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Perspective

Advanced Applications of Torrefied Biomass: A Perspective View

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Abstract: Because of the social, economic, and environmental issues linked with fossil resources, there is a global interest in finding alternative renewable and sustainable resources for energy and materials production. Biomass could be one such renewable material that is available in large quantities. However, biomass physicochemical properties are a challenge for its industrial application. Recently, the torrefaction process was developed to improve the fuel characteristics of biomass. However, in recent days, energy production has slowly been shifting towards solar and wind, and restrictions on thermal power plants are increasing. Thus, there will be a need to find alternative market opportunities for the torrefaction industry. In that regard, there is a quest to find alternative applications of torrefaction products other than energy production. This paper presents a couple of alternative applications of torrefied biomass. Torrefaction process can be used as a biomass pretreatment option for biochemical conversion processes. The other alternative applications of torrefied biomass are using it as a reducing agent in metallurgy, as a low-cost adsorbent, in carbon-black production, and as a filler material in plastics. The use of torrefied biomass in fermentation and steel production is validated through a few laboratory experiments, and the results are looking attractive. The lower sugar yield is the main challenge in the case of the microbial application of torrefied biomass. The lower mechanical strength is the challenge in the case of using it as a reducing agent in a blast furnace. To date, very few studies are available in the literature for all the highlighted applications of torrefied biomass. There is a need for extensive experimental validation to identify the operational feasibility of these applications.

Keywords: biomass torrefaction; reducing agent; fermentation; adsorbent; carbon black; torrefied biomass applications; thermochemical conversion; biochar; biocoke

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1. Introduction

Today, global warming is one of the major threats the world is facing. The consequences of global warming are the melting of glaciers, uneven weather patterns, droughts, and rising sea levels. The widely accepted reason for global warming is the increased greenhouse gas emissions into the atmosphere. The commonly known greenhouse gases are CO_2, NO_2, CFC, and water vapor, and among these CO_2 is playing a major role in the global warming. The usage of fossil resources in fuel and material production is the main reason for the ever-increasing CO_2 level in the atmosphere. Today, the global economy depends on fossil resources. However, measures are being taken over a long time in order to reduce society's reliance on fossil resources. At the regional level, the EU is aiming to reduce the CO_2 level by 85% compared with the pre-industrial level. To achieve these ambitious targets, fossil resources need to be replaced with renewable resources. In that regard, biomass is being considered as a renewable resource. Even today, biomass is mankind's primary resource for several applications. However, these applications may differ between different countries depending on their socioeconomic development. In developing countries, biomass is being used for primary energy applications, and in developed nations, the same is being used for advanced applications such as biochemicals and bioenergy production [1].

Although biomass is renewable and available in large quantities, it also possesses some drawbacks which include high moisture content, reluctant nature, hydrophilicity, ash, and microbial degradation. In order to overcome these issues, biomass needs to be pretreated. The selection of these pretreatment methods depends on the type of conversion process and the desired end product. Torrefaction is one such pretreatment method that improves the biomass properties to the level of competing with coal. In the last decade, research activities on torrefaction have gained bigger momentum. At the moment, a couple of commercial scale operations are also established around the globe. The primary intended application of torrefaction is to produce torrefied biomass for energy applications. However, around the globe, there is a shift in energy production, and in the future, solar and wind can play a major role. At the same time, the restrictions on thermal power plants are also increasing globally [2]. However, the closing down of the power plants will still take a long time. In addition, the demand for torrefied biomass pellets exists in other industries such as pharmaceuticals, cement, and food industries, where process heat energy is required. Still, to improve business prospects in the future, the torrefaction industry needs to find alternative applications of torrefaction products.

The majority of the previous studies on biomass torrefaction focused on the properties of the solid torrefied biomass and its subsequent applications in thermal conversion processes such as combustion, pyrolysis, and gasification. Few studies focused on the diversified applications of torrefaction products. Technically, the torrefaction process can also be integrated with other biomass conversion processes, and torrefaction products can be used in different applications other than energy production. In this regard, the perspective applications of torrefied biomass are presented in this paper. The main aim of this paper is to highlight the applications of torrefied biomass other than energy production. The challenges and future research directions are also highlighted.

2. Torrefaction Process

Torrefaction is a low-temperature thermochemical conversion process, which is carried out in the temperature range of 200–300 °C. Generally, torrefaction is carried in the inert environment using either N_2 and/or CO_2. However, some researchers also studied oxidative torrefaction in a reducing environment (i.e., low oxygen). The main intended purpose of the torrefaction process is to improve the biomass fuel characteristics. For example, torrefaction reduces the volatile matter content of the biomass and increases the heating value. It increases the hydrophobicity of the biomass by removing the O-H groups in the biomass. The increased energy density is one of the major advantages of the torrefaction process, which helps to improve the transportation economics of the biomass [3].

Detailed information on product distribution and mass and energy balances during biomass torrefaction can be found in [4,5]. During torrefaction, the volatile fraction of the biomass is released through different reaction mechanisms. The solid (i.e., torrefied biomass) and gases (torrefaction volatiles) are the products of the torrefaction process. During torrefaction, biomass undergoes drying, depolymerization, devolatilization, and carbonization [6]. The extent of these processes depends on the operating conditions such as temperature (i.e., severity of the torrefaction process). Deoxygenation is one of the advantages of the torrefaction process. During torrefaction, the oxygen content of biomass is released as volatiles, mainly in the form of water, CO_2, CO, and other condensable products (i.e., organic acids).

Torrefaction volatiles contain both condensable and uncondensable gases. The torrefaction condensate mainly contains water and organic acids (i.e., acetic acid, propionic acid, formic acid), furfural, furans, and phenols. Although the torrefaction condensate contains several compounds, water and acetic acid are the major compounds. The uncondensable gases mainly contain CO_2, and CO, and the other gases such as CH_4 and H_2 in low concentrations [7].

The solid, i.e., torrefied biomass is the main intended product of the torrefaction. The other products, i.e., torrefaction volatiles released during torrefaction, are combusted in a boiler together with utility fuel to match the heat energy requirement. The yield of the solid and volatiles varies in the range of 40–80 wt.% and 20–60 wt.%, respectively, depending on the operating parameters. Using it as a solid fuel in energy production is the main intended application of the torrefied biomass. Because of the migration of oxygen in the form of volatiles, the carbon content in the biomass increases relatively. This increases the C/O and C/H ratios and ultimately results in the increased energy content of the biomass. The heating value of the torrefied biomass varies in the range of 15 to 25 MJ/kg depending on the operating conditions and type of biomass. The fuel ratio of the torrefied biomass varies in the range of 0.2 to 0.7 [2]. In terms of fuel characteristics, the torrefied biomass can be compared with low-rank coals such as bituminous and lignite. As the intention of this paper is to present the futuristic applications of torrefied biomass, a basic overview of torrefaction is presented here. The readers are guided to check the recent torrefaction review papers [6,8] for a detailed understanding of the process. For more information on the current status of torrefaction process, authors suggest to check the publication [8] from International Biomass Torrefaction Council (IBTC).

3. Perspective Applications of Torrefied Biomass

As an alternative to energy production, torrefied biomass can be used as a source of sugars in fermentation, as a low-cost adsorbent in soil amendment applications, as a supporting material in microbial processes (i.e., anaerobic digestion), and as a reducing agent in metallurgy applications.

3.1. Fermentation of Torrefied Biomass

Lignocellulosic biomass mainly contains cellulose, hemicellulose, and lignin. Generally, the sugars derived from cellulose are interesting for microbial conversion. However, these polymers are in a highly ordered complex matrix and reluctant to microbial degradation. Thus, it is essential to alter the structure and fractionation of lignocellulosic biomass components prior to their application in microbial processes. There are several processes previously developed to pretreat biomass which include milling, extrusion, microwave treatment, acid treatment, alkali treatment, organosolv, fiber explosion, and steam explosion [9]. During the pretreatment, the lignin is degraded and disintegrates. Hemicellulose is degraded into multiple compounds such as organic acids and furans. Pretreatments also alter cellulose's crystalline structure and improve the enzymatic degradation in subsequent hydrolysis. All these conventional treatments have their own operational challenges. Alternatively, torrefaction could also be considered as a treatment option to alter the lignocellulosic biomass structure for its subsequent application in microbial processes.

In the case of torrefaction, hemicellulose is the mainly degraded biomass polymer, thus by optimizing the torrefaction temperature, the selective removal of hemicellulose can be achieved with minimal degradation of cellulose and lignin. The conventional pretreatments are single-pot processes; therefore, the removal and recovery of hemicellulose and lignin degradation compounds are challenging especially for chemical pretreatments. In the case of torrefaction, hemicellulose and lignin are degraded in the form of volatiles which can be condensed and collected separately. Torrefaction can also be considered as a chemical-free treatment, such as a steam explosion. The operating temperature of the torrefaction is in the range of 200 to 300 °C. However, to minimize cellulose degradation, the maximum temperature can be between 250 and 275 °C. This is not much higher compared with other pretreatments, for example, acid treatment (100 to 200 °C) and steam explosion (170 to 210 °C) [9].

On the other hand, biomass needs to be milled and grounded prior to pretreatment to increase the surface area, especially in the case of chemical treatment. However, because of its fibrous nature, the grinding of biomass is energy-intensive. As torrefaction increases, the brittleness of the biomass, grinding energy could be reduced by multiple times [8]. Considering the above advantages, the torrefaction process could be considered as a pretreatment option prior to the microbial conversion of lignocellulosic biomass. Some research activities are already focused on this direction. Recently, Li et al. [10] studied torrefaction as a pretreatment option for the biohydrogen production from the corn stover. The authors observed that the reducing sugars' yield and biohydrogen production increased significantly with torrefaction treatment compared with the untreated corn stover. For example, the cumulative hydrogen yield increased from 362 mL to 618 mL for the corn stover torrefied at 200 °C. However, the authors observed that the optimum temperature was 200 °C, and the further rise in the torrefaction temperature resulted in a significant decrease in the hydrogen yield.

Recently, Tripathi et al. [11] studied the influence of alkali treatment before and after the torrefaction on the glucose yield during hydrolysis. The authors reported that torrefaction severity had a significant influence on sugar yield. Finally, the authors concluded that alkali treatment of the torrefied biomass could increase the glucose yield from the torrefied biomass. In another study, Normark et al. [12] also observed that treating the torrefied biomass with ionic liquids had a higher yield of sugars. A few other studies [13–15] also evaluated the feasibility of torrefaction as a pretreatment option for biochemical conversion.

All these studies commonly reported that the sugar yield is lower during the hydrolysis of torrefied biomass. Generally, the thermal degradation range of cellulose is between 260 and 320 °C. Thus, the loss of cellulose during torrefaction, especially when the temperatures are below 250 °C, is low. The previous studies also observed the same. For example, Cahyanti et al. [3] reported a cellulose loss of 14% at a torrefaction temperature of 275 °C for forestry wood waste. The morphological changes in the cellulose structure and/or biomass matrix could be the possible reason for the lower sugar yield for the enzymatic hydrolysis of torrefied biomass. The water biomass interactions and further mass transfer implications within the solid biomass particle play an important role in the hydrolysis yield [16]. In the case of torrefaction, the hydrophobicity of the biomass starts increasing with increasing temperature because of the reduced hydroxyl groups. This increased hydrophobicity of the torrefied biomass could be having a negative effect on the enzymatic hydrolysis. Further extending the discussion, the cellulose crystallinity also shows an effect on the enzymatic hydrolysis efficiency. The biomass contains both amorphous and crystalline cellulose with varying concentrations depending on the type of biomass. Because of the lower thermal stability, the amorphous cellulose is mainly degraded during torrefaction, compared with crystalline cellulose, and thereby the crystallinity of the torrefied biomass increases [17]. According to Fan et al. [18], the hydrolysis rate and yields were more than 100 times lower in the case of crystalline cellulose hydrolysis compared with amorphous cellulose. Thus, the increasing crystallinity could also be the possible reason for the lower sugar yield during torrefied biomass hydrolysis.

According to the above discussion and based on previous studies, torrefied biomass must be treated to modify the cellulose structural changes prior to its enzymatic hydrolysis. The literature survey shows that treating crystalline cellulose with ionic liquids significantly reduces the cellulose crystallinity. Previously, the authors of [12] reported that treating torrefied spruce with ionic liquid increased the sugar yield by 647% compared with the hydrolysis of non-treated torrefied biomass.

3.2. As an Adsorbent

The research interest in using torrefied biomass as a low-cost adsorbent is increasing in recent days. Few attempts were made to understand the feasibility of using torrefied biomass as a low-cost adsorbent. Recently, Lee et al. [19] studied the feasibility of spilled diesel oil recovery using torrefied spent coffee grounds. Interestingly, the authors observed a high adsorption capacity (i.e., 1.36 times higher) for the spent coffee grounds torrefied at 300 °C compared with activated carbon. In another study, Lu et al. [20] studied a comparative analysis on the adsorption of uranium and methylene blue using torrefied and pyrolyzed antibiotics' production fermentation residue. Interestingly, the torrefied residue showed better performance, and the authors attributed the superior adsorption capacity of torrefied residue to the availability of high oxygen and nitrogen functional groups compared with the pyrolysis char. Another study also showed that torrefied biomass had a higher adsorption performance (i.e., 2-times higher) compared with the pyrolysis char produced from the same biomass [21]. Recently, another study used torrefied Cyprus cone as an adsorbent for the adsorption of oil contaminants from oil spills. The authors observed that torrefied biomass had superior adsorption properties with a removal efficiency of 92% [22].

The literature data showed that torrefied biomass has superior adsorption properties compared with pyrolysis char and activated carbon. This is mainly because of the presence of high-oxygen functional groups. Previous studies strongly advocated the application of torrefied biomass as a low-cost adsorbent for the removal of pollutants. However, there is a need for more studies to further understand the relation between torrefaction operating conditions and morphological changes with an aim of higher adsorption efficiency. At the same time, there is also a need to analyze the economic feasibility.

3.3. As a Reducing Agent in Metallurgy

Using torrefied biomass as a reducing agent in metallurgical applications (steelmaking) is another interesting application. In order to reduce the negative environmental impacts, the steel industries are looking to replace fossil coke with biobased reducing agents. Previously, the biochar from pyrolysis and gasification was mainly considered as the biomass-based reducing agents. In recent days, the interest in torrefied biomass as a bio-reducing agent is increasing. A few studies have already focused on this direction. The EU-funded Torero project is one such practical example [23]. Compared with either conventional coke or with pyrolysis and gasification-derived char, torrefied biomass could possess some advantages. According to Konishi et al. [24], the rate of iron oxide reduction could be much higher for bio-coal with higher volatile matter than that of coke or coal-derived char because of the release of the reducer gases, i.e., H_2 and CO. The gasification rate of torrefied biomass is also higher because of the porous structure. In another study, Ubando et al. [25] observed that torrefied biomass with high volatile content decreased the Wustite formation temperature. These preliminary experimental data showed the better performance of torrefied biomass than conventional coke and/or pyrolysis chars. However, there is a need for extensive studies to better understand the overall feasibility of using torrefied biomass as an alternative reducing agent.

4. Challenges and Future Opportunities

The preliminary data show that torrefied biomass can be used in applications other than energy production and/or in subsequent thermal conversion processes. However, the literature survey shows that very few studies are available on the alternative application of torrefied biomass. The fermentation of torrefied biomass could be one interesting application to be considered. As presented in Section 3, the torrefaction process presents several operational advantages compared with other biomass pretreatments. In addition, lower energy input and superior supply chain benefits give torrefaction an edge over other pretreatment processes. At the same time, torrefaction process can also be integrated with the fermentation process either in terms of energy integration or handling the fermentation residue. As with every biomass pretreatment process, torrefaction also has negative effects when considered as a pretreatment option for fermentation.

The sugar loss at higher torrefaction temperatures is one challenge. The increasing crystallinity and hydrophobicity of biomass play a negative effect and result in a low sugar yield during hydrolysis. The sugar loss (cellulose degradation) can be controlled by optimizing the torrefaction-operating parameters. The sugar yield during hydrolysis can be improved by treating the torrefied biomass through chemical treatment (acids or ionic liquids). Although the operational costs of the torrefaction are comparable with other biomass pretreatments, the initial investment costs can be higher for torrefaction compared with some of the pretreatment processes. So far, very few research studies are available on this topic. Thus, there is a need for extensive experimental studies to better understand the fermentation of torrefied biomass. The future studies must focus on relating to the morphological changes of biomass during torrefaction and overall fermentation efficiency. The operating parameters also need to be optimized relating the ash content and the fermentation efficiency. The ash present in biomass could significantly influence sugar degradation during torrefaction. At the same time, the economic and environmental feasibility of integrating torrefaction with fermentation needs to be explored.

The other applications such as using it as an adsorbent and reducing agent are also interesting applications with high market potential. This is especially true as a reducing agent, as the steel industry is aiming to use sustainable carbon in their processes. Regarding the excess heat energy available in the steel industry, for example, the heat energy recovered from slag could be used for the torrefaction process, which reduces the utility fuel input and improves the feasibility of the torrefaction process. Interestingly, the torrefied biomass showed better performance compared with pyrolysis-derived or coal-derived cokes. This is mainly because of the positive effect of the higher volatile matter present in the torrefied biomass (i.e., lower C/O ratio). However, there are several other physiochemical properties of reducing agents which can influence the blast furnace operations, for example, compression strength, reactivity, and density. Generally, a reducer with high compression strength is required for efficient blast furnace operations [26]. Previously, Adrados et al. [27] reported that bio-reducers (pyrolysis chars) are not suitable to use as a top burden in blast furnaces because of their lower mechanical strengths, and suggested injecting through tuyere. As stated in the previous sections, there are only a countable number of studies on these advanced applications of torrefied biomass. The future studies must focus on establishing the relationship between the physiochemical properties of the torrefied biomass and the efficient blast furnace operational requirements.

The other application includes the production of nanocellulose and black carbon from torrefied biomass. The torrefied biomass can also be used as a filler material in plastics and as a supporting material in anaerobic digestion. However, these applications are still in their infancy stage.

5. Conclusions

In terms of operational feasibility today, torrefaction is already an established process and is being operated on a commercial scale. In a view of changing energy scenarios and increasing restrictions on thermal power plants, there is a need to find alternative applications of torrefied biomass. In that regard, the perspective application of torrefied biomass is presented in this paper. The alternative applications of torrefied biomass are microbial conversion into biochemicals; as a bio-reducer in the steel industry; low-cost adsorbent, black-carbon production; and as a filler material in plastics. The fermentation of torrefied biomass and using it as a reducing agent are validated through a few studies, and the preliminary data look promising. However, it is difficult to conclude on the feasibility of using torrefied biomass in fermentation and metallurgical applications because of the lack of experimental data. There are several challenges that still need to be addressed through extensive experimental validation.

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