

Review

An Insight into Valorization of Lignocellulosic Biomass by Optimization with the Combination of Hydrothermal (HT) and Biological Techniques: A Review

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Abstract: Biomass valorization plays a significant role in the production of biofuels and various value-added biochemicals, in addition to lowering greenhouse gas emissions. In terms of biorefining methods, hydrothermal (HT) and biological techniques have demonstrated the capability of valorizing biomass raw materials to yield value added end-products. An inter-disciplinary bio-economical approach is capable of optimizing biomass's total potential in terms of environmental perspective and circular bioeconomy standpoint. The aim of this review is to provide an in-depth overview of combinatorial HT and biological techniques to maximize biomass value, which includes biological valorization following HT pretreatment and HT valorization of lignocellulosic substrates emanating from biocatalytic hydrolysis/anaerobic digestion and/or pretreated food waste for the ultimate yield of biogas/biochar and biocrude. In this study, we discuss recent advances regarding HT and biological treatment conditions, synergies between the two technologies, and optimal performance. Additionally, energy balances and economic feasibility assessments of alternative integrated solutions reported in previous studies are compared. Furthermore, we conclude by discussing the challenges and opportunities involved in integrating HT and biologicals methods toward complete biomass utilization.

Keywords: biomass; valorization; hydrothermal treatment; anaerobic digestion

1. Introduction

To attain a low-carbon society, people are trying to develop feasible processes in order to utilize renewable energy derived from biomass. In 2011, approximately 10% of the world's primary energy demand was met by biomass energy, among the many renewable energy sources available [1]. It is possible to categorize biomass resources into seven types, namely viz. energy crops, agricultural residues, industry, forestry, gardens (parks), waste, etc. [2]. Currently, new energy and environment policies combined with the advancement of cutting-edge technologies have led to a global expansion of energy markets. A further consequence of this expansion is the increasing demand for biomass-based energy. As a biofuel and bioproduct producer, biomass has the biggest advantage of inheriting a vast array of energy-rich precursors. Over many decades, the demand for energy has increased significantly, mainly due to the burning of fossil fuels. There will be different energy scenarios for industries in the future, since disruptive trends will emerge. With

these new developments, technologies will shift to the biomass energy sector to optimize the possibilities [3,4]. Therefore, the demand for sustainable energy against the supply of biomass feedstock is enormous. For the past decade, food and non-food biomass has been mainly used to produce biofuel and other biochemicals to meet energy demand [5]. Sugarcane, corn, and sorghum are among the biomass used to produce first generation biofuels and have resulted in food, fodder, and fuel shortages [6]. Biofuels and chemicals can be manufactured from lignocellulosic (second-generation biomass) and macroalgae (third-generation biomass), both of which are useful as biomass blueprints [7,8].

Research on bio-based resources has been sparked by the limitations of fossil fuels, as well as by the need to reduce the emission of greenhouse gases (GHGs). In addition to energy, biomass produces multiple products and can be used to replace fossil fuels. This makes biorefineries fundamental to the development of a knowledge-based and environmentally sound circular bio-economy [9,10]. Biorefineries are considered to be a promising approach for the use of biomass as a green energy source. By connecting the flow and loops of the biorefinery, a circular bio-economy can be realized, valuing multiple products in one pot. Various products and fuels can be produced from biomass using biorefineries [11,12]. The exact configuration of the biorefinery may differ depending on local factors, such as agricultural practices, climate, feedstock availability, and transportation. This review includes an overview of the technology, as well as its importance and strategic applications in circular bio-economy. Since biomass valorization techniques are becoming increasingly interdisciplinary, they offer a range of products that span physical, chemical, and biological technologies [13,14]. One of the most effective techniques is hydrothermal (HT) treatment, which can convert raw biomass into valuable biochemicals by overcoming its recalcitrant nature [15]. A variety of sustainable biomass feedstocks, i.e., agricultural waste, food waste, municipal solid waste (MSW) can be treated using biological techniques for waste management and biomass valorization [16,17]. However, both HT and biological approaches are not without their downsides, as HT processes require a high energy input and the addition of solvents or catalyst, whilst biological processes take a long time and tend to be ineffective against resistant feedstocks [18]. The ecological and economic value of biorefining must be enhanced with quantifiable and scientifically validated data. Additionally, sustainability is the primary consideration throughout the entire value chain when establishing biorefineries [19]. The sustainability of biorefining depends on economic, environmental, and societal factors, but is not limited to greenhouse gas emissions (GHGs) and energy efficiency. As a consequence, reliable data stream coupled with sustainable, cost-effective production chain are required to optimize the design and operation of biorefineries. The advantages of biorefinery energy products and fuels are that they are more environmentally friendly than conventional products [20]. A systematic review of the published literatures on fuels and biorefinery products are presented in this review to address the gaps in research. The current review entails an in-depth analysis of the environmental and economic feasibility of biorefineries, as well as their strategic role within a circular bio-economy.

Conversion of biomass, a renewable resource, can be used to make chemicals and products. Biological bio-based resources include a wide variety of resources from plants and animals. Plant-based materials and biowaste, as well as aquatic organisms, are available as resource materials. It is important that we value renewable biomass sources since the way we use them can have a broad impact on our environment, including safer feedstocks, reduced emissions, geographic distribution of resources, and the development of circular economies [21–24]. Owing to the recent technological advancements, biomass refining technologies have been upgraded through multiple processes, as mentioned in Figure 1.

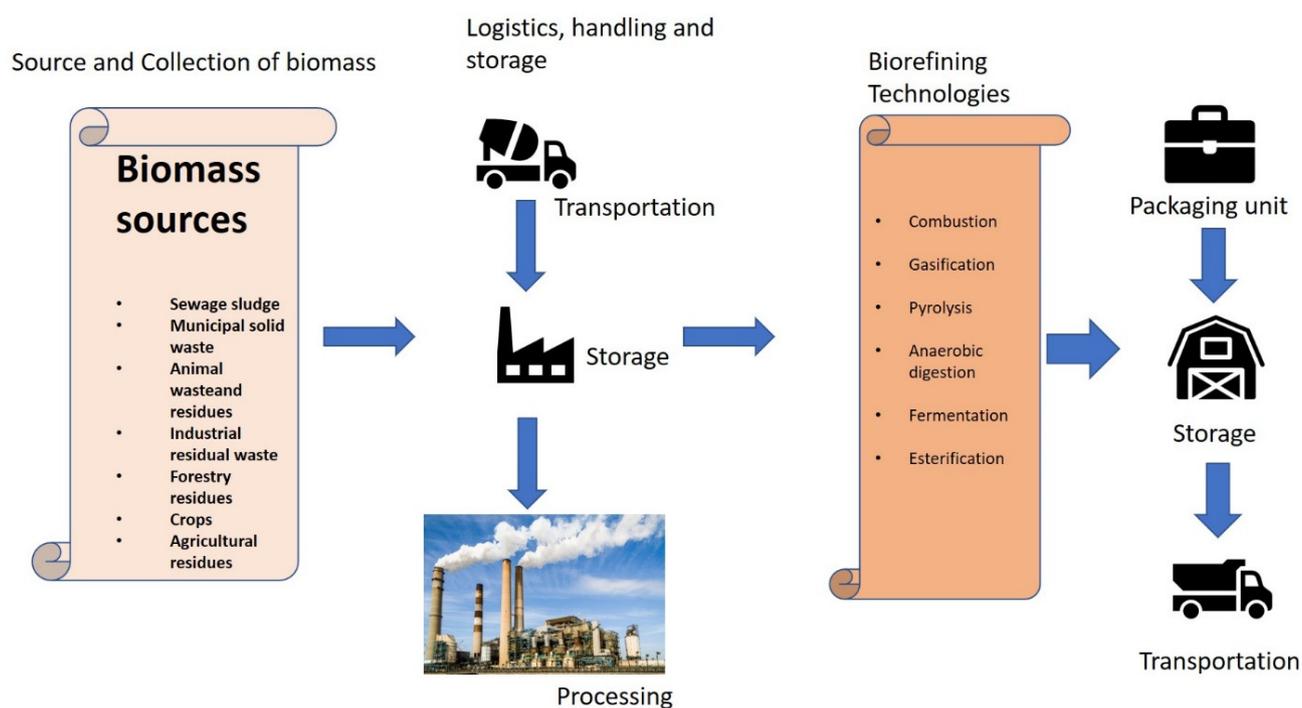


Figure 1. Technologies for refining biomass and logistics for handling, transport, and distribution.

The circular economy approaches the use of resources, such as carbon (C), nitrogen (N₂), and phosphorus (P), in a circular manner, rather than linearly, such as in a take-make-dispose system [21]. Using photosynthetic processes to generate CO₂, biomass can be valorized [25], in particular, biodegradable plastics undergo this process. In addition, the rapid spread of non-edible plants parallel to the development of high-throughput agriculture will contribute to the establishment of a C-neutral cycle in a short period of time, that realigns the increased levels of CO₂ emissions caused by fossil fuel use [26]. According to the literature on biofuels, biomass can be divided into first, second and third generation biomass. First-generation biomass, which constitutes sugar or starch sugars, is relatively simple, and has little recalcitrance (e.g., corn, sugarcane, barley etc.). Bioethanol is produced through the fermentation of sugar polymers and is currently the most widely studied drop-in biofuel [27]. The first-generation biomass is derived from food vegetable oils and is synthesized into biodiesel via transesterification [28]. It is important to remember that this type of biomass competes with food resources (which will become more precious with the growing population on the planet), as well as consumes large amounts of water and land for their production [29]. In addition to food raw materials, second-generation biomass includes by-products and waste items. These feedstocks (a mix of cellulose, hemicellulose, and lignin) require a pretreatment to be converted to biochemicals and biofuel, and multiple steps impede the process of economics, resulting in lower overall conversions [30–32]. The increasing complexity of the feedstocks makes it difficult to use lignocelluloses efficiently. Therefore, pretreatments are necessary, which have their own drawbacks depending on the methods used. Third-generation biomass (renewable biomass) includes nonedible feedstocks produced without the need for agricultural land, by implementation of algae and bacterial species (e.g., cyanobacteria). Transesterification can produce biodiesel from feedstocks containing mono/polyunsaturated hydrocarbons for gasoline-like fuel in some strains, whereas cracking can yield oil-like fuels for biodiesel in others. Microorganisms are more susceptible to environmental factors, such as low humidity, high water content or long drying times. However, algae have a high-water content, which hinders their transportation or requires considerable energy input. Due to the low cultivation volumes and the low resource efficiency of processing, these feedstocks have limited industrial application due to economic challenges [33–35]. In addition to the third-generation biomass, they are also

contemplating a fourth-generation of biomass, exemplified by modified microorganisms that can yield solar energy through photosynthetic processes [36,37]. Although these microbes require advancements in genomics-based breeding, they also pose the usual concerns that accompany bioengineered organisms, including the possibility of unexpected resistance to the organism. To identify the leading factor for chemical sustainability, it is vital to know the volume of each type of biomass.

The European Union (EU) released a report in 2018, which estimated that agricultural biomass (i.e., first generation) produced 956 million tons (Mt) of dry matter annually. Five out of ten of these residues (e.g., leaves and stems) were used directly for food consumption, and the remaining 46% were used for animal bedding or bioenergy production. A large proportion of agricultural biomass used to make foods and feed shows that the first-generation biomass does not have considerable potential for chemical and energy production. In regard to the third-generation biomass, such as algal biomass (including macro and micro), only 0.027 Mt of dry mass was calculated, representing 0.23 Mt of wet matter. Additionally, dry biomass from above-ground trees (second-generation) was estimated to a total of 18,600 metric tons [38]. Unfortunately, biomass conversion strategies typically have poor resource efficiencies, resulting in higher production costs and a limited ability to compete with the well-established petroleum market. Therefore, to gain an economic advantage, volumes should be high, production should be easy, and there should not be a considerable competition with other markets (e.g., food). As a result, using lignocellulosic biomass as a replacement for fossil fuels can be considered a promising alternative [39]. Lignocellulose and other waste materials are less efficient sources of energy than nonrenewable ones, such as coal, oil, and natural gas. In comparison, a fossil fuel plant emits substantial amounts of greenhouse gases during its lifetime. However, a biopower plant emits none through photosynthetic processes. In addition to ethanol, 2-methylfuran, and other downstream products, biomass can be converted to key molecules that can be used in aviation and can offer varying energy contents depending on the components of biomass processed. These processes require the separation of the components of biomass [16]. The present review entails combinatorial approaches based on biological and HT premises in elucidating the methodologies to biomass valorization and the subsequent accompanying challenges. Figure 2 illustrates a scheme to explore the possibilities presented by combining hydrothermal technologies with diverse biological treatments. Detailed bibliographical references and case studies of previous biomass treatment approaches implementing the integrated HT and biological technologies have been discussed thoroughly. Key findings that spanned over the research of the last decades, pertaining to the HT and biological treatment, have been highlighted, and a tabulated comparison between the study outcomes with the associated techno-economic analysis has been presented in terms of energy balance. In this study, we discuss the current advances and bottlenecks in interdisciplinary research in biomass valorization with proposed study designs to overcome these deficiencies, which will prepare the future ground for an optimized study design.

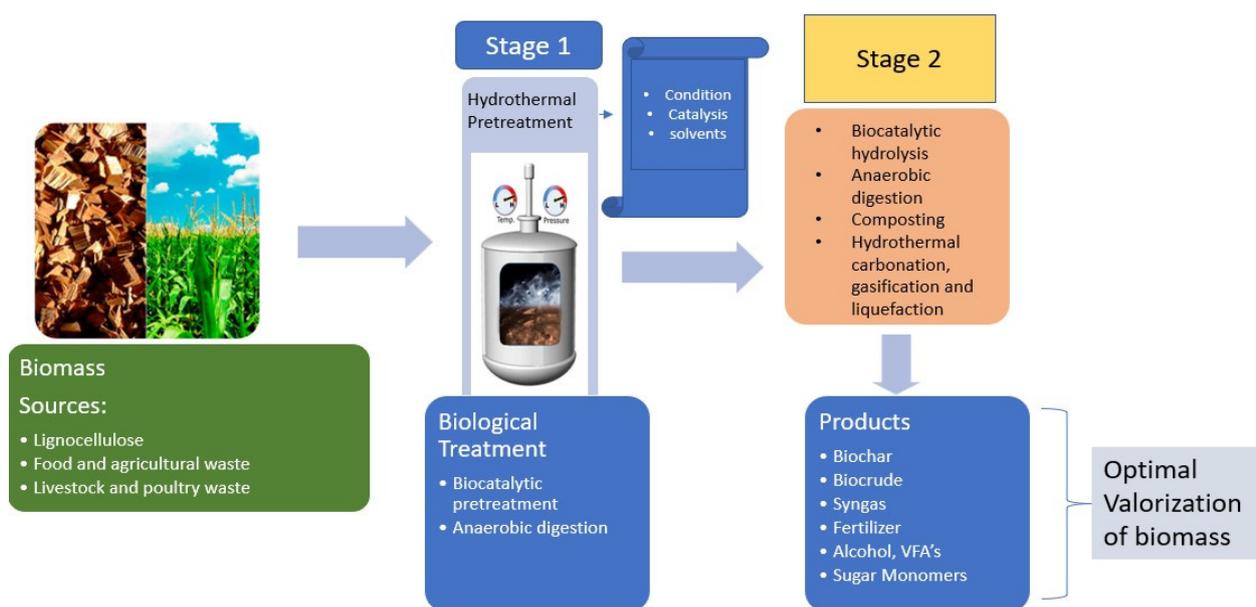


Figure 2. Pictorial representation of the flow-through process entailing the valorization of biomass by hydrothermal and biological means.

2. Valorization Mediated by Hydrothermal (HT) Treatment Preceding Biological Pretreatments

Hydrothermal (HT) treatment operates via the implementation of variable parameters of temperature and pressure. According to Toor et al., the pretreatment conditions w.r.t HT can be classified as, namely (i) with water, i.e., the treatment condition can be categorized into: (1) Supercritical temperature HT pretreatment, where the operating temperature is 374 °C or more with 3190.83 psi pressure. (2) Subcritical temperature HT pretreatment, where the operating temperature is between 100–374 °C, with 3190.83 psi saturated pressurized steam required to maintain the steam in liquid form. (3) Ambient temperature HT pretreatment, where the operating temperature is between 25–100 °C, with the steam pressure at 14.5038 psi [40]. As the critical properties of fluids change dramatically with the different percentages of cosolvents, the aforementioned definition is flexible in nature [41].

2.1. Analysis of Combinatorial Effects of HTL Pretreatment and Biocatalytic Hydrolysis

The breakdown of raw lignocellulosic biomass (RLB) by subsequent HTL and biocatalytic processes is directed towards saccharification of RLB to reducing sugars. However, RLB resists enzymatic hydrolysis due to the presence of a complex network of hemicellulose and lignin surrounding the cellulose layer, hindering the access of the enzymes [42]. Xylose oligomers with hemicellulolytic precursors, once again, prevent cellulose hydrolysis with lignin imbibing of the cellulase causing an eventual decrease in enzyme activity, thereby stalling the biocatalytic processing of crystalline structure of cellulose [43–45]. By eliminating lignin and hemicellulose, it is possible to improve the biocatalytic performance during hydrolysis, thereby overcoming the RLB recalcitrance. A study by Mosier et al. reviewed various criteria for evaluating an effective pretreatment, taking into account a host of factors ranging from reducing sugar production to the economical point of view per se. A number of preceding pretreatment methods were compared in the study, including steam explosions, alkali/acid/water, and ammonia methods as feasible pretreatment methods for the removal of RLBs. During enzymatic hydrolysis, the HT pretreatment has recently proven to be a crucial technique for selective fractionation of RLBs with high sugar recovery [46,47]. Recent advancements in the HTL of RLB has led to the pretreatment at lowered temperatures and sustainable solvents with optimized fractionation, thereby indicating that the HT pretreatment is a better enzymatic hydrolysis technique. Table 1 lists some representative studies with hydrothermal (stage 1) and biocatalytic (stage 2) treatment

conditions. Based on their reaction medium, which is used during the HT pretreatment, these studies are grouped into different classes in this review.

Table 1. Summary of the literature related to the combined HT pretreatment and enzymatic hydrolysis studies for biomass valorization.

Type of Biomass	HT Treatment	Biocatalytic Hydrolysis Phase	Outcome	Ref.
Eucalyptus barks	Water, 150–200 °C, 20 min–4 h	Cellulase and xylanase loading amount: 12.5–40 FPU/g for 24–72 h	Biocatalytic digestibility increased by more than 91%, and ~10% glucose was lost during the HT process.	[48,49]
Poplar lumber wood	H ₂ SO ₄ and/water followed by ~190 °C for 50–60 s	Cellulase loading at 20–60 FPU/g for 120 h	Acid pretreatment elucidated hemicellulose release.	[50]
Wheat straw	Water/IL/Acetic acid 80–200 °C for 10 min–6 h	Ctec 2+Htec 2 at 11–15 FPU/g for ~50 h	Hemicellulose removal with glucose yield of ~90% at 190 °C. ILs removed 50% lignin with increased digestibility of the raw biomass.	[51,52]
Rice straw	Water/IL at 90–220 °C for 50 min–6 h	Cellulase loading at 42 U/mL	Identification of cellulase inhibitors and analysis correlation between biocatalytic digestibility and lignin content.	[53,54]
Bamboo	Water at 120–240 °C for 10–120 min	Cellulase loading at 14.5–20 FPU/g for 96–120 h	Enzymatic conversion of >80% of the pretreatment material with increment in cellulosic crystalline index.	[55,56]
Sugarcane bagasse	Water/ethanol at 140–180 °C for 40 min	Cellulase loading at 15 FPU/g	Increased enzymatic digestibility with enhanced digestibility of cellulose.	[57,58]
Corn cob	Acid/water at 120–160 °C for 4–6 h	Cellulase loading at 20–40 FPU/g	Eighty percent hemicellulose released during HT.	[59]
Residues from akebia	ES/water/acid at 80–120 °C for ~8 h	Cellulase loading at 10–40 FPU/g for 72 h	Optimized conditions of lignin removal were ascertained.	[60]

2.1.1. Pretreatment with Hot Compressed Water (HCW) and Its Effect on Enzymatic Hydrolysis

Water that remains at elevated temperatures above 180 °C under high pressure can be defined as HCW. Under these conditions, water displays a unique property that allows for various types of chemical reactions to take place. At this juncture, the properties of liquid and gas have become essentially identical beyond a certain critical point [61].

To eliminate lignin content and hydrolyze hemicellulose, using HCW as a pretreatment step before RLB can be used to eradicate lignin. Compared to cellulose hydrolysis, this usually happens at lowered temperatures, such as 200 °C. With the help of enzymes, cellulose will increasingly have the capability to be hydrolyzed with HCW or dissolved into soluble sugars through polysaccharide saccharification. Enzymatic saccharification combined with the pretreatment with HCW is preferred, since glucose generation is improved greatly [62]. A large portion of lignocellulosic agricultural wastes, as well as food wastes contain starch. Therefore, the pretreatment with HCW is the preferred way to hydrolyze these wastes. In contrast to cellulose hydrolysis, starch breakdown by HCW is rendered more effective as the semi-crystalline nature of starch, held by weak hydrogen bonding increases the yield of reducing sugars and 5-hydroxymethylfurfural [63]. There are several research methodologies associated with the biotransformation of these carbohydrates into

organic acids, followed by its conversion to biohydrogen gas. However, biohydrogen production needs to be studied in detail before the pretreatments can be implemented. In addition to sugars, the HCW hydrolysis of lignocellulosic material generates a concoction of harmful materials detrimental to bacterial growth or process fermentation. Mostly, three types of degradation products are associated with sugar degradation in the form of furans, aliphatic acids, and phenols [64]. Hydrolysis of polysaccharides using hot compressed water is a promising method for the pretreatment of RLB, which can lead to the production of renewable raw materials for further bioprocessing. The only drawback of pretreatment with HCW is that the hydrolyzed polysaccharides are potential generators of degradation products that may adversely affect the native microbial community.

By pretreating RLB with HCW, the hemicellulose content is significantly reduced. Most of the hemicellulose was removed by pretreatment at 210 °C for 20 min. Following hemicellulose removal, RLB can be made more efficient at enzymatic hydrolysis, since arabinose and xylose [hemicellulose-derived sugar oligomers] inhibit cellulase activity [65]. Research studies show that the xylose concentrations at 1.0 g/L lowered the enzymatic efficiency of cellulase hydrolysis from appx. 100 to 65% when hemicellulose derived sugars were investigated [53,59]. The HT pretreatment of cellulose can boost its biodegradability to a certain extent by eliminating hemicellulose [59]. The response surface methodology was employed by Lanraudie et al. to optimize the pretreatment conditions, and multiple factors were found to affect the eventual sugar yield ranging from pH, enzyme dosage, and the solid/liquid fractionations [66]. The generation of glucan in the process results in rendering the increase in the crystallinity of the cellulosic residues following the pretreatment. Previous studies investigating the bamboo pre-treatment methodologies were of the opinion that a HT pretreatment decreased glucan content by 15%, whilst the crystalline index rose marginally from 45 to 50% with an increase in severity factor at temperature and time durations of 150–210 °C for 15–130 min, respectively [56]. Nitsos et al. reported that poplar wood, which underwent pretreatment at 220 °C for 15 min, increased its crystalline index from 72 to 83% [67]. Nevertheless, the crystalline index increase has no direct effect on the final glucose recovery.

Despite the increase in crystallinity, enzymatic hydrolysis of RLB showed improved digestibility and conversion rates following the HCW pretreatment, showing that crystallinity is not the determining factor influencing the enzymatic hydrolysis of RLB [55]. Moreover, downstream processing can generate various substituted phenolics from the decomposition and dissolution of lignin, although a small population of lignin decomposition occurs via HCW in comparison to hemicellulose. The eradication of chemicals derived from lignin before enzymatic hydrolysis is crucial, since phenolics resulting from lignin decomposition can alter the biocatalytic performance of cellulose. In one of the studies, the enzymatic hydrolysis rate was lowered by 90% with a phenolics concentration at 1.0 g/L [53]. The study by Li et al. indicated that almost 80% of the lignin was revived after the use of the hot-compressed water pretreatment in solid residual form with a subsequent decrement in the glucan content by 20% [55]. Nevertheless, the fraction loss of lignocellulose per se can be optimized through proper conditions, and therefore will be well suited to enzymatic hydrolysis [43]. In addition, the HCW pretreatment affects the digestibility of enzymes owing to the alteration of the LCB physical properties during the HT pretreatments [68,69]. However, when enzymes are loaded onto solid surfaces for enzymatic hydrolysis, these changes are favored since this pretreatment increases the porosity of the surface area rendering it more accessible for the biocatalyst to work upon [70].

The problem with using acid-based catalysts is their homogeneity, which makes it difficult to recover them in the ensuing reaction steps and to re-use them in the next cycle of reactions, with additional steps required for the removal and neutralization of acid-based byproducts. Organic materials and biochar were immobilized on heterogenous acids as solid support [71]. Studies on the corn cob pretreatment implemented on acid based solid increased the enzymatic saccharification by 40% compared to the untreated sets. It may be clear that the acid catalysts increase the overall efficiency of HCW. However, the major

drawbacks of the treatment are the intact lignin residues which remain in the samples, making it difficult for the enzymes to act as an optimized hydrolysis [59].

2.1.2. Pretreatment Methods Implemented through Basic Catalysis

In the last few years, solid base catalysts have emerged to replace homogeneous bases in a number of case studies concerning the pre-treatment of biomasses. Different basic solids have been recently employed over a range of different basicity to focus on generating a factory of superbasic catalysts [72,73]. For many reactions, it is not clear which basic sites will be present on the catalysts. Therefore, its acid-base properties must be tuned to increase the reaction's activity and selectivity. Metal oxides can most often be mixed by varying their chemical composition to control their acid-base properties [74,75]. The most commonly used base catalyzed reactions in biomass processing are aldol condensation of carbonyl compounds, carboxylic acid ketonization, Guerbet reaction which involves aldol condensation between successive alcohols, and transesterification reactions involving vegetable oils [76]. The utilization of biomass for the production of fuels and chemicals, C-C bonds, can be built with biomass-derived platform molecules. These C-C bond forming reactions have been utilized not only for the transformation of platform molecules into new chemicals, but also for upgrading platform molecules into the gasoline, kerosene or diesel range, serving the adjustment of the molecular weight in the process. Oxygen must be removed from the oxygenated compounds to yield liquid fuel-grade alkanes. A major disadvantage of deoxygenation is its high hydrogen consumption [77]. However, with hydrocarbon-neutral processes, such as alkene oligomerization, it is not possible to produce linear alkanes with slight carbon branching suitable for jet and diesel fuels. By dehydrating furfural, pentoses and hexoses, as well as HMF are platforms for biological applications [78]. A variety of aldol condensation products, such as propanal, acetone, and a variety of furanic aldehydes can be formed from aldol condensation of furanic aldehydes. Aldol condensation has been studied with homogeneous and heterogeneous basic catalysts using acetone and furanic aldehydes. Condensation of furfural with acetone can result in high yields of single and double bond condensation products. HMF decomposition and acidic by-products from HMF degradation resulted in a considerably lower formation of condensation products when compared to other catalysts [79]. Moreover, the hydrogenation of these aldol products produces alkanes of C7 and C5 using hydrogen [80].

Biodiesel can be made from renewable resources and recycled lipids to develop sustainable transportation fuels [81]. However, the transesterification process is one of the most common methods used to make long-chain esters of fatty acids from a wide range of animal fats and oils [82]. Methanol is usually used as part of the transesterification reaction since it is relatively cheap. In addition, the resulting fatty acid methyl esters (FAME) finally transform into a host of downstream value-added products. In the same way as aldol condensation, homogeneous alkali metals can be used for transesterification of biomass-derived triglycerides [83]. It is possible to solve the problems of after-reaction separation and catalyst recycling by replacing homogeneous bases with heterogeneous bases. Transesterification reactions can be affected by a variety of solid base catalysts, ranging from alkaline earth metals and metal oxides/hydroxides. CaO is considerably the most popular catalyst. For the transesterification of soybean oil, Kouzu et al. studied the effect of calcium oxide and hydroxides and several commonly used solid bases [84].

2.1.3. Effect of Organic Solvent and Ionic Liquids on Subsequent Enzymatic Hydrolysis

Biomass pretreatment has also been extensively studied using organic solvents [85]. Solubilizing lignin with organic solvents mitigates the difficulty of accessing the cellulose layer by enzymes, thereby increasing the impact of the biocatalytic work force. Hansen's parameters of solubility can be implemented to ascertain the pattern of lignin solubilization in various solvents, as suggested by Zhang et al. [86]. With their physicochemical properties, organic solvents are categorized into aprotic (polar) and protic solvents for effecting the biomass HT pretreatment [87]. The combinatorial effect of ethanol and water pretreatment

following enzymatic hydrolysis was studied by Pan et al. at 190 °C for the treatment of RLB [88]. Another study by Santo et al. assessed the decomposition of RLBs by ethanol and water as solvents [89]. The study found that the combinatorial effect of ethanol and water pretreatment led to lignin dissolution and partial removal of the fractions from RLB. The study by Lai et al. showed that alkylation of lignin by ethanol and water reduced lignin enzyme affinity for ethanol and water, resulting in enhanced enzymatic hydrolysis of RLB [44]. Gamma-valerolactone (GVL) can be used as the solvent in all stages of RLB pretreatment for levulinic acid production and production of GVL from levulinic acid [90–92]. In addition, it has been demonstrated that GVL can be recovered from GVL/water treatment systems, as well (Table 2) [75]. Several studies have examined the effect of GVL as an isomerization solution on cellulose and its glucose derivatives by Song et al. [93,94]. As a result of the addition of GVL, the isomerization of sugar compounds was suppressed, which lowered the rates of generation of 5-HMF side products while benefitting the enzyme hydrolysis.

Table 2. Advantages and shortcomings of solvent systems for HT treatments of biomass.

Solvent	Advantages	Shortcomings
Water	(1) Dearth of pollutants. (2) Helps in the removal of hemicellulose.	(1) Lignin fractionations remain unaffected and produce inhibitors. (2) Lower sugar recovery with increased energy input.
Water (acid-catalyzed)	Highly efficient hemicellulose removal and lowered energy consumption w.r.t water.	(1) Generates toxic catalysts, corrosive in nature. (2) Unable to remove lignin.
Water and ethanol	Highly efficient hemicellulose removal with easier recovery of ethanol.	(1) Use of ethanol increases the overall economy. (2) Low concentration of lignin with high treatment severity.
Water and GVL	(1) Simple recovery of solvent and economically viable. (2) High recovery of sugars with increased fractionation of RLB.	Increased cost of GVL recovery.
Water and ILs	High recovery of sugars with increased fractionation of RLB.	Highly toxic solvents and not a cost-effective process with the cumulative process incurring high cost.
Water and ES	Emerging alternatives for ILs as biodegradable in nature.	The process is still in its infancy and has high viscosity.

Ionic liquids (ILs) have been shown to be effective at removing lignin during the pretreatment of RLB. Over the last few decades, researchers have studied ILs and their applicability as pretreatment solvents in catalytic procedures [95]. In the initial stages of exploring the IL pretreatment methodologies, its implementation on woody biomass lignocellulosic was conducted in two separate research studies [96,97]. The outcome of one of these researches recommended that Kamlet-Taft solvent parameters correlated with the swelling and dissolving of RLB in cellulose and pinewood pretreatments [98]. Using ILs, different lignin, hemicellulose, and cellulose solubilities can be utilized for RLB fractionation. A previous study used the structural design to tune the selectivity of ILs for RLB dissolution [99]. Another study demonstrated how the rice straw pretreatment for 12 h with arginate at 90 °C resulted in RLB fractionation into cellulose, hemicellulose, and lignin-rich fractions, culminating into 75% glucose recovery following enzymatic hydrolysis [100]. In this study, ILs were reutilized for eight cycles of activity with indiscernible change in properties between cycles <8%. A recent study demonstrated that cholinium-based ILs could enhance the lignin removal and optimized the physical properties of substrates for enzyme loading with the simultaneous improvement in enzyme digestibility of cellulose-rich fractions. There have been several concerns regarding the proper use of ILs in the

pretreatment studies. Initially, the ILs offer milder treatment conditions than a HT pretreatment with water or acid. In addition to these concerns, the use of ILs as a pretreatment method for biocatalytic hydrolysis has been subjected to substantial scrutiny, since the process of recovering products from ILs can be laborious with multiple stages of washing and extraction. In order to isolate and purify the products and IL, a large amount of solvent and energy is required, which results in a greater processing cost to add to the detrimental effects on the environment. The high cost incurred in the implementation of ILs when compared to other common solvents in the form of ethanol or acetone, makes them once again unsuitable for the upscaled process and the cumulative economy. A recent study has also reported the use of triethylammonium hydrogen sulfate (TEAHS) for the scale-up of enzymatic hydrolysis after the RLB pretreatment [101].

2.1.4. Effect of Eutectic Solvents and HT Treatments on Subsequent Enzymatic Hydrolysis

Eutectic solvents (ES) are similar to ILs in their preparation and application for RLB pretreatment. Based on the strength of hydrogen bonding between solid compounds, ES production is accomplished by the simple mixing of chosen solids (compounds) [102]. The utilization of ES can be achieved in a sustainable manner through biologically derived chemicals, i.e., xylose, sucrose, and glucose derived from biomass. In addition, these biochemicals are biodegradable and can be disregarded in terms of their toxicity quotient on enzymes [60,103]. Biomass pretreatment with ES has only recently gained a large amount of interest [104]. In a recent study, researchers achieved 60% lignin reduction by the pretreatment of rice straw with lactic acid based ES under thermophilic conditions (55–60 °C) with 40% efficient saccharification following biocatalytic hydrolysis [105]. As a result of the pretreatment with ES, Procentese et al. achieved optimal hemicellulose and lignin removal, with a glucose yield of nearly 90% with pre-treatment conditions at 110–150 °C [106]. The biocatalytic digestibility of switchgrass residue was enhanced by 90% after the pre-treatment with chloride based ES at 130 °C for 50 min [107]. In their study, Kim et al. devised novel ES prepared from the sequential pretreatment of biomass and enzymatic hydrolysis emphasizing the potential for ES as sustainable biofuels [108]. A second study by Satlewal et al. based on enzymatic hydrolysis demonstrated that dual acid and/water and alkali and/water pretreatments were less effective than ILs and water alone (Table 2) [109]. Chen et al. produced a lignin-derived ES significantly enhancing the sugar release proportion to 85% in contrast to 48.08% for the control at the pre-treatment temperature of 150 °C [110,111]. A survey based on the current results indicates that the combinatorial pretreatment methodologies and biocatalytic hydrolysis with subsequent conversion technologies will offer a win-win approach for RLB valorization. However, there is a lack of research regarding the use of ES pretreatment and biocatalytic hydrolysis, which requires additional studies investigating these topics, as well as identifying scale-up techniques.

There has been a change in the solvent system used for the HT pretreatment of RLB via enzymatic hydrolysis. To allow hemicellulose removal and lignin structural modification, it generally takes a higher treatment severity for hot-compressed water pretreatments of 4.0 or greater. Compared to the lower treatment severity of 2.0, adding acid enhances hemicellulose removal. Utilizing new solvents, such as ES and ILs, researchers isolated specific components in RLB at ambient conditions by taking advantage of the solvents' selective dissolution properties (100 °C). RLB biorefinery has advanced toward valorization of all components based on the development of novel solvent systems. It is preferable to remove hemicellulose and lignin with water or catalyst, but the removal of lignin is limited. Despite the fact that ethanol is often produced by biorefineries, lignin has limited solubility in those kinds of solvent systems. A major advantage of solvents based on GVL, IL, and water is their ability to selectively dissociate lignin and hemicellulose, which increases hydrolysis kinetics of cellulose by enzymes (Table 2). While some ILs may be toxic and generally expensive, these two systems are the most studied and likely to be the most

widely applicable [112]. In light of ES/water's lower cost and lower toxicity, more studies on these solvents need to be conducted.

2.2. Combinatorial HT and Biological Pretreatment

2.2.1. Effect of Anaerobic Digestion, Fermentation, and HT Pretreatment on Biomass

Organic feedstocks (wet), which are comprised of food wastes and sludges, are degraded by AD toward biogas generation which can henceforth be purified and upgraded to methane production. The biodegradation potential of bio-feedstocks and waste (subjected to putrefaction) has been increased manifold by the HT pretreatment, which includes waste from food and other biomass (Table 3) [113]. The utility of HT solvents is influenced by the type of feedstocks used. To prevent the optimal functionality of the AD microorganisms and to sustain their active population, food waste is generally treated with hot compressed water (HCW) without the addition of chemical and organic solvents, such as ILs and/or ES. On the other hand, RLB requires solvents to initiate the delignification process, since lignin inhibits carbohydrate degradation. According to an early study by Qiao et al., the HT pretreatment of pig manure, treated sludge, and food waste increased the yield of biogas. However, the yield decreased when cow manure and food waste were taken into account. The HT pretreatment of lignin led to a simultaneous increment in methane yields and digestion time akin to enzymatic hydrolysis of RLB [114]. In addition to the mixing ratios of multiple feedstocks, a water-soluble carbohydrate is generated during the HT pretreatment of methane production as a result of the mixing ratios [115]. The HT treatment improves the dissolution of carbohydrates and proteins in food waste, thereby increasing digestibility and the yields of methane and volatile fatty acids (VFA) during pyrolysis. Using the HT pretreatment, Jia et al. investigated the effects of AD for food waste valorization at 90 °C for 30 min [116]. In comparison to the untreated food waste, the HT pretreatment yielded an 85% increased net energy gain. In addition to this, Passos et al. studied the HT pretreatment with subsequent microalgae AD and found that methane yield was significantly increased by 40% [117]. In another study, Yang et al. found that the AD of waste activated sludge with the HT pretreatment resulted in 60% protein dissolution, 80% polysaccharide dissolution, and roundabout 30% increase in methane yield [118]. Evidently, the HT pretreatment can be applied to a wide variety of feedstocks to improve their AD performance. The production of inhibitors during the HT pretreatment poses a significant challenge to this process, especially under conditions of high severity. Chemicals derived from sugars, such as furfural, 5-HMF, and acids inhibit the biological processes [119]. The Maillard reaction may also produce toxics during the HT pretreatment of food waste, which could affect the AD treatment afterwards [120]. Therefore, it is encouraged to develop low-severity pretreatments to reduce the production of these toxics, as well as approaches for removing them [121]. The nature of AD seed sludges makes it difficult to combine microorganism species from different AD systems. To minimize this variety, a brief discussion on some studies from the same research group using the same feedstocks have been presented in the following section.

The pretreatment of *Pennisetum hybrid* was conducted through a microwave [feedstock: 200 g; power: 1180 W; and $t = 3$ min] [122]; hot compressed water (160–200 °C for 20–60 min) [123]; pretreatment with NaOH and water (temperature: 37–125 °C; $t = 0$ –24 h) [124]; GVL and/or water pretreatment (temperature: 150–180 °C; $t = 2$ h) [125]; and grinding pretreatment (grinding + sieving) [126] for valorization. If lignin is to be selectively removed, then other methods to achieve the maximum value from feedstocks may be more effective under a complete valorization of all compositions. In a recent study, it was found that the GVL/water pretreatment increased the yield of biomethane, while precipitation of the pretreatment liquid waste resulted in the production of lignin nanoparticles [125]. Due to the diversity of microbial species in food wastes and sludges, the AD performance of these materials could be very variable. The AD of these wastes is cost-effective when the thermal pretreatment was conducted at a lower temperature between the range of 110–115 °C [119].

Table 3. Combinatorial HT treatment and AD for biomass valorization.

Biomass Type	Temperature for AD	Conditions for HT Treatment	Outcome	Ref.
Manure and straw (maize)	41 °C	H ₂ O, 2 h at 270 °C	Zeolite improved the HT treatment performance with decreased oxygen/carbon and hydrogen/carbon ratios in biochar.	[127]
Maize (silage)	55 °C	H ₂ O, 5–10 h at 270 °C	Cumulative yield of biochar was 50–80% of starting carbon.	[128]
Maize (silage)	55 °C	H ₂ O, 5–8 h at 200–280 °C	Total biochar production was 60–70% at the end of 8 h.	[129]
Manure	Ambient temperature	H ₂ O, 30 min at 350 °C	Production of biocrude increased by 20% with energy recovery up to 70%.	[130]
Straw + silage + manure	55 and 37 °C	H ₂ O, 350 min at 240 °C	Nutrient recovery after carbonization.	[131]
Manure	mesophilic	Acid/ H ₂ O, 40 min at 300 °C	Biocrude production at 60% of carbon recovery with production of cyclic compounds.	[132]
Sunflower biomass (stalks)	mesophilic	Acid/ H ₂ O, 30–60 min at 150–200 °C	Partial lignin removal with complete eradication of hemicellulose with 2.5-fold increase in methane yield.	[127]
Microalgae	mesophilic	H ₂ O, 15 min at 100–130 °C	Forty percent increase in methane yield.	[117]
Straw (sunflower)	mesophilic	H ₂ O, 5 h at 180 °C	Complete removal of hemicellulose and lignin with increase in methane yield.	[133]
Grass (energy)	mesophilic	H ₂ O-CaOH (calcium hydroxide), 30 min at 75 °C	Increase in cellulose and lignin ratio with high VFA production.	[134]
Grass (energy)	mesophilic	H ₂ O/GVL, 90 min at 180 °C	Thirty percent lignin removal with simultaneous biomethane and lignin nanoparticle.	[125]
Food waste	mesophilic	H ₂ O, 30 min at 90 °C	Increased methane yield and energy efficiency.	[116]

Biorefining also utilizes fermentation extensively, particularly in the production of bulk products such as ethanol, acetone, and butanol, derived from RLB. Composting, AD, and enzymatic hydrolysis are the three stand biological treatments that are comparable with fermentation in terms of feedstock properties and inoculum conditions [135]. Fermentation follows enzymatic hydrolysis of RLB due to its requirement of feedstocks. The direct integration of RLB with the HT pretreatment and fermentation can be optimized following the subsequent pretreatment. Using the fractions of cellulose, hemicellulose, and alginic acid, the microwave-assisted HT treatment at 210 °C was used to develop fermentable species by a group of researchers. By administering *Metschnikowia pulcherrima*, (Green Chemistry Centre of Excellence, University of York, Department of Chemistry, Heslington, York, UK) it was demonstrated that fermentable species can be produced by the HT treatment, which includes cellulosic and hemicellulosic fractions and alginic acid derived monomers and oligomers [136]. By fermenting RLB in dark or acidogenic conditions, the thermal pretreatment can also be incorporated with biohydrogen production. In another study, biomass (stover, sorghum) were hydrothermally pretreated for 30 min at 180 °C with CO₂ and water [137]. A dark fermentation process was used to produce hydrogen

from the obtained liquid fraction, and an AD system was used to produce methane directly from the obtained solid fraction. A combination of HTL, AD, and dark fermentation produced energy yields at the rate of 12.0 MJ/kg biomass, which was 40% higher than the combinatorial effect of HT pretreatment and AD. Another study explored an extensive HT pretreatment on seaweeds with subsequent dark fermentation and adsorption [138,139]. Apart from the HT pretreatment and fermentation, the HT pretreatment has also been used for food waste valorization. As an example, starch was treated at 240 °C for 15 min before dark fermentation with *E. coli*, resulting in an 8.57% cumulative increase in the integrated yield of hydrogen [63]. The pretreatment of food waste with water and acetic acid was utilized by Matsakas, and subsequent fermentation was shown to increase the yield of ethanol by 16% as a result of the hydrogenation [140]. For the integrated dark fermentation and AD of food waste, Ding et al. performed the HT pretreatment with subsequent hydrogen and methane conversion rates of 79% under optimized pretreatment conditions, compared to a 32% efficiency when using untreated food waste [141]. In addition to producing volatile fatty acids, the HT pretreatment also promotes anaerobic fermentation. Food waste was hydrothermally pretreated at 220 °C for 30 min before anaerobic fermentation was employed to produce VFAs in another study [142]. Food waste was pretreated at 180 °C for 30 min by Nakasaki et al., followed by composting using inoculated activating bacteria [143].

2.2.2. Biochar and Biocrude Production Following HT Liquefaction and Carbonization

Similar to lignocellulosic biomass, the HT carbonization of digestate is based on low temperatures and long reaction times in the vicinity of 2 h at 300 °C [144]. As a result of the nature of AD, digestate has a high moisture content (over 90%), whereas other carbonization treatments require feedstocks to have a low moisture content [145]. In a recent study, hydrothermally treated maize silage derived digestate for 2 h at 190 °C to achieve the highest biochar yield with close to 85% of the initial carbon in digestate [128]. By increasing the treatment severity to 270 °C for 10 h, the biochar higher heating value increased by 28.85% MJ/kg, suggesting that it can be used as a solid biofuel. With the increasing interest in using digestate-derived biochar for AD systems, the application of digestate-derived biochar can extend further with the increased biogas yield and improved performance [146].

By reducing the size of biochar (digestate derived) to a nanoscale, it is possible to improve its low specific surface area and poor porosity [147,148]. Liquefaction of digestate and biomass takes place at higher temperatures (250–400 °C) and for a shorter period of time (1 h) to result in rapid hydrolysis, dehydration, and condensation of major components. A study reported how the digestate obtained from the AD of cow manure was hydrothermally liquefied at 350 °C for 30 min [130]. The higher heating was able to recover 80% of the original energy from inorganic biocrude at 30 MJ/kg. A recent research suggested that HT liquefaction at 300 °C for 40 min of digestate can be influenced by adding an acid that enhances dehydration reactions and suppresses carboxylic acid formation [132]. In addition, the HT treatment can collect digestible organics from digestate for the AD treatment using acid-catalyzed liquefaction. This increases the yield of biocrude carbon by 74.2%. Using the HT treatment, another research study was conducted to extract organic compounds containing C, P, and N from sewage sludge digestate for use in AD for biogas production [149]. Kim et al. found that biomass was converted into tar and charcoal, primarily by hydrothermal carbonization and hydrothermal liquefaction (below 280–370 °C and high pressure) [150]. Compared to supercritical liquefaction and pyrolysis, where fuel is used, the hydrothermal liquefaction process produces excellent results (Figure 3) [151]. In a study by Chen et al., *Sedum alfredii* underwent a hydrothermal transformation that produced bio-oil and removed metal impurities [152]. From the supplemented *Sedum alfredii*, cadmium, copper, lead, and zinc were recovered using hydrothermal processes.

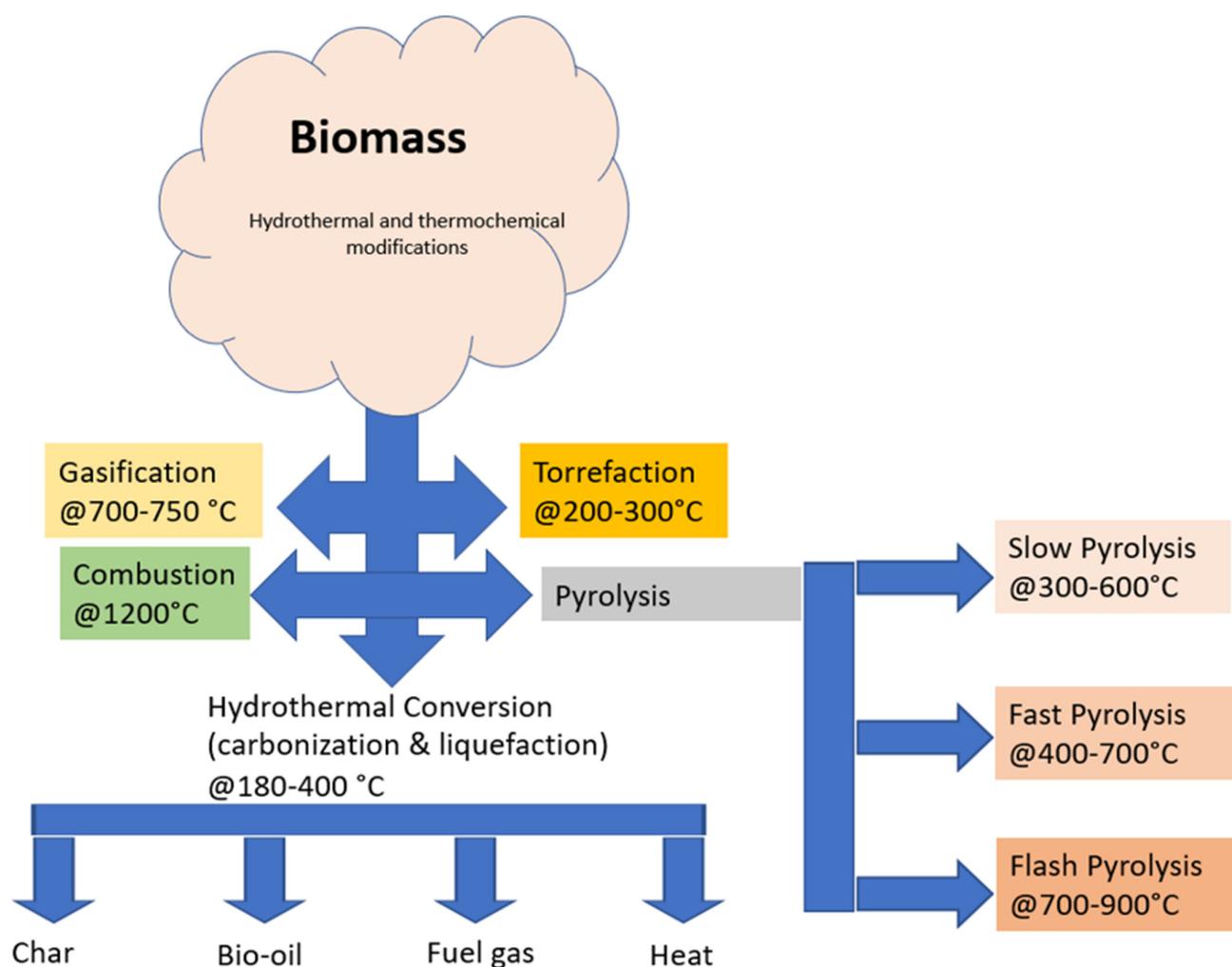


Figure 3. Thermochemical and hydrothermal conversion of biomass.

Similar to biomass and other organic wastes, digestate can also be gasified hydrothermally under supercritical conditions into syngas. An established catalytic HT gasification system was used by Boukis et al. to study the gasification of digestate. A syngas rich in hydrogen and methane was produced (0.31 mol gas/mol carbon in feed), with the salt content collected as liquid byproducts [153]. According to the study, the HT gasification of digestate combined with AD can fully valorize organic wastes (Table 4).

Table 4. Financial assumptions for the hydrothermal treatment.

Technology	Feedstock (kt/yr)	Operating Hours (h/yr)	Capital Cost (USD Million)	Plant Life	Ref.
Gasification (300 MW)	450	7000	2600	50	[154]
Hydrothermal treatment	442	7920	420	30	[155]
Combustion	450	7000	2270	35	[154]
Slow pyrolysis	65	6570	77	20	[156]

3. Summation of the Findings and Insights

Over the last several decades, HT and biological treatment methodologies for biomass valorization have advanced considerably, although there are significant challenges ahead. Given the aforementioned domains of research progress, a future biorefinery should be

based on the principle of complete valorization of biomass, based on the lowered emission of greenhouse gases, bordering on economical sustenance and environmental safety within the cores of green chemistry and circular bioeconomy [157]. To ensure a sustainable flow of biomass materials, it is important to consider the valorization of by-products generated from various treatment processes. For instance, in the HT pretreatment of RLB with water and acid, hemicellulose-derived compounds are most often generated as the byproduct. However, the subsequent enzymatic hydrolysis creates solid byproducts containing lignin and cellulose. In addition, the lignin and cellulose-rich residue can be valorized through fractionation, while the hemicellulose-rich fraction can be fed into AD. HT valorization or carbonization/gasification and liquefaction can accomplish this. Stemming from the differences in the use of different catalysts and solvents as well as treatment conditions, the chemistry of biomass composition varies under HT conditions. A study has shown that during the HT pretreatment of lignocellulosic biomass, pseudo-lignin can affect the enzymatic hydrolysis [158,159]. Furthermore, the Maillard reaction occurs during the HT treatment of food waste, producing toxic compounds, such as melanoidins that affect the overall AD process [141]. There are other biomass HT reaction pathways that result in polymers from the isomerization of sugar oligomers and the self-assertion of lignin, which complicates the optimal valorization of biomass [160,161]. At present, it appears that combining HT and biological methods for biomass valorization can be beneficial in some cases, but is not attractive for large scale investments due to a relatively low technology readiness level. In the near future, when the incorporation of HT and biological methods is more attractive, the standardization and application of the carbon credit concept, which yields a negative carbon emission will witness a booming biorefinery industry.

4. Conclusions

In this article, the HT pretreatment and subsequent enzymatic hydrolysis in the course of saccharification of RLB were the sought-after combinations of HT and biological methods. The downstream efficacies of these solvents in the form of ILs and ES, the most frequently studied for biomass fractionation, have been discussed at length. The HT pretreatment influences biomass fractionation. In addition, its recyclability and improper application can be toxic to both humans and enzymes. During the implementation of this method, the optimal dosage should be addressed in the development of these techniques for biorefining. Keeping this in mind, the newly developed solvent systems with easier recycling processes, lower costs, and less toxicity are preferred over those which are currently available.

Owing to its high energy consumption during the HT pretreatment, the HT pretreatment with subsequent AD is currently not considered as cost-effective. The enhanced biomethane yield is shown to produce substantially lower net energy gains compared to the co-digesting methods and HT pretreatment, making it redundant and costlier. To understand the limits and opportunities of this integration, more studies on the energy balance and economic assessment are needed. Currently, the focus is on carbonizing digestate to create biochar. As a result of the specific composition of solid digestates, it is recommended that more studies be conducted on different fractionation and valorization approaches. Emerging technologies pertaining to combinatorial enzyme pretreatment and fermentation followed by HT carbonization have a reduced energy currency compared to the HT pretreatment, followed by fermentation. The ultimate goal is to conduct multi-dimensional analyses of biomass value addition via the combined HT and biological techniques, in order to develop applied technologies for process optimization. These analyses would cover the carbon footprint, environmental load, sustainability of energy use, as well as economic benefits.

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