemicals, which took over a decade. Nowadays, due to the dramatic increase in the worldwide population and industrial activities, as well as the decrease in natural resources making them more costly, i.e., hydrocarbons, the scientific and industrial communities started seriously investigating the valorization of biomass materials again into high-value products as an alternative sustainable route (Gallezot 2012; Alonso, Bond, and Dumesic 2010). In academia, the scientific community has made a lot of effort within the last two decades to find the best ways to convert biomass materials effectively into specific chemicals. For that, several technologies are applied, such as combustion (Khodaei et al. 2015), pyrolysis (Kan, Strezov, and Evans 2016), gasification (Sikarwar et al. 2016; Molino, Chianese, and Musmarra 2016), direct liquefaction (Ali and Zhao 2020), and recently several advanced oxidation processes. i.e., Fenton (Kato et al. 2014; Wu et al. 2020), electro-Fenton (Chen et al. 2021), ozonolysis (Travaini et al. 2016) and photocatalysis (Granone et al. 2018; Li et al. 2021).

Combustion is one of the most widely used technologies for biomass conversion, wherein more than 90% of bioenergy production is obtained. It is considered a traditional people's daily route to generate heat (Demirbas 2007; Koppejan and Van Loo 2012). However, the large-scale combustion of biomass is still facing some technical challenges related to fuel characteristics, combustor types, and co-firing issues. Pyrolysis focuses on the thermal decomposition of biomass in an oxygen-free environment to produce different products, including solid charcoal, oils, chemicals, or even gas at higher temperatures (Vamvuka 2011; Chhiti and Kemiha 2013). This process could be applied largely because of its efficiency and sustainability (Demirbas et al. 2016; Yang et al. 2016). Gasification is the process that involves drying biomass waste, pyrolysis, and combustion of by-products, followed by gasification to generate multiple high-value products in different air environments, which could be oxygen, water steam, or carbon dioxide (Sikarwar et al. 2016; Heidenreich and

Foscolo 2015). Direct liquefaction is based on breaking down biomass macromolecules into fragments of small molecules in water or appreciative organic solvents. Then, these fragments could be combined through polymerization to produce high-value products such as oily compounds (Demirbaş 2000). Direct liquefaction is done at low temperatures and high pressure.

Advanced oxidation processes, such as photocatalysis, are based on generating reactive oxygen species (ROSs) to break down lignocellulosic biomass into high-value products. Photocatalysis can be initiated in the presence of a photocatalyst and light irradiation with energy equal to or higher than the band gap of the photocatalyst. In this sense, the electrons move from the valence band to the conduction band, leaving positive holes. $^{\bullet}OH$ radicals can be generated by oxidation water molecules by positive holes at the valence band, while $O_2^{\bullet-}$ species can be produced by reducing O_2 on the conduction band. Photocatalytic biomass conversion is a new alternative technique with many hopes and technical challenges (Li et al. 2021; Liu et al. 2019). One of the common issues in photocatalytic technology towards biomass conversion is mass transfer limitations because of the solid nature of biomass; therefore, ROSs cannot easily access biomass macromolecules resulting in low efficiency. On the other hand, since biomass materials are not dissolved in water, several organic solvents are used to dissolve the biomass. However, organic solvents would be less sustainable in large-scale applications, and extracting wanted products could be more difficult. In addition, the reaction of solvents with generated products might affect the purity of the final products. Organic solvents can also be ROSs scavengers, inhibiting biomass conversion. Recently, combining photocatalysis and sonolysis for biomass conversion has attracted much attention (Giannakoudakis, Łomot, and Colmenares 2020; Chatel et al. 2017). Sonolysis, or ultrasonic technology, is based on generating a cavitational field via ultrasonic vibration (Meroni et al. 2021). Sonophotocatalysis has been widely applied to the oxidation of organic pollutants in water (Joseph et al. 2009; Panda and Manickam 2017; Preeyanghaa, Vinesh, and Neppolian 2022); however, it is still under investigation for biomass conversion.

This work critically discusses the lignocellulosic biomass valorization into high-value products by photocatalytic and sonophotocatalytic means from a mechanistic and technological perspective. Several aspects that cover this field were discussed in different sub-sections. The first section discusses the composition and characterization of lignocellulosic biomass and the importance of valorization as an emerging circular bioeconomy approach. This sub-section discusses comparatively the existing pretreatment techniques of biomass by stressing their pros and cons. Afterwards, the photocatalytic conversion of lignocellulosic biomass, including the role of ROSs to initiate the fragmentation of aromatic rings and formation of intermediate radicals, the role of the photocatalytic design material towards the selective conversion, the effect of operating parameters and technical issues of photocatalytic process. Then, the ultrasonic technique was discussed, from the principle to its application for biomass pretreatment. The synergistic effects of combined ultrasonic vibration and photocatalytic towards biomass valorisation were discussed in depth. Finally, prospects and future directions were provided to help the reader further research the field. This review would effectively push forward the progress of biomass valorization and understanding the mechanism of photocatalytic and sonophotocatalytic towards producing a high yield of high-value products from biomass materials.

2. Lignocellulosic biomass conversion

2.1. Characterization of biomass

Lignocellulosic biomass is the dried waste of plants or food, which mostly consists of three main elements cellulose, lignin, and hemicellulose (Cai et al. 2017). Lignocellulosic biomass is the most available resource on the planet, which could be used to produce alternatively different high-value products and energy (Ambaye et al. 2021; Ambaye et al. 2022). It can be primarily obtained from different sectors, including forest, agriculture, industrial companies, etc. The worldwide industrial and environmental communities highly recommend valorisation into high-value products because of their high carbon richness and worldwide availability. The production of chemicals and energy from biomass could significantly reduce gas emissions via substituting fossil energies (Binder and Raines 2009). The quantitative and qualitative physicochemical characterization of lignocellulosic biomass is crucial to optimize the conversion into wanted products flexibly. Different parameters are needed to be known. The primary biomass analysis could be divided into four types, as shown (Dahlquist 2013; Cai et al. 2017), which include (i): as received basis to estimate the total weight of biomass as it arrives without any type of pretreatment, (ii): air dried basis evaluates the biomass sample that is in an equilibrium of humidity, and it excludes moisture except the inherent, (iii): dry basis is the analytical result of free-moistures biomass; it leaves both external and intrinsic moisture, (iv): dry ash-free basis estimates the biomass, excluding all moistures and ash. This analysis is mainly used to present the accurate yield of compounds in the biomass sample.

2.2.Emerging circular bioeconomy concept

The circular economy has recently been a hot topic in academic and industrial research, notably global (Brandão, Goncalves, and Santos 2021). According to the European Commission strategies and related action plans, the circular economy is the closed-loop approach. Many literature reports have been published on the circular economy alone and how the circular economy and bioeconomy are co-related; the authors emphasized the most important differences and overlaps and how we can use them in the current business (D’Adamo et al. 2021). It is worth noting that there may not have been a single definition of the circular bioeconomy (Befort 2020). According to Muscat et al. (Muscat et al. 2021), circular bioeconomy is an emerging concept that helps to mitigate the rapid depletion of fossil resources, promotes regenerative practices, prevents the degradation of natural resources such as water, carbon, and nutrients, and boosts the holistic approach of recycling and reuse of waste as feedstock to produce many bio-based products that have potential to replace fossil-based products in various industrial applications. Furthermore, biorefinery has attracted increasing attention as it converts different waste feedstocks such as lignocellulosic biomass, algal biomass, urban waste, and microbial-treated waste into high-value-added products such as biofuels, biopolymers, and biochemicals in sustainable and cost-effective manners (Muscat et al. 2021). Therefore, the biorefinery is a strategic mechanism to achieve the circular bioeconomy concept (Awasthi et al. 2022). Due to advancements in biomass conversion and biocatalyst technologies, it has become possible to construct an integrated biorefinery approach to produce multifaceted products. This approach improves resource efficiency and product yield, reduces reaction time, and paves the path toward the bio-based circular economy via a closed-loop method (Velvizhi et al. 2022). Thus, by closing the loop under the circular bioeconomy premises, sustainability and economic feasibility for bio-based products can be achieved (Carus and Dammer 2018).

In recent years, the use of lignocellulosic biomass as a renewable source for producing high-value-added products has gained more attention, constituting "green technology" in the biorefinery (Clark 2019). Currently, the primary use of lignocellulosic biomass in the industry is combustion. Its use as feedstock in the biorefinery for the production of green products has vast potential to replace fossil-based feedstocks in the chemical and polymer industries, so it combats the global environmental challenges and helps to improve sustainability in the production process (Yang et al. 2019). The compositions can vary from one biomass to another, as shown in **Table 1**, ranging from (32-50%) cellulose, (14-26%) hemicellulose and (13-50%) lignin. The utilization of each biomass component, i.e., cellulose, hemicellulose, and lignin, is crucial to realize the circular bioeconomy in biorefinery (Liu et al. 2021). However, the recalcitrant structure of biomass is a significant barrier to its utilization in the biorefinery plant to produce value-added products (Bhatia et al. 2020). Pretreatment is the critical step for converting lignocellulosic biomass into fermentable sugars and improves the accessibility of cellulose to enzymatic or chemical hydrolysis by depolymerizing recalcitrant lignin structures and hemicelluloses or decreasing the crystallinity of the cellulose (Baral et al. 2019**).** According to the recent consensus, simple, green, and economically feasible pretreatments are needed to enable sustainability in biorefinery. In addition, pretreatment should not produce any toxic by-products or loss of fermentable sugars and should isolate the lignin. Until now, no standardized pretreatment method has been available for converting all biomasses. Hence, combining one or more pretreatment strategies will be highly beneficial to improve the efficiency of the biomass conversion process (Carrasquillo-Flores et al. 2013).

2.3.Conventional pretreatment approaches

Pretreatment methods are classified into physical, chemical, and biological. Among these three methods, chemical methods have been widely used for biomass depolymerisation (Baral et al. 2019). The most common chemical methods for biomass depolymerization involve the addition of acids, bases, organic acids, organosolv, ammonia, supercritical fluids, or ionic liquids (Bhatia et al. 2020). The pros and cons of these methods are shown in **Table 2**. For many years, these conventional methods have been used for the depolymerization of a variety of biomass. These methods' significant limitations have cost, high-energy demand, time consumption, low yield of fermentable sugars, produced toxic by-products, and lack of the recycling of solvents. These conventional methods are not suitable for the sustainable future of lignocellulosic biomass-based products (Sidana and Yadav 2021). To overcome these challenges, the advancement in pretreatment technologies is needed to efficiently convert carbohydrates to fermentable sugars and provide a route for valorising lignin.

Table 1. Overview of bio compositions of different lignocellulosic biomass from literature

Lignocellulosic biomass	Types	Cellulose content (%)	Hemicellulose content (%)	Lignin content (%)	Reference
Agricultural Wastes	Rice-husks	34.15	14.36	25.5	(Heng et al. 2017)
	Tequila Agave Bagasse	50.0	21.1	13.1	(González-García et al. 2019)
	Wheat bran	32.43	26.34	20.15	(Annamalai and Sivakumar 2016)
	Wheat straw	43.44	26.22	21.2	(Wang et al. 2021)
	Corn stover	37.15	14.03	27.69	(Wang et al. 2016)
	Wall-nutshell	26.7	23.4	49.8	(Ahorsu et al. 2019)
	Sugarcane bagasse	41	15	20	(Carrasquillo-Flores et al. 2013)
Forest residues	Beechwood	41	24	24	(Carrasquillo-Flores et al. 2013)
	Birch saw dust	37	32	23	(Lempiäinen et al. 2022)
	Pine saw dust	44	26	26	(Rusanen et al. 2019)
Energy crops	Switch grasses	39.42	20.25	21.22	(Wang et al. 2020)
	Miscanthus sp	41.7	25.3	22.2	(Gismatulina and Budaeva 2017)

Table 2. Critical comparison of conventional pretreatment methods with their merits and demerits

Name of method	Impact on the biomass	Merits	Demerits	Reference
Ball Milling	• Reduce crystallinity of cellulose	• Solvent-free • Easy to operate	• High energy consumption • Do not provide a route for lignin valorisation	(Lan et al. 2022)
Acid pretreatment	• Break recalcitrant lignin and hemicellulose	• Simple and low-cost • Expensive enzymatic hydrolysis is not needed since acid has the potential to hydrolyse biomass into fermentable sugars	• Loss of fermentable sugar • Generate toxic inhibitors for the fermentation process • Sustainable issues	(Solarte-Toro et al. 2019)
Alkaline pretreatment	• Remove hemicellulose and lignin fractions	• Partially remove the lignin • Compared to acid pretreatment less degradation of fermentable sugars	• Harsh condition needed • Generate toxic by-products • Sustainable issues	(Donkor et al. 2022)
Organosolv	• Extract the lignin and hemicellulose	• Efficiently gives a recovery of lignin • Improve enzymatic digestibility of cellulose	• Expensive • Recycling of solvents is needed	(Sun et al. 2022)
Ionic liquid	• Reduce crystallinity of cellulose • Extract lignin	• Operate in mild conditions • Efficiently dissolution of cellulose • Selective, less toxic inhibitors produced during pretreatment	• Expensive • Recycling issue • Toxicity and poor biodegradability	(Roy and Chundawat 2022)
Liquid hot water	• Extract lignin and hemicellulose	• No catalyst is needed • Simple operational setup • High lignin conversion	• Time-consuming • High energy demand • High water consumption	(Chen et al. 2022)

3. Photocatalytic biomass conversion: mechanisms and challenges

3.1. Generalities and mechanisms

Lignin, the main element of lignocellulosic biomass, is considered the most complex polymer among the other components. It is more interesting than cellulose and hemicellulose because of its carbon-rich monomers and high reduced O_2 yield (Colmenares 2019). It consists of methoxylated phenylpropanoid units (Li et al. 2015). The appropriate scission of crosslinked C–C/C–O can produce high-value products, including phenolic compounds and benzaldehydes (Huang et al. 2022). In addition, the deoxygenation of lipid-derived fatty forms long-chain alkane fuels, i.e., jet fuel and diesel. The most critical parameter in these reactions is the selectivity of bonds' scission or deoxygenation reaction. Photocatalysis can generate reactive oxygen species (ROSs) under light irradiation, which can undergo different complex transformations (Zhang and Wang 2020). ROSs can participate in breaking down specific bonds under mild conditions. At the same time, such scission transformations require a higher temperature of up to 150°C and the presence of stoichiometric reducing or oxidizing agents (Zhang and Wang 2020). **Figure 1** shows examples of high-value chemicals from biomass through the photocatalytic pathway. Under light irradiation, the photocatalyst is subjected to the excitation of electrons followed by e-/h+ pairs generation. Oxidation and reduction reactions can occur on the photocatalytic materials' surface. Lignocellulosic biomass can act as an electron acceptor or donor, depending on conditions, properties of the photocatalyst, and potential of biomass compound as compared to energetic levels of conduction or/and valence band. In general, the transfer of ROSs to biomass is very slow because of the solid nature of biomass; however, many efforts have been reported to optimize the mass transfer between the generated ROSs and the biomass compound.

Specifically, photogenerated ROSs activate the biomass elements into a given radical intermediate, facilitating other reaction processes, such as the scission of bonds or intermediates combination to produce the desired product (Capaldo and Ravelli 2019). In terms of lignin, the main factor is the breaking down of interunit linkage, which produces several high-value aromatic monomers (Tsui, Wang, and Knowles 2020). ROSs attack the lignin structure and leads to activate the O–H bond, which undergoes the formation of the alkoxy radical. Alkoxy radicals provoke the weakness of adjacent C–C bonds, enabling its scission to open aromatic rings (Yayla et al. 2016; Ota et al. 2019). In this case, the issue is that Cα–H could be activated instead of C-O, which partially limits the fragmentation process of C-C bonds. The oxidation potential of the Cα–H bond compared to the O–H bond in the lignin structure is a determining factor for selective O-H activation to boost the fragmentation of C-C bonds. In some lignin structures, O-H activation is spontaneous and thermodynamically favourable; however, Cα–H activation would be more plausible in other cases, requiring different catalytic reactions to reverse it (Nguyen, Murray, and Knowles 2019). One of the common strategies to boost the activation of the O-H bond is the addition of an appropriate base to undergo a proton-coupled electron transfer (Zhou et al. 2018), as O–H exhibits a high polarity. Pretreatment of biomass with the chemical could boost the activation of O–H.

The photocatalytic activation of Cβ–H can lead to the oxidative cleavage of Cα–Cβ bonds of lignin structure (β-O-4 and Cβ–H models). The photogenerated superoxide radicals ($^{-\bullet}O_2$) react with the Cβ radicals released from Cβ–H bond to form an active peroxide intermediate, followed by dehydration which in turn boosts the Cα–Cβ bond cleavage in lignin. ROSs participate in the cleavage of C-C bonds of biomass, and photogenerated holes and electrons can play essential roles. It was reported that positive holes could activate Cα radical for the boosted weakness of Cβ–O bond, followed by bond cleavage via the photogenerated electrons (Wu et al. 2018).

The advantages of photocatalysis over conventional techniques can be summarized as follows

- Photocatalysis can be operated for biomass conversion at mid conditions in terms of temperature. The scission of many bonds requires heating up to 150°C.
- The non-use of stoichiometric reducing or oxidizing agents to initiate the fragmentation of biomass.
- The heterogeneous nature of the process allows the easy separation of produced products. In many systems, extraction and column separation would be necessary to separate the generated products. In addition, recycling the photocatalyst is possible, which might reduce the cost of the valorization at a large scale.
- The quality and yield of products obtained by photocatalysis could be different than those obtained by other techniques. Therefore, photocatalysis could be competitive with existing methods to produce a specific product.
- The selectivity of biomass valorization can be controlled by the design of photocatalytic materials.
- ROSs can activate selectively some specific bonds, which could be difficult through techniques. E.g., $^{-\bullet}O_2$ reacts with Cβ radicals to form an active peroxide intermediate.

3.2. Photocatalytic materials for biomass conversion

Studies on the conversion of different biomass substrates have been undertaken using the genealogy of different photocatalysts such as semiconductors, carbon-based, metal sulfides, and organometallic, among several others. However, using TiO_2-based semiconductors as photocatalysts remains the most studied for biomass conversion, primarily due to their low cost, stability, and toxicity. Substrate choice plays a significant role in determining the type of products likely to be obtained during the application of biomass. **Table 3** summarizes the application of different photocatalysts to various biomass substrate fractions (lignin and carbohydrates).

Photo-conversion of TiO_2-based for model, industrial and native lignin conversion to various aromatic building blocks have been reported. **Table 3** shows the conversion of different biomass substrates, such as lignin/model biomass, via TiO_2-based photocatalysts. Except for a few scenarios, the use of TiO_2 as a standalone homogenous catalyst has led principally to the depolymerization of model compounds. TiO_2 shows the possibility of overoxidation (selectiveness) due to its excessive generation of ROSs. Hence various strategies have been reported to improve the performance of TiO_2-based photocatalysts. Kobayakawa wrote the first report on the application of TiO_2 for lignin degradation in 1989 (Kobayakawa et al. 1989). However, lignin was degraded entirely to CO_2 and H_2O. Consequently, numerous studies have been conducted to increase the photocatalytic effectiveness of TiO_2 utilizing various methods. Enhancing contact between the catalyst and lignin substrate is reported to be one strategy to improve the yield of monomers using TiO_2 (Nair, Dhar, and Vinu 2016; Srisasiwimon et al. 2018). Under UVA conditions, Srisasiwimon et al. (Srisasiwimon et al. 2018) recorded about 40% conversion of kraft lignin and vanillin yield of 1%, with other aromatic-based monomers in low concentrations when a composite of TiO_2/lignin was prepared using a microwave sol-gel method. The mechanistic study revealed effective co-radical ($\cdot O_2^-$ and $\cdot OH$) production through enhanced contact. Tsapekos et al. (Tsapekos et al. 2018) utilized an AgCl-modified TiO_2 for rice husk depolymerization. Mechanistic studies showed that electrons from the Fermi level of Ag migrated to the TiO_2 under equilibrium occurring at the interface of the two materials, forming a new energy level with additional free electrons. This type of substitution is also reported to enhance the selective oxidation of cyclohexane to cyclohexanone (Vinu and Madras 2009). Other support-based catalytic systems have been reported. Bi and Pt as co-catalyst were supported onto TiO_2 (1% Bi/Pt1%-TiO_2) for photo-depolymerization of lignosulfonate lignin (Gong, Imbault, and Farnood 2017). The co-modified system successfully depolymerized lignin to vanillin, 4-phenyl-1-buten-4-ol, and vanillic acid, with yields higher than Bi-TiO_2 and Pt-TiO_2. Bi and Pt loaded on TiO_2 would result in the production of $O_2^{\bullet-}$ instead of highly oxidative radicals' success $^{\bullet}OH$. Preferably, $O_2^{\bullet-}$ (0.89 V, vs SHE) is less oxidative than $^{\bullet}OH$; hence $O_2^{\bullet-}$ is likely to be more selective towards aromatic monomers than radicals $^{\bullet}OH$. Overall, the 1% Bi/Pt1%-TiO_2 system produced the highest conversion and yield of guaiacol of 84.5%, with 22.7%, respectively. Metal sulfides have also been used to achieve key platform chemicals, which were extensively reviewed. The described sulfide photocatalysts encompass binary sulfides (CdS and ZnS) and multinary sulfides (like $Zn_{1-x}Cd_xS$ and $Zn_mIn_2S_{m+3}$). The most extensively studied metal sulfide photocatalyst for biomass valorisation is undoubtedly CdS, which has a bandgap of 2.4 eV and is responsive to visible light (>520 nm). But during the photocatalytic process, sulfide photocatalysts experience photo-corrosion, which needs greater attention in future studies. Liu and colleagues (Liu et al. 2012) observed an improvement in performance towards the conversion of different model lignin compounds using 1D CdS@TiO_2 over CdS nanowires as compared to using CdS catalyst only. The 1D CdS@TiO_2 composite semiconductor nanoparticle system converted 34% benzyl alcohol, 39% 4-methoxyl benzyl alcohol, and 41% 4-methyl benzyl alcohol, compared to 13%, 21%, and 7% for CdS nanowires, respectively. The plausible performance in the 1D CdS@TiO_2 compared to the 1D CdS NWs is ascribed to the extended prevalence of O_2•- and photoinduced electrons in the 1D CdS@TiO_2 than the 1D CdS NWs. Notwithstanding this progress, the application of photocatalysis alone systems for lignin depolymerization have not been realized for large scale production. Carbohydrates have, over the years, been desirable substrates for producing high-value chemicals and fuels (H_2). The initial stage in hydrogen production on metal (such as Pt) loaded TiO_2 is the photocatalysis-driven conversion of cellulose to glucose (Caravaca et al. 2016). The challenge of photoreforming biomass in water is difficult due to the strict pH demand. Hence, to achieve photo-reforming of cellulose, a simple one-pot strategy was reported by Zou et al. (Zou, Zhang, and Xu 2018). Their study used 0.6M sulphuric acids to hydrolyse cellulose at 130˚C under UV photocatalysis with platinized TiO_2. The in-situ production of electron donors stimulates direct conversion since the converted products are acceptors, and donors, with low oxidative power. A novel plasmonic nanostructure made of TiO_2 nanofibers (NFs) supported H-form Y- zeolites (HY) embellished with Au-NPs (Au-HYT) was employed (Wang et al. 2015). At 130 °C for 24 hours under mild conditions, the yield of glucose and 5 hydroxymethylfurfural (HMF) was greater than 60%. The cellulose conversion process is greatly aided by the localized surface plasmon resonance (LSPR) action of Au-NPs and the HY's potent acidity. Significant studies have also been done to study other carbohydrates products as explicitly detailed in **Table 1**. While cellulose has received significant attention to produce H_2, lignin has received little attention using TiO_2-based photocatalyst. However, the transformation of lignin to H_2 has been reported to work well using metallic sulfides as photocatalysts. Li et al. (Li et al. 2018) reported the activity of NiS (20% loading)/CdS is 5041 times higher with apparent quantum efficiency (AQE) of 44.9% than pristine CdS when the lignin and lactic acid acting as a hole scavenger.

Table 3: Application of TiO_2-based catalysts on photocatalytic biomass conversion

Substrate	Catalyst	Solvent	Light source	Reaction conditions	Product	Yield	Sel. (%)	Reference
Cellulose	TiO_2-S-Ni	H_2O	Xe lamp 500 W	80◦C, N_2, 3h	H_2	ND	181.2 µmol	(Hao et al. 2018)
Cellulose	TiO_2(Pt)	H_2SO_4	Iron doped halide lamp 250 W	130◦C, Ar, 10h	H_2	ND	123 µmol	(Zou, Zhang, and Xu 2018)
Cellulose	Pt/TiO_2	H_2O	UV-A irradiation (4*15 W)	ND, N_2, 4h	H_2	ND	54 µmol	(Speltini et al. 2014)
Lignosulfonate	TiO_2	H_2O	Xe lamp 300 W	r.t., ND, 1h	Guaiacol	ND	8.7	(Gong, Imbault, and Farnood 2017)
Lignin (1g/L)	TiO_2 Laccase H_2O_2 (5.55g/L)	Sodium acetate buffer solution (pH 5.0)	UV (315–400 nm)	rt, ND, 24h	Organic acids Fatty acids carbohydrates	ND	ND	(Kamwilaisak and Wright 2012)
Lignosulfonate (100mg/L)	Bi1%/Pt1%-TiO_2	H_2O	Xe lamp 300 W	rt, ND, 1hr	Guaiacol	22.7%	ND	(Kamwilaisak and Wright 2012)
Organosolv black liquour (50mL)	TiO_2	60% (v/v) ethanol Solution, H_2SO_4 added (pH 2)	300W UV	rt, ND, 0.5h	Syringaldehyde Vanillin Syringol Pirocathecol Sinapylaldehyde Oil	20% oil	ND	(Prado, Erdocia, and Labidi 2013)
1:1 w/w lignin TiO_2 ball milled mixtures (0.4 g)	0.4 g of 1:1 w/w ligninTiO_2 ball milled mixtures	H_2O	125 W High pressure mercury light	rt, ND, 6h	Ethyl benzene acetovanillone, acetosyringone, syringaldehyde, vanillin,	ND	ND	(Nair, Dhar, and Vinu 2016)

ND-no data

3.3. Operating factors for biomass conversion

Photocatalytic conversion of lignin depends on factors such as pH, temperature, type of solvent, treatment time, and type of photocatalyst, among other factors. Fundamentally, these tuneable factors can broadly be studied through the (i) identification of solvents capable of reducing complex interlinkages, (ii) identification of novel and highly selective photocatalytic systems adapted to biomass chemical structure (iii) identification of biomass activation strategies (Chatel, De Oliveira Vigier, and Jérôme 2014). These factors affect product yield, selectivity, and biomass conversion to value-added products (Colmenares, Varma, and Nair 2017; Nair, Dhar, and Vinu 2016). The appropriate design of parameters affecting photocatalysis could open doors for developing new and efficient/eco-friendly strategies for high-value chemicals from both carbohydrate and lignin biomass fractions.

The optimal selection of solvents plays a significant role in the photocatalytic conversion of biomass. An ideal solvent in the best-case scenario must possess characteristics such as (a) does not act as a photocatalysis quencher or a strong light absorber; (b) easily dissolves biomass (c) is recyclable, reusable, and non-toxic, and (d) inert to prevent wearing (Raikwar, Majumdar, and Shee 2021; Xiang et al. 2020). Unlike lignosulfonates made by the sulfite process, kraft lignin, for example, is difficult to dissolve in water but is easily soluble in highly alkaline conditions (Colmenares, Varma, and Nair 2017; Nair, Dhar, and Vinu 2016). Han et al. (Han et al. 2019), in a similar study, recorded almost a 100% yield and selectivity of 2-phenoxy-1-phenylethanone (PP-one) from 2-phenoxy-1-phenylethanol (PP-ol) under visible conditions (440−460 nm) and Ni/CdS as the catalyst. Mechanistically, it was clear that the outstanding performance in this system is linked to the excellent solubility of PP-one in pure Acetonitrile (MeCN) permitting enhanced dissociation on the surface of

Ni/CdS catalyst. Interestingly, by carefully changing the solvent mixture, MeCN/H_2O (v/v = 2:8), PP-one (yield=47%) with other products such as phenol (yield=52%) and acetophenone (yield=51%) were formed. This clearly shows that pH also plays an advanced role during depolymerization reactions. According to Kitano et al. (Kitano et al. 2014), increasing pH in the presence of -OH anions produces highly oxidative •OH species by scavenging photogenerated rhodium ion-modified TiO_2.

Aside lignin related studies, Colmenares et al. (Colmenares, Magdziarz, and Bielejewska 2011) reported the conversion of glucose to arabitol, glucaric acid, and gluconic acid using TiO_2 as a photocatalyst under UV light irradiation. The photocatalyst type, reaction time, and solvent all impacted the selectivity and conversion of glucose. For instance, when the ratio of acetonitrile and water was changed (1:9 and 1:1), selectivity of organic compounds of 39.3% and 71.3% were achieved, respectively.

3.4. Technical challenges

Though some progress have been made so far (especially using model lignin), the sole application of photocatalysis for biomass conversion still poses some significant challenges, especially the application of photocatalysis for the depolymerisation of lignin. TiO_2's broad use as a photocatalyst has two key limits that confine its photocatalytic proficiency: (1) photogenerated electron-hole pairs recombine very fast, (2) a large bandgap of TiO_2 causes only 3 to 5 % of the available solar spectrum to be used for photocatalysis (Du et al. 2016; Hussain et al. 2017). Therefore, further research should be targeted at developing mild or innovatively coupling green strategies to produce lignin-derived platform chemicals from lignin (Questell-Santiago et al. 2020; Shivhare et al. 2021; Wan and Lee 2021). Therefore, exploring a novel synergetic approach or highly selective catalyst to enhance both the pretreatment and cracking steps is critical for the large-scale application of photocatalysis. New strategies are needed to improve the intimate contact between the solid catalyst and solid native lignin or lignocellulosic biomass (Renders et al. 2019). Regarding lignin, firstly, selective cleavage of certain bonds has been predominantly studied using lignin model compounds, which may not fully represent the structure of technical and native lignin. The target of most depolymerization studies has been limited to the cleavage of C-O ether bonds due to their higher amount and low energy requirements relative to C-C (Wan and Lee 2021). Currently, problems such as robust reaction conditions, unselective, poor bond cleavage, and numerous reaction steps are problems facing C-C bond cleavage (Questell-Santiago et al. 2020). However, one-step/one-pot depolymerization of both C-O and C-C bond appear fascinating, which could enhance selective cleavage and full utilization of lignin (Nguyen, Murray, and Knowles 2019).

4. Sonophotocatalysis for biomass conversion

4.1. Principle of ultrasonic cavitation

Ultrasound is an emerging technology for chemical and processing applications referred to as sound waves described by frequencies exceeding 20 kHz working in specific media (Meroni et al. 2021; Harifi and Montazer 2015). It can be described by low- (20-100 KHz, i.e., wavelengths in water in the 7.4-1.5 cm interval), intermediate- (100 KHz – 1 MHz, corresponding to 15-1.5 mm wavelength window in water medium), and high- (1-10 MHz, i.e., wavelength lower than 150 µm in water) frequencies. Ultrasound can break the cell wall, successfully inducing natural product component extraction processes (Ruiz-Jiménez, Priego-Capote, and de Castro 2004; Cravotto et al. 2008). In particular, ultrasound cavitation is a unique physical phenomenon induced by the propagation of an ultrasound wave in liquid media. In this case, the ultrasound waves cause the growth of bubbles thanks to the nucleation of existing gas bubbles or gaseous sacs present at the surfaces of solid impurities; in turn, an oscillatory pressure field is applied to the resulting bubbles. This latter generates high-pressure cycles, compressing the gas within the bubble, and low pressure causes the forced expansion of the bubble. The ultrasound field induces the bubble growth according to the rectified diffusion of the dissolved gases and solvent to the bubble oscillation and coalescence (Wood, Lee, and Bussemaker 2017). Once a bubble achieves the resonance size, it grows to a maximum in the acoustic cycle due to its strong coupling to the acoustic field (Xu, Zeiger, and Suslick 2013). Then, the bubble implosion occurs together with the consequent fragmentation into smaller bubbles, which can dissolve or repeat the process (**Figure 2**). The above phenomenon of ultrasound-induced nucleation, growth, and collapse of bubbles is called acoustic cavitation (Mason et al. 2011).

In this context, each bubble can continue its growth-collapse cycle without fragmenting or giving only single bubble cavitation. The collapsing effect results in heat generation in the liquid medium, causing adiabatic heating of the bubble content (Schanz et al. 2012). In this frame, high values of temperature and pressure are achieved, inducing the formation of radical species (e.g., hydroxyl radicals formed *via* decomposition of water molecules), giving rise to sonochemical reactions (Mahamuni and Adewuyi 2010), or light emission (sonoluminescence) (Gao et al. 2020). In addition, shock waves in the liquid medium can be created thanks to the bubble implosion: these can induce mass transfer by turbulent mixing or the sonofragmentation due to the acceleration of suspended solid particles (Kim and Suslick 2021).

In the case of an asymmetric bubble collapse at either the boundaries or surfaces of solids, liquid jets of high speed (also named microjets) can be propagated from the bubble to the surface, causing surface erosion, pitting, and deformation (**Figure 3)**. Besides that, microjets can also be exploited for metal surface activation and surface engineering. Eventually, the ultrasound irradiation, which occurs during the crystallization step, can result in the sonocrystallization, i.e., the crystal seeds generation that causes the decrease of the induction time together with the increase of the crystallization yield and promotion of the selectivity to the desired morphology of the crystals (Ruecroft et al. 2005; Sander, Zeiger, and Suslick 2014).

Considering all these premises, an evident complexity related to the cavitation phenomenon emerges. Indeed, different experimental parameters need to be appropriately optimized to develop a specific application with the lowest operating costs possible.

In this context, the frequency of the sound field is the first point to analyze: the higher the frequency, the higher the number of cavitation bubbles, and the smaller the average bubble size. In other words, the higher frequency entails a short phase of expansion during the oscillation growth. This leads to a lower vapor in the bubbles, so smaller bubbles are present (Yasui 2002). Then, the higher the frequency, the shorter the oscillating period: this directly impacts the collapse and fragmentation phases, which are quicker. These phenomena strongly affect cavitation activity. By way of example, the size of the collapsing bubbles influences the maximum temperature that can be achieved during the implosion step. Moreover, larger bubbles obtained at lower frequencies contain more vapor because of the longer acoustic period (Yasui 2001). In this way, the heat consumption by the endothermic chemical reactions causes the decrease of the collapse temperature at low frequencies (Ashokkumar 2011). Therefore, the composition of the vapor in the bubble and the collapse temperature have a fundamental role in determining the number of radicals formed during the bubble collapse (Yasui et al. 2007). In this context, it thus emerges that the number of radicals formed *per* collapsed bubble is more significant at lower frequencies, even if the radical yield also depends on the whole number of bubbles, which is higher by increasing the frequencies.

Another point, which deserves to be considered, is the prevalence of physical or chemical effects. Indeed, when frequencies are in the 20-100 kHz range, cavitation bubbles are few, but they possess large sizes. Thus, cavitation mainly produces physical effects on liquid circulation and turbulence, and chemical effects are negligible. In particular, the decrease in the intensity of the cavitation collapse is observed with the increase in the ultrasound frequency (Mason and Lorimer 2002). In this case, larger intensities are needed to induce the cavitation phenomenon.

In the depicted scenario, it thus emerges that low frequency is preferred when intense physical effects are required (i.e., extraction, cell disruption, or polymer degradation). Then, when frequencies are higher than 500 kHz, the increasing bubble number promotes the overall radical yield, and the chemical effects prevail (Sancheti and Gogate 2017). Eventually, the frequency values between a few hundred kHz and 1 MHz are selected for chemical syntheses and pollutant degradation in wastewater degradation. In these cases, the optimal frequency is the result of the balance between chemical and physical effects (Sancheti and Gogate 2017).

4.2. Ultrasonic pretreatment of biomass

The conversion of biomass into high-value products by ultrasonic treatment would face several problems and challenges, most of which are listed as follows:

- Crude biomass exhibits a very recalcitrant structure due to the reticular connection of lignin, which requires strong solvents and harsh and costly operating parameters (Yu, Lou, and Wu 2008; Huber, Iborra, and Corma 2006).

- Raw biomass from different regions and resources exhibit different chemical compositions or uncertain ratios of lignin, cellulose, hemicellulose, sugars, proteins, and other traces of organic/inorganic constituents (Chemical, Biofuels, and Huber 2008). This matter makes biomass conversion at a large scale more challenging/complicated, and several in situ analysis and modifications in the conversion processing are required.

- The selectivity of catalytic processes to produce the desired chemicals and fuels is very challenging because of the complicity and sensitivity of catalytic processes themselves and the heterogeneity of raw biomass, as mentioned above (Friend and Xu 2017; Bayu, Abudula, and Guan 2019). The catalytic materials type also could affect biomass conversion's selectivity (Dutta 2012; Dusselier et al. 2015).

- Low mass transfer between catalytic materials and biomass mass is a severe issue. In addition, biomass conversion has low thermal conductivity (Mettler, Vlachos, and Dauenhauer 2012; Lifka and Ondruschka 2004).

- The high cost of biomass treatment could be a critical problem for transferring this technology because of the use of a lot of energy and reagents/solvents to carry the biomass conversion.

- The extraction of the final products from the mixture is also challenging. The recovery of catalysts and the removal of solvents would affect the degree of the purification of final products.

In this section, the role of the ultrasonic process in assisting biomass conversion into high-value products or as a pretreatment approach will be addressed. Ultrasonic cavitation can assist biomass conversion as it can deliver to the medium an exceptional condition by providing chemical and physical effects (Ensminger and Bond 2011; Meroni et al. 2021). In the cavitation field, the lignocellulosic biomass undergoes facile fragmentation and transformation into the desired products within a lesser reaction time. The ultrasonic vibration can boost the mass and heat transfer between the catalysts and the biomass constituents, allowing a faster conversion and use of less catalyst quantity and less solvent (Lu et al. 2016; Luo, Fang, and Smith Jr 2014). Ultrasonic vibration can boost the interaction of intermediates to form the final products.

The bubbles collapsing on the surface of solids in water can produce high temperatures and high pressure, which ensures different physicochemical effects. In terms of chemical effects, free hydroxyl radicals can be generated due to the breaking down of H_2O molecules. Such radicals can participate in the oxidative conversion of biomass. In contrast, the physical effect can be applied to promote biomass's dissolving and enhance mass transfer (Bussemaker and Zhang 2013; Ebringerová and Hromádková 2010). Water or solvent circulation around the catalysts and biomass is significantly enhanced due to generated pressure from the cavitation. Several reports mentioned cavitation is a critical factor in boosting the delignification and relocalization of biomass (Iskalieva et al. 2012).

The ultrasonic process has been associated with different techniques for biomass conversion and mainly provides the same physicochemical environment, which boosts any catalytic process. Of these combinations, we might cite ultrasound-assisted biological biomass conversion (Bundhoo and Mohee 2018), ultrasound-assisted electrochemical biomass conversion (Neha et al. 2020), ultrasound-assisted Fenton biomass conversion (Zhang et al. 2016), ultrasound-assisted acid hydrolysis biomass conversion (Bizzi et al. 2019), ultrasound-assisted metal-based catalytic biomass conversion (Chai et al. 2021; Guldhe et al. 2014), and ultrasound-assisted photocatalytic biomass conversion (Guldhe et al. 2014).

4.3. Effect of cavitation on the photocatalytic biomass conversion

As mentioned above, biomass conversion by heterogeneous catalysts suffers from low mass transfer and the requirement to use organic solvents to enhance the contact and dissolution of biomass for effective conversion. However, these conditions result in different issues, including the difficult extraction of the final products, contamination of final products, possible interaction of solvents with intermediates (inhibition of conversion process) or scavenging of photogenerated reactive oxygen species (ROSs), and then, of course, the high cost of the valorisation. However, combining ultrasonic with photocatalysis for biomass conversion would solve many issues and boost the conversion in terms of the high yield of desired products, better quality, and low cost (Chatel et al. 2017). Because of the violent physical effect of the ultrasonic vibration, water can be used instead of organic solvents to dissolve the biomass.

Under ultrasonic vibration, biomass hydrolysis can be enhanced several times, facilitating its conversion into high-value products. This behaviour is essential in catalytic and photocatalytic processes toward biomass valorisation. In terms of catalysis, many reports concluded that the presence of ultrasonic vibration during the catalytic conversion of biomass is a significant factor that boosts biomass conversion. It was reported that the acid hydrolysis of palm oil to xylose was improved more than twice in the presence of ultrasonic cavitation (Yunus et al. 2010).

In photocatalysis, dissolved oxygen in the medium can have two roles in biomass conversion, positive and negative. The conversion of O_2 by photogenerated electrons produces superoxide radicals ($^{-\bullet}O_2$) which participate in the oxidation and fragmentation of biomass into desired products. On the other hand, too many ROSs, including $^{-\bullet}O_2$ species, can reduce the selectivity via unwanted oxidation of intermediates into fewer value products or CO_2. One of the roles of the ultrasonic process is to reduce the content of O_2 in water because of the cavitation effect.

Ultrasonic cavitation can enhance the surface area of the catalysts and allows better dispersion. Hot spots can be produced on the surface of the catalyst at a temperature of 5000°C and 1000 bars, causing a jetting phenomenon that might generate a high velocity of up to 600 km/h (Giannakoudakis, Łomot, and Colmenares 2020), as shown in **Figure 3**. In general, water molecules can form a layer on the surface of the photocatalyst, which limits the surface reaction and mass transfer; therefore, organic solvents are primarily used to get fast reactions. However, in the presence of an ultrasonic field, this water molecules barrier can be broken due to hot spots and physical effects, allowing the use of water as a solvent (Giannakoudakis et al. 2019). Because of these synergistic effects, sonophotocatalysis offers enhanced biomass conversion as compared to single photocatalysis. Piyali et al. reported that lignin depolymerization by sonophotocatalysis was 2.7 times superior to photocatalysis (Dhar, Teja, and Vinu 2020). As shown in Figure 6, both the yield and number of products can be improved because of synergistic effects. Four products were found in sonophotocatalysis with a total yield of 67 mgL^{-1}, against only two products with a total yield of 40 mgL^{-1}.

5. Research needs and future directions

To intensify the photocatalytic process, the involvement of ultrasonic vibration with the photocatalytic conversion of biomass brings several advantages. It would make the process more effective and sustainable on a large scale. From the kinetics point of view, the photocatalytic process can be enhanced by improving the mass transfer because of the effect of shock waves and jetting phenomena, promoting the mixing of the photocatalyst with biomass, as well as improving the transfer of ROSs to the biomass matter. Ultrasonic ROSs production can participate directly in the oxidation process of biomass and radical intermediate formation. Ultrasonic fields can control the dissolved oxygen in the medium, which is very beneficial for photocatalytic biomass conversion. In general, biomass should be dissolved in organic solvents to allow its fragmentation and conversion by photocatalytic means; however, using solvents is not recommended from a sustainable and economic point of view. On top of that, the presence of solvents could play the role of ROSs scavenger; interaction with radical biomass intimidates, reducing the quality of the final products. Also, separating some products from solvents might be difficult at the end of the conversion. The presence of ultrasounds can allow the use of water as a solvent, as the produced heat and shock waves can lead to excellent biomass dissolution in water. The ultrasonic process makes shock waves, and heat can also clean the photocatalyst’s surface. The photocatalytic conversion of biomass in the presence of ultrasonic vibration leads to an increase in yield and the variety of produced products since many transformation reactions are slow or difficult by single photocatalysis.

Several challenges are still facing the appropriate application of sonophotocatalysis for biomass conversion. The selectivity of the conversion is an essential factor that needs to be intensively investigated in future studies. The optimization parameters of the ultrasonic process to assist the photocatalytic biomass conversion is imperative, such as the intensity of ultrasound, the frequency, and the time. The geometry of sonophotocatalytic reactor is essential to obtain a homogenous reaction medium. Further studies on optimizing biomass dissolution in water by the ultrasonic process are highly recommended from the sustainable and large-scale application points of view. Even though many studies have been reported on sonophotocatalytic biomass conversion; however, a careful understanding of mechanisms is still required.

From a mechanistic perspective, understanding the conversion of biomass into the desired products is still under debate because of several factors. The biomass structure is not unique; therefore, the transformation and the obtained products would be different by changing the biomass support. Most reported studies have emphasized using model lignin which is easy to convert, and its mechanistic conversion would be understandable and unique in some cases. However, it is very challenging to understand the photocatalytic mechanistic pathways of native or/and industrial biomass conversion due to the complex structure and the formation of various radical intermediates. In this sense, it is expected that several side interactions among different radical intermediates would take place to form a variety of final products. Studying the selectivity of the photocatalytic and sonophotocatalytic processes towards the valorisation of native and industrial biomass should receive more attention. Even though sonophotocatalytic has proved to be an effective synergistic process to enhance biomass valorization, the negative side of ultrasonic vibration could be studied. Sonolysis, if not optimized, could probably lead to a considerable number of products because of the effective fragmentation of biomass. The effect of sonolysis on the plausible total mineralization of biomass to CO_2 could be checked during the photocatalytic experiments. A strong cavitation field could occur by ring-opening desired products into other ones. Finally, research studies regarding the commercialization/industrial aspects are highly recommended.

6. Conclusions

This review critically discusses the combining of ultrasonic and photocatalytic processes for biomass conversion into high-value products. Photocatalysis as a single process suffers from many issues, including low mass transfer, weak fragmentation and low yield of generated products. Several aspects that govern biomass transformation by photocatalysis and sonophotocatalysis from the mechanistic and technical perspectives were discussed in this review. Based on the literature, further studies on the optimization of affecting factors and understanding the sonophotocatalytic biomass conversion mechanisms are still needed. Overall, sonophotocatalysis would be an attractive competitive option for biomass valorization into high products.

CRediT authorship contribution statement

Ridha Djellabi: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Validation, Visualization.

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Figures

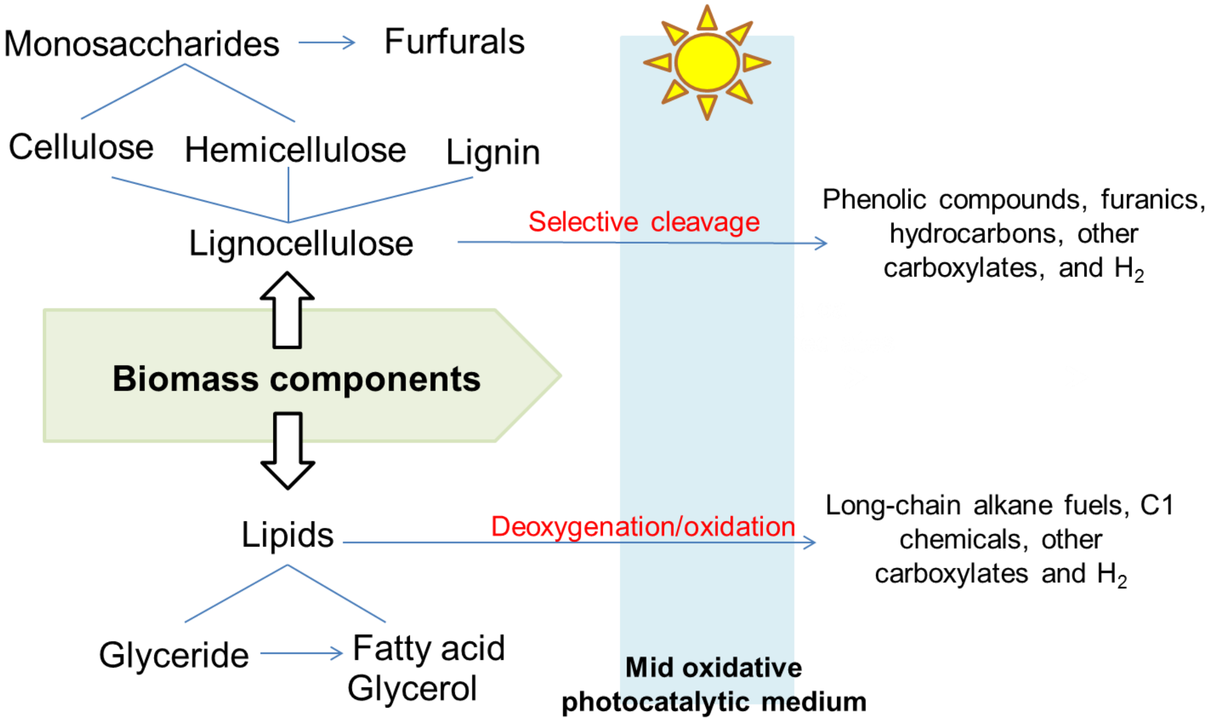

Figure 1. The scheme shows the photocatalytic production of various high-value products from biomass materials.

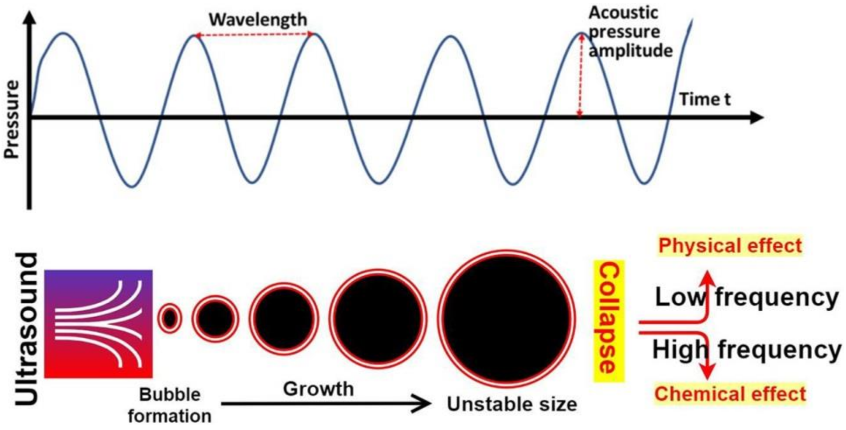

Figure 2. Scheme of the acoustic cavitation phenomenon, reproduced with permission from Ref (Meroni et al. 2021).

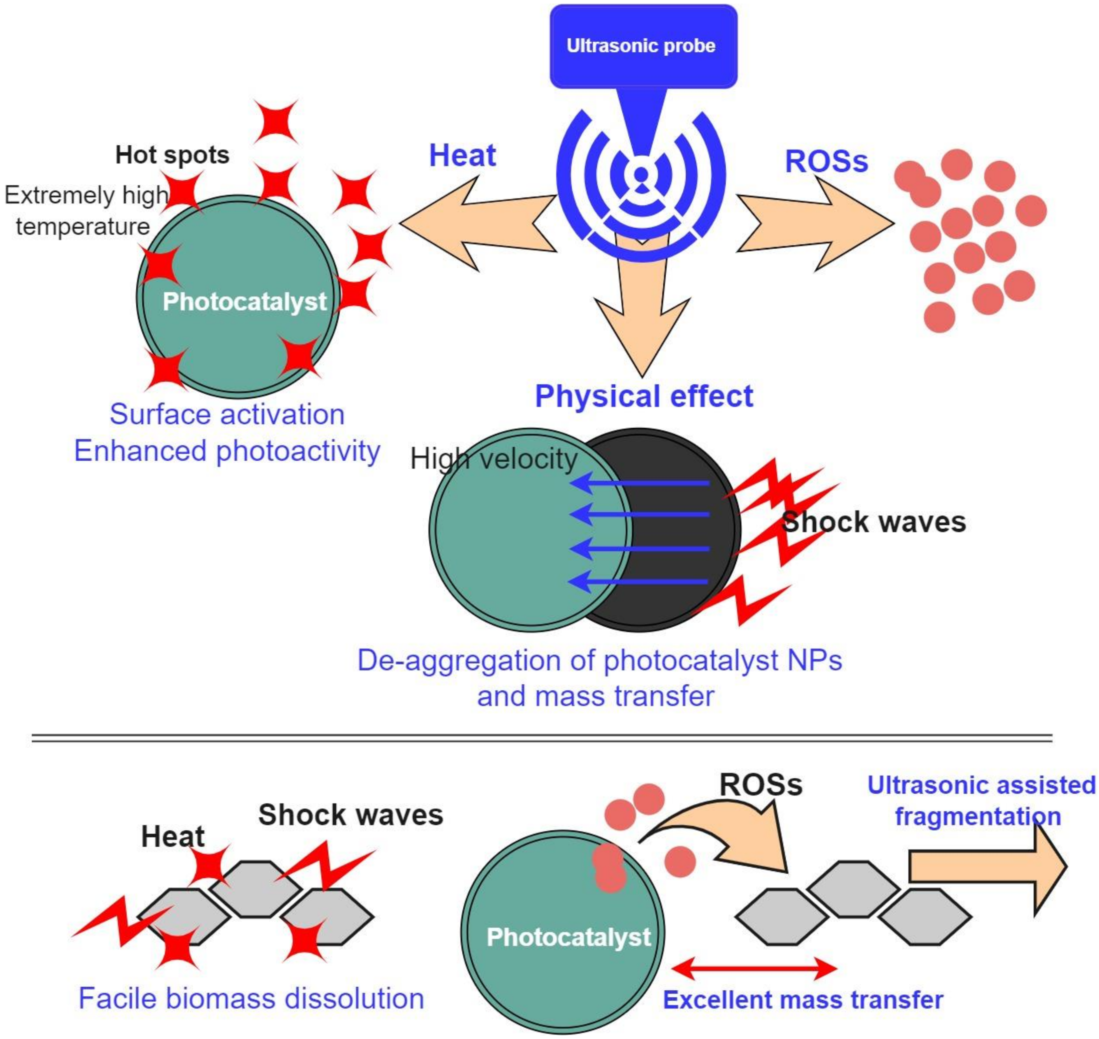

Figure 3. Main mechanisms of sonophotocatalytic biomass conversion: ultrasonic vibration could produce ROSs, physical vibration effect, and heat to boost the photocatalytic process; shock waves can promote the mass transfer through jet phenomenon, causing an effective de-aggregation of nanoparticles: shock waves can also assist the transfer of biomass molecules to the surface of photocatalyst for enhanced ROSs attack; the dissolution of biomass can be improved under ultrasonic vibration, and on top of that, water can be used instead of organic solvents by the force of cavitation and produced heat; ROSs produced from ultrasonic vibration can participate in the radical conversion of biomass; also, ultrasound can assist the interaction of radical intimidates and control the yield of dissolved oxygen.

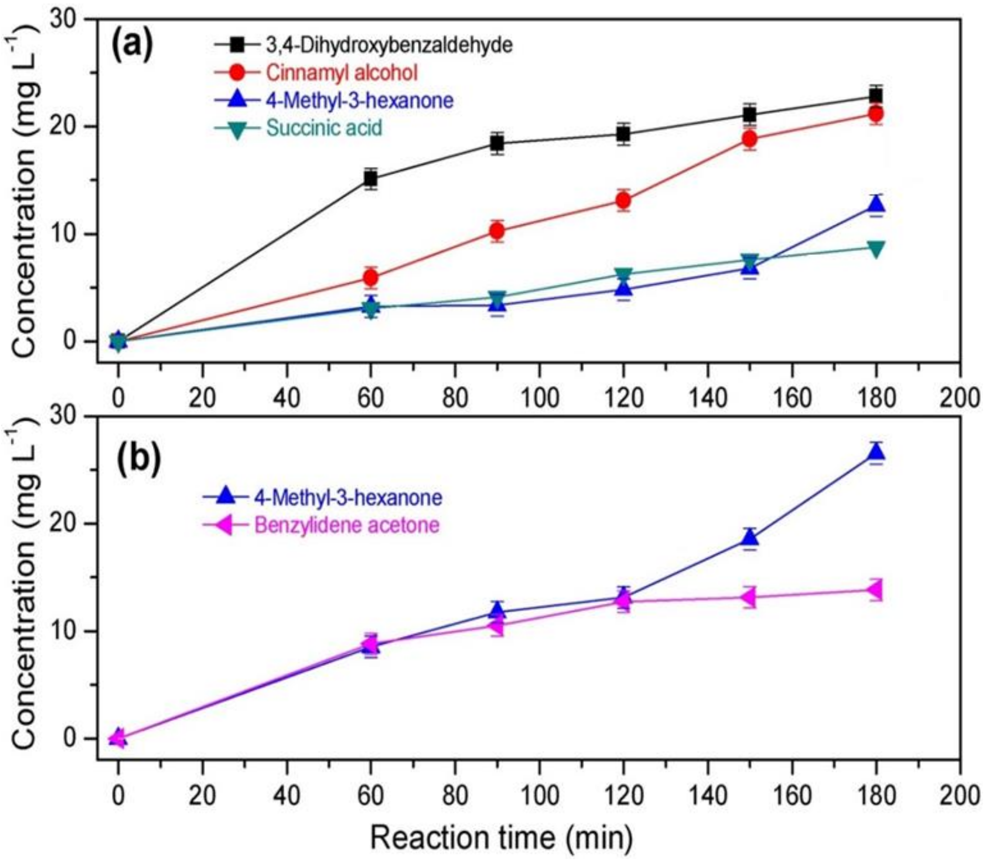

Figure 4. Generated profiles obtained by sonophotocatalysis (a) and photocatalysis (b) in lignin depolymerisation, reproduced with permission from (Dhar, Teja, and Vinu 2020).

Declaration of Interest Statement

Competing interests: The author declares no competing interests.