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Review

Effectiveness of Torrefaction By-Products as Additive in Vacuum Blackwater under Anaerobic Digestion and Economic Significance

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Abstract: Blackwater (BW) is a vital source of bio-energy and nutrients for the sustainable development of human society in the future owing to its organic and nutrient-rich properties. Therefore, biomass and water must be used properly to avert environmental challenges and promote the viable development of nutrient recovery and bioenergy production. Moreover, vacuum-collected BW (VCBW) as a renewable source can offer outstanding potential in bioenergy and nutrition sustainability. This review reports previous and present investigations on decentralized wastewater, water conservation, the recovery of nutrients, and the ecological implications and economic significance of integrating torrefaction with anaerobic digestion (AD), notably the continuous stirred tank reactor. The mixtures (torrefied biomass and VCBW) can be converted into valuable materials by combining torrefaction and AD technology for environmental and economic gains. This way, the heat and energy used in the process could be reused, and valuable materials with high energy contents could be obtained for financial gain. The economic evaluation shows that the minimum selling price of the torrefied biomass to reach breakeven could be reduced from 199 EUR/t for standalone torrefaction to 185 EUR/t in the case of torrefaction integrated with AD. The concept can be applied to an existing waste- or wastewater-treatment facility to create a cleaner and more efficient BW with biomass recycling. However, a comprehensive techno-economic analysis must be conducted: (1) Application of tor-biochar towards vacuum BW in AD process is feasible; (2) Digestate as a soil conditional to improve soil condition is effective; (3) Mesophilic and thermophilic conditions are applicable on AD vacuum BW; (4) Economic significance indicates technological feasibility.

Keywords: vacuum blackwater; resource recovery; torrefaction; economic significance; continuous stirred tank reactor

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1. Introduction

There will be no life on this planet if water is not present, as it comprises around 75% water. Unfortunately, just 2.5% of the water is fresh [1]. Different studies have shown that many areas around the world are experiencing intense water shortages due to lack of or only partial water availability. It has been investigated by Salehi et al. (2022) [2] that over half of the world could face water shortage challenges, as water demand will sharply increase up to 55% by 2050. In fact, most countries around the world are experiencing shortages of water [3]. Due to this water depletion, the conservation of fresh water and wastewater for bio-energy applications must be improved. Blackwater (BW) characteristics are supersaturated with organic and inorganic materials and could lead to a high yield of biogas production and post-nutrient recovery, such as that of nitrogen (N) and phosphorus (P). BW has traditionally been treated using a combined discharge-collection-treatment system, which increases the burden of wastewater-treatment plants, leads to excessive energy and operational expenses, wastes water resources, and depletes nitrogen and phosphorus supplies [4]. The BW, on the other hand, is collected by centralized sewer systems and processed at sewage-treatment plants placed across urban areas [5]. However, due to the world's inherently distributed population, the aforesaid centralized treatment of wastewater (particularly BW) and sophisticated treatment of BW for its sustainable reuse are absent in rural areas. Massive investments are required to install sewer pipes across a broad but sparsely populated area.

Anaerobic digestion (AD) is well known as the best treatment technique to cleanse numerous kinds of concentrated wastes, including wastewater such as vacuum-collected BW (VCBW). In fact, a vacuum toilet consumes a small amount of water for a single flush, which helps to achieve a low dilution of BW and hence the recovery of valuable nutrients. Thus, vacuum toilets are considered a great source of BW to be used in the AD process [6]. Some research has discussed the essence of BW-treatment efficiencies in bio-energy production and nutrient recovery based on the distinct running state and nature of reactors [7]. Typically, there are different types of toilets, such as dry toilets, dual-flush toilets, and conventional toilets. Depending on the previous studies, each toilet has a unique flushing system style. For instance, a dry toilet uses 1 L of flush, a dual-flush toilet uses 3–6 L of flush, and a conventional toilet uses 9 L of flush. Though a small number of reports showed that BW could be treated by AD systems in a variety of configurations, including the continuous stirred tank reactor (CSTR), up-flow anaerobic sludge blanket (UASB), and expanded granular sludge bed (EGSB), in recent years, AD via CSTR has attracted much attention because of its outstanding potential for treating wastewater and generating bioenergy. It has frequently been used in research due to the large amount of chemical oxygen demand (COD)-removal capacities within the range of 61–80% and biogas production of 31–60% [8]. After AD treatment of VCBW with kitchen refuse under CSTR for 20 days, the digester was stable without the inhibition effects of ammonium concentrations, which are highly present in BW, and the result showed efficient removal of COD and high-yield production of methane gas [9]. In addition, CSTR is commonly used in AD treatment, as it is easy to design and install and provides steady control of system parameters such as mixing, temperature, substrate, and chemical concentration.

Biochar, a carbon-rich substance, is also generated when biomass is thermochemically transformed without oxygen [10], along with other by-products such as syngas and bio-oil. By using a low amount of energy, a high quantity and quality of tor-biochar can be obtained through the torrefaction process. In comparison to others that use heat to generate biochar, like gasification, carbonization, and pyrolysis, they are considered to lower greenhouse gas (GHG) emissions and generate products such as syngas, bio-oil, and biochar. These torrefaction by-products can be used as additives in AD-treatment processes to improve performance, improve soil properties, purify wastewater, and lower soil acidity [11], though the process is energy-intensive. Torrefaction seemed to be the most feasible for biomass operations. It is a relatively new process of thermochemical treatment that is considered a partial pyrolysis process and is performed in the range of 200–300 °C, and it can be achieved under atmospheric conditions anaerobically [12]. Usually, for optimization of the torrefaction process, the temperature range can be increased to 270–300 °C. Comparatively, biomass pyrolysis usually operates at a temperature range of 300–650 °C, unlike gasification, which is operated at 800–1000 °C [13]. The primary product of torrefaction is a phase of solid (tor-biochar) that has physiochemical properties similar to biochar from pyrolysis. The use of tor-biochar in the AD process has shown remarkable results: The methane yield was in the range of 481–772 mL/g, and the AD was more stable with lower inhibition, generating a high level of biogas under mesophilic conditions [14].

Integrating torrefaction with other treatment processes such as AD will facilitate the production of bio-energy, the recovery of nutrients, and the development of economic competitiveness. Studies are rare on VCBW/BW with tor-biochar/tor-biomass valorization with AD-CSTR. The purpose of this review is to examine the possible impact of a tor-biochar/tor-biomass additive in the AD-treatment process for VCBW using CSTR. This review emphasizes the challenges related to the integration routes that promote high bio-energy generation, water conservation, and nutrient recovery. It also highlights the economic value of these integration routes and provides recommendations to alleviate associated bottlenecks.

2. Background of Blackwater

BW is a kind of wastewater that comes into contact with human excretion, such as urine and feces. In Table 1, the main differences between a dry toilet, a dual-flush toilet, and a regular toilet that flushes with BW are shown. In Figure 1, different types of wastewaters from households are shown. Typically, flushed wastewater, which contains urine, feces, flushing water, and toilet paper, is called BW, whereas without urine, it is called brown water, and low-fractionally polluted household wastewater from the kitchen, bath, and laundry is known as greywater [15,16]. BW is highly loaded with organic and nutrient substances, accounting for more than 50% of the organic substances and more than 80% of the nutrients in household BW [8], despite being generated in a smaller volume. BW also contains volatile fatty acids such as acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, and valeric acid [17]. In fact, 2.57 gcpd of acetic acid and 1.01 gcpd of propionic acid were constantly detected in fresh BW within 2 years. This presents another clear way to treat BW under the AD process because both acids (acetic and propionic acid) are produced and consumed in the whole metabolism pathways of methane gas production and act as essential intermediates during the AD decomposition of organic materials.

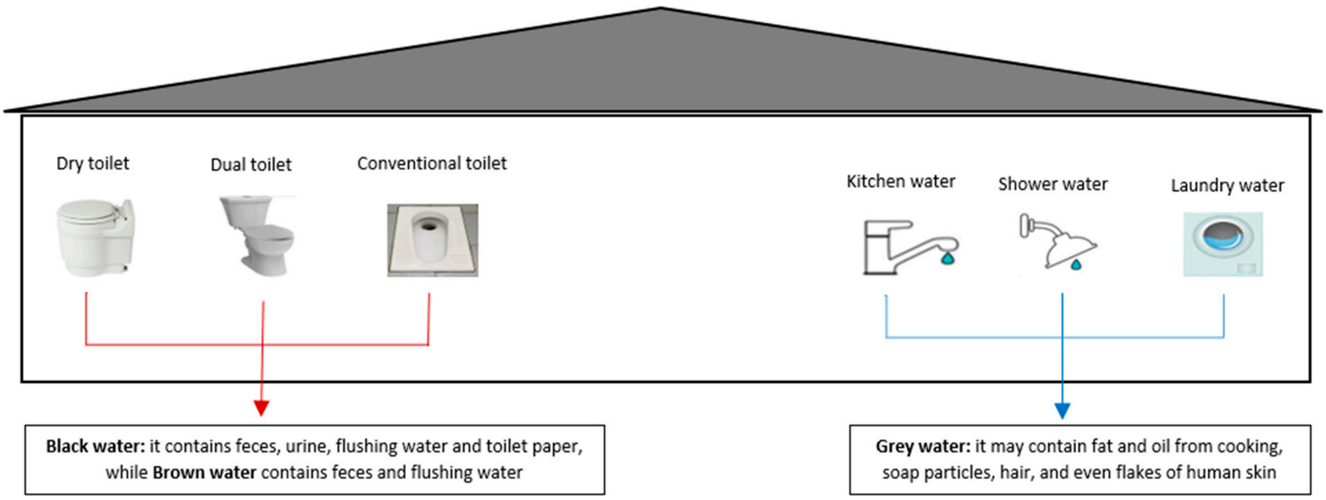

Figure 1. Different domestic source of wastewater.

All the three types of wastewaters can be generated domestically. Their composition varies broadly depending on the source of water, quality of water supply, home activities, amount of water used, and cultural and socio-economic factors. Physical, chemical, and biological treatments are the three main methods used to treat domestic wastewater (grey, brown, and black). A number of cutting-edge technologies, including membrane-based technology, enhanced electrocoagulation, nature-based solutions (built wetlands), and solar-based techniques, have drawn attention recently in addition to conventional treatment techniques [18]. However, the treatment of BW, which is source-separated from the other home wastewater streams, is the main topic of this review.

2.1. Assessment of Vacuum Toilet Blackwater

Vacuum toilets attract much attention because of their high water-saving potential and concentrated organic contents to optimize bioenergy and nutrient recovery. Vacuum toilets use small amounts of water per flush; for this reason, human excreta can be collected in concentrated form. The VCBW is highly recommended for treatment under anaerobic conditions, which will improve bio-energy production and nutrient recycling from domestic wastewater. VCBW consists of concentrated streams, offers about 30% of overall domestic water savings, and embodies more than 50% of organic substances and 80–95% of nutrients [19]. It contains valuable minerals for agriculture, such as nitrogen and phosphorus. The Haber–Bosch process uses a lot of energy to produce nitrogen; hence, the AD treatment of BW provides another method for recovering a large amount of nitrogen [20].

In addition, the treatment of domestic BW can generate 70–90% of the phosphorus and meet 15–20% of the global demand [21]. Meanwhile, the effectiveness of struvite precipitation and phosphorus removal exceeds 90% [22]. The bio-electrochemical systems that recover nitrogen, such as air stripping of ammonia from anaerobic digestate, can restore 70–92% of the nitrogen in the form of NH_3 or $(NH_4)_2SO_4$ [23]. Different studies have reported AD as the core treatment for BW. A mathematical model proved that concentrated wastewater sources, for instance, VCBW, have better performance than diluted wastewater sources such as dual and conventional toilets when treated under the AD process [24]. Many kinds of anaerobic digesters for BW can be operated in a mesophilic or moderately thermophilic environment to allow optimal development of the bacteria, which involves the decomposition of organic materials. In most former cases, AD was operated under mesophilic conditions, but it has some drawbacks because of the incomplete removal of some harmful pathogens. The thermophilic condition is highly recommended when treating VCBW, as it allows the elimination of pathogens such as *Escherichia coli* and extended-spectrum β-lactamases producing *E. coli* [25]. Hence, thermophilic AD for treating concentrated BW is preferred in order to enhance methane production and recover hygienically safe digestate, which can be applied as fertilizer products.

2.2. Assessment of Dual-Flush Blackwater

Dual-flush toilets come second to vacuum toilets, as they also contribute to water conservation. They utilize the options of 3–6 L per flush. In the past, a multitude of innovations in toilet technology have trended. Although dual-flush toilets, next to VCBW, are water-efficient, they apply more bulk flush for waste solids and less bulk flush for waste liquids. Even if this kind of toilet gives the user the option of flushing with either a great or small amount of water, it is still considered to involve a high water consumption, above 26.7% of the ordinary daily household usage of water generated from toilets [26].

2.3. Assessment of Conventional Blackwater

Conventional toilets are considered water-wasting toilets, and BW provides a lower pollutant level. This toilet type consumes 9 L per single flush. There is a reduced effect of free ammonia in conventional BW and hence high biogas production via AD [27]. In another study, VCBW exhibited a higher methane production rate without any noticeable inhibition of the microbial community under an up-flow anaerobic sludge blanket [28]. Vacuum BW has shown great potential in all aspects, such as water saving, high yield of biomethane, and sufficiency of nutrient recovery. Therefore, VCBW is highly recommended and considered more favorable than other types of collected BW.

AD is the standard BW treatment system, consisting primarily of sedimentation septic tanks and extremely efficient anaerobic reactors. The difference between sedimentation septic tanks and AD is due to its configuration, as AD may maximize resource recovery for nutrients, dramatically remove pathogens and micropollutants, and increase energy output compared to sedimentation. With an average load of 62 gCOD/p/d and a methanization level of 60%, BW can yield 12.5 L CH_4/p/d (0.35 L CH_4/gCOD) [29]. However, by including solid kitchen waste (60 gCOD/p/d), biogas output can be doubled, resulting in 25 L CH_4/p/d or 335 MJ/p/y (35.6 MJ/Nm^3 CH_4); hence, heat and electricity may be produced at an efficiency of 85% using combined heat and power generation systems (of which 40% is electricity and 60% heat) [30]. When employing the methane produced from blackwater and solid kitchen garbage, this would result in the generation of 32 kWh/p/y electricity (2.1% of the power consumption in a household; 87 PJ electricity consumption in the Netherlands in 2006, i.e., 1487 kWh/p/y) and 47 kWh/p/y heat [31,32]. An additional study examined the viability of using a bioprocess to treat VCBW at 25 °C. According to their findings, at an average HRT of 8.7 days, 78% of the influent load of COD was eliminated. The generated methane can be used to generate 56 MJ/p/y of electricity and 84 MJ/p/y of heat by combined heat and power [32]. In addition, the properties of BW generated from different toilets are well illustrated in Table 1.

Table 1. Characteristics of different blackwater flush systems.

Properties	Unit	Vacuum Toilet	Dual Toilet	Conventional Toilet	Reference
pH	-	8.62	8.50	8.40	[33]
TS	-	17140	3570	2390	[7]
VS	-	14200	2825	1847	[7]
COD	mg/L	18500	4600	2600	[34]
FVAs	mg/L	222	75	79	[35]
NH_4^+-N	mg/L	1115.1	182	96.4	[36]
Free ammonia	mg/L	355 (±10.3)	53 (±1.2)	24 (±0.9)	[34]

Total solid (TS); volatile solid (VS); chemical oxygen demand (COD), free volatile fatty acids (FVAs); ammonium nitrate (NH_4^+-N).

3. Torrefaction of Biomass Scenario

The torrefaction process is a thermochemical technique that is operated in the temperature range of about 200–300 °C under an inert or nitrogen atmosphere. The final properties of the pulverized fuel are better after this process. They are more hydrophobic, resistant to biodegradation, and have higher solid and energy yields. These characteristics make the pellet generation, handling, and storage of biomass more suitable. In addition, great ignitability and grindability can be achieved [37]. The fundamental purpose of this method is to produce tor-biochar in great quantity and quality. Thus, biomass must be torrefied under wet or dry torrefaction. In wet torrefaction, biomass can be treated at 180–260 °C under dilute acid and water to improve its features, and the product of this process is called tor-hydrochar. Under 180 °C, biomass undergoes no significant reaction when torrefied in hydrothermal or hot water [38]. On the other hand, in dry torrefaction, biomass can be treated at a temperature of 200–300 °C in non-oxidative conditions, in which carbon dioxide and nitrogen have been used as carrier gases [39]. Table 2 presents the torrefaction technology of different biomasses and their torrefied by-product properties. In addition to the two techniques, stream torrefaction can also be used to upgrade biomass properties. However, the major tor-biomass treatment method is non-oxidative, as it offers numerous advantages, such as easy temperature control, high energy, and solid yield production. Hence, it offers great potential in industrial applications.

Table 2. Torrefaction technology of different biomasses and their torrefied by-product properties [40].

Biomass	Torrefaction Technology	Torrefaction Condition	Torrefied By-Product Properties	Reference
Sawdust	Non-oxidative torrefaction	240–300 °C, 50 and 120 min	Solid yield: 32.6–65.1% HHV: 19.56–25.95 MJ/kg Energy yield: 73.3–99.6%	[41]
	Oxidative torrefaction	240–300 °C, 50 and 120 min, O_2 gas	Solid yield: 41.3–60.1% HHV: 19.30–23.50 MJ/kg Energy yield: 65.7–94.5%	

Table 2. *Cont.*

Biomass	Torrefaction Technology	Torrefaction Condition	Torrefied By-Product Properties	Reference
Commercial fir pellets	Non-oxidative torrefaction	200–250 °C, 15 min, 20 °C min^{-1}, N_2 gas	Solid yield: 52.72–90.12 wt% Liquid yield: 3.68–18.90 db HHV: 20.71–24.20 MJ/kg Energy yield: 65.06–93.65%	[42]
Fiberboard	Dry torrefaction	200–300 °C, 5–120 min, N_2 gas	Solid yield: 50.18–97.02 wt % Energy density ratio: Highest 1.24	[43]
Rice husk	Oxidative torrefaction	220–300 °C, 30 min, 0–15 vol% O_2	Solid yield: 55–85% Energy yield: 64–89%	[44]
	Non-oxidative torrefaction	220–300 °C, 30 min, N_2	Solid yield: 92.71% HHV: ≤18.91 MJ/kg Energy yield: 80.56%	
Sugarcane bagasse	Dry torrefaction	200–275 °C, 15–60 min, 20 °C min^{-1}, N_2 gas	Solid yield: 54–80% HHV: ≤24.01 MJ/kg Energy yield: 69–89%	[45]
Olive pomace pellets	Non-oxidative torrefaction	200–250 °C, 15 min, 20 °C min−1, N_2 gas	Solid yield: 56.34–79.92 wt% Liquid yield: 3.37–13.8 db HHV: 24.42–27.16 MJ/kg Energy yield: 75.22–94.50%	[42]
Plywood	Dry torrefaction	200–300 °C, 5–120 min, N_2 gas	Solid yield: 52.26–96.68 wt% Energy density ratio: Highest 1.23	[43]
Bamboo residue	Dry torrefaction	200–300 °C, 60 min, 10 °C min^{-1}, N_2 gas	Solid yield: 49.48–86.24% HHV: 17.57–21.96%	[46]
Olive pomace pellets	Oxidative torrefaction	200–250 °C, 15 min, 20 °C min^{-1}, air	Solid yield: 53.04–71.41 wt% Liquid yield: 10.34–24.7 db HHV: 23.53–26.15 MJ/kg Energy yield: 68.40–82.12%	[42]

The entire torrefaction process of non-oxidative can be classified into five stages, such as initial heating, drying, post-drying, intermediate heating, torrefaction, and cooling, with specific conditions, reaction, time, and temperature for every stage [12]. Moreover, tor-biochar is regarded as one of the most efficient biofuel manufacturing processes, creating highly efficient biomass for bioenergy chains [47]. The thermal process methods, temperature, reaction time, carrier gas, carrier gas flow rate, catalyst, and particle size are crucial parameters that can affect the characteristics of tor-biochar [40]. Temperature is the most essential among the other operating conditions. The torrefaction process has three classes, namely light (200–235 °C), mild (235–275 °C), and severe (275–300 °C) torrefaction [48]. The decomposition of cellulose and hemicelluloses can be achieved in the temperature range of 315–400 °C and 220–315 °C, respectively, whereas the operating temperature of torrefaction is around 200–300 °C, and also, by raising the temperature, the carbon in tor-biochar is increased. Changing the temperature from 250 °C, 270 °C, 300 °C, and 340 °C, the quantity of carbon rises to 52.4, 58.1, 63.5, and 71.9, respectively, within the same 60-min residence time [49]. Hence, temperature has a significant influence on the tor-biochar produced. Apart from the torrefaction operational temperature, another torrefaction-influencing factor is the reaction time.

Ideally, torrefaction can be conducted within several hours or minutes. The heating value and carbon content of tor-biochar can be increased with an increase in reaction time. The torrefaction of different species of softwood residues under 250 °C for 30, 60, and 90 min increases the calorific values of tor-biochar from 20.0 to 22.7 kJ kg^{-1}, though increasing of the reaction time consumes much thermal energy [49]. In the past, torrefaction has been operated under an inert or nitrogen atmosphere. However, some researchers have examined the influence of carried gases, for example, air, flue gas, carbon dioxide, etc., on tor-biochar. Several studies showed that the use of carbon dioxide as a medium (carrier gas) influences volatile material thermal cracking and biomass thermal degradation. Nyakuma et al. (2022) [50] performed carbon dioxide torrefaction of oil palm empty-fruit-bunch pellets. The findings showed that liquid yield and gas yield increased, while mass yield and energy yield decreased, with an increase in the severity of the torrefaction medium. The higher heating values, energy density, and severity factors were improved after torrefaction. In addition, torrefied pellets indicated great enhancements in their microstructure, physiochemical, hydrophobic, and grindability characteristics compared with the raw biomass. Hernández et al. (2017) [51] conducted sewage sludge torrefaction under a carbon dioxide and nitrogen medium in a thermogravimetry–infrared spectrometry analyzer and a laboratory-scale furnace. The result proved that carbon dioxide slightly influences the mechanism of torrefaction in terms of shifting the degradation peak to a lower temperature of around 7 °C. In general, the results revealed that carbon-dioxide-torrefied biomass exhibits practical methods for the sustainable generation of bioenergy and increases surface area compared to nitrogen-torrefied biomass.

Furthermore, inorganic metals that are present in biomass can act as catalysts in the thermochemical operation by promoting biochar production. Alkalines earthmetals are promising catalysts for the thermochemical conversion of biomass. Combining kinetic and particle models has assisted in describing the influence of heating rate and potassium during the pyrolysis process [52]. This finding indicated that potassium has a stronger catalytic effect on reactions and the formation of biochar at low and intermediate heating rates compared to high heating rates. This suggests that, at higher torrefaction temperatures (around 270–290 °C), the catalyst effect of potassium will be more impactful and accelerate the thermal decomposition of cellulose and hemicellulose in biomass. Biomass is the world's most abundant renewable energy source, but its intrinsic disadvantages, such as low energy and mass density, hydrophilicity, difficult grinding, and serious ash-related problems, preclude its widespread application. Unlike other thermochemical technologies, torrefaction temperature has the biggest effect on improving the characteristics of biomass. The aforementioned problems are effectively resolved by torrefaction, which is carried out at 200–300 °C in an inert atmosphere. At an ideal torrefaction temperature of roughly 250 °C, biomass applications, physical qualities (energy density and grindability), and chemical thermal conversion characteristics are all improved [53].

3.1. Properties of Tor-Biochar

3.1.1. Bulk Density

Torrefaction causes the loss of chemicals that are volatilized during the torrefaction process. This increases the porosity of the tor-biochar, lowering its bulk density. This reduction property is determined by the parameters of the feed biomass and the torrefaction setup. Research was conducted on the effect of torrefaction temperature on different biomasses, such as bagasse, wheat straw, and rice husk, in pure or different proportions [54]. Results showed a sharp decrease in the moisture contents, hence the augmentation of bulk density owing to the reduction in moisture content within biomass. The torrefaction of *Eucalyptus grandis* wood was conducted at different temperatures. The change was insufficient at low temperatures; at 220 °C, the bulk density was 2%, which increased to around 14% at 280 °C [55]. Numerous studies have been conducted to examine the change in energy content of the tor-biochar generated at different temperatures and reaction times. The major biomass elements are hydrogen, carbon, and oxygen, which are considered building blocks of lignin, cellulose, and hemicellulose, and a low amount of sulfur and nitrogen are also present in biomass. Carbon is oxidized during the torrefaction process, which causes the release of heat. Also, hydrogen is an essential element that produces heat throughout biomass combustion, but in most cases, it appears in O-H or C-H bonds. Biomass, which contains a high amount of oxygen, is helpful for combustion, but its calorific value will be reduced owing to this high oxygen level in biomass. Thus, torrefaction is the best process to eliminate unwanted elements such as oxygen and hydron in tor-biochar in order to achieve a high calorific value, which is almost close to that of coal (25–35 MJ kg^{-1}) [56]. Torrefaction operated at 270 °C for 30 min on lodgepole pine increased the calorific value from 19 MJ kg^{-1} to 24 MJ kg^{-1} [57], and stool tree (*Alstonia congenisis Engl.*) woody biomass offered a heating value of about 24 MJ kg1 when the temperature was increased up to 300 °C [58]. Therefore, the increase in torrefaction reaction time and temperature leads to a significant rise in calorific value.

3.1.2. Hydrophobicity

Some of the hydroxyl groups in raw biomass are broken down during the torrefaction process. This is because volatile materials are removed, and hemicellulose goes through a dihydroxylation reaction. Hence, there is no formation of hydrogen bonds, which turns tor-biochar into hydrophobic properties. These features increase degradation resistance when stored. As lignin shows low water affinity, while hemicellulose has high water affinity, the hydrophobicity of tor-biochar depends on the amount of cellulose, lignin, and hemicellulose. Though dehydration of biomass during torrefaction causes the reduction of hydrogen–carbon bonds and oxygen–carbon bonds as well as hemicellulose degradation [59]. In addition, tor-biochar generated from a high torrefaction temperature has the lowest water affinity. Four different mechanisms of hydrophobicity include decomposition of hemicellulose, which unbinds the lignin and cellulose; hemicellulose breakdown, which causes the brittleness of lignin and cellulose; the elimination of the OH functional group; a decrease in hydrogen bond formation; and decomposition of hemicellulose, which forms more molecules that are non-polar [60]. Thermogravimetric analyzer (TGA) curves were used to assess the hydrophobicity of torrefied biomass [61]. The weight loss of samples in the torrefaction process was highly related to the torrefaction temperature. It was shown clearly that hydrophobicity formation has a high linear correlation with the formation of micropores and the elimination of hydroxy groups. In addition, making the torrefaction process stronger can make the sawdust tor-biochar more hydrophobic. The tars that form inside the pores in tor-biochar lower the amount of saturated moisture by preventing moist air from passing through the torrefied biomass. Thus, dihydroxylation, tar, and dehydration have a considerable effect on the transformation of biomass from hygroscopic to hydroscopic tor-biochar.

3.1.3. Grindability

The grindability enhancement of tor-biochar is crucial for upgrading biomass after the process. In torrefied biomass, the cell wall has large pores and ruptures, revealing the breakdown of the cell walls, which is attributed to the removal of volatile material during the torrefaction process [62]. Due to the destruction of cell walls, it is easier to grind the material into tor-biochar. This grindability improvement is important for the application of bioenergy. Thus, biomass with high grindability is favorable for energy conservation when it is crushed into minor particles. Wang et al. (2018) [63] studied the grindability of torrefied bark, stump, and Norway spruce stem wood. Torrefaction significantly improves Norway spruce stem wood grindability. They reported that when the stump and stem wood of Norway spruce torrefied under 225 °C, nearly 50% of the grinding energy was needed compared to grinding the raw biomass. Colin et al. (2017) [64] evaluated the impact of the torrefaction process on wood chips. They observed that the grinding energy consumption of tor-biochar can be saved approximately ten times with torrefied wood chips when compared to the raw feed. Moreover, the most common indicator to evaluate the grinding scale of biomass is called the Hardgrove grindability index (HGI), which is used for crushing and examining the complex of grinding solid biomass into powder [65]. The torrefaction severity determines GHI, and a high degree of GHI is required for a simple grinding treatment. The size and shape of powder particles can be reduced, which will improve bulk and energy density. Therefore, the grinding process of tor-biochar indicates remarkable applications for co-firing and furl pulverization. The chemical characteristics of tor-biochar are shown in Table 3.

Table 3. Chemical characteristics of the tor-biochar.

Biomass	Proximate Analysis (wt%)			Ultimate Analysis (wt%)				Reference
	Volatile Materials	Fixed Carbon Ash	Ash Content CV	C	N	H	S	
Oak wood	79.12	-	3.24	48.53	0.34	5.89	0.02	[66]
Pine wood	83.7	15.9	0.4	48.1	0.4	6.3	0.18	[67]
Bamboo residues	66.98	13.67	12.40	40.51	1.30	5.72	0.14	[46]
Vegetable biomass	76.5	34.8	23.8	51.82	4.1	6.79	0.19	[68]
Tobacco stalk	71.6	10.9	17.5	39.56	3.18	4.85	-	[69]
Maize straw	82.4	-	4.2	42.3	0.63	5.61	0.07	[70]

4. Impacts of Torrefaction By-Products on Anaerobic Digestion and Other Processes

Torrefaction is a thermal treatment process that can be used to convert biomass into a more energy-dense and stable form. In recent years, there has been growing interest in the integration of torrefaction with AD to enhance biofuel production. The integration of torrefaction with AD allows for the recovery of valuable organic chemicals from the aqueous waste stream produced during hydrothermal torrefaction. The use of torrefaction condensate in AD offers the opportunity to increase waste-to-energy recovery. For example, digested sludge from AD of BW can be pretreated with hydrothermal torrefaction, a process that can handle wet biomass. This will not only increases the fuel flexibility but also enhances the commercial attractiveness of torrefaction. The aqueous waste stream from hydrothermal torrefaction contains valuable organic chemicals such as sugars, furans, furfurals, and organic acids. These chemicals can be further utilized or extracted for various applications, creating additional economic value. Table 4 presents the different outcomes and impacts of torrefaction by-products on AD and other applications. These impacts are further highlighted in the subsections.

Table 4. Impact of different torrefaction by-product application in AD and other processes.

Torrefaction by Products	Applications	Outcome	Reference
Tor-biochar	Additive in AD	Torrefied biochar as an addition in CSTR might be considered an alternate pre-treatment strategy.	[71]
Tor-biochar and tor-condensate	Contaminants removal	Good technical and economic feasibility, particularly when coupled with AD treatment for absorption of contaminants.	[72]
Urea and potassium hydroxide (KOH) together in torrefaction pretreatment.	Straw valorization with AD at the upstream section	This leads to 41% more methane production than batch AD straw that has not been treated. High digestate quality for farming.	[73]
Tor-biochar	Facilitation of biogas in AD	Offers 275% and 250% biomethane yield.	[74]
Biochar from torrefied biomass	Additive in AD	Optimizes tor-biomass biochar features to enhance bioprocess.	[40]
Tor-biochar and pyro-biochar performance	Pollutant adsorption capacity evaluation for dye	Tor-biochar adsorption capacity is 192.67 mg/g and 56.21 mg/g, while pyro biochar is 50 mg/g and 100 mg/g, respectively.	[75]
Tor-biochar	Climate mitigation	Improves soil quality and support carbon sequestration in the soil.	[76]
Tor-biochar from tor-biomass	Additive in AD	Adsorbent for organic and inorganic pollutant. Mitigates inhibition in AD.	[77]
Tor-biochar	Facilitation of soil amendment	Acts as organic fertilizer; when tested for soil amendment, improves crop growth.	[78]

4.1. Additive in Anaerobic Digestion Processes

AD has been adopted for the treatment of BW and other wastes for suitable enhancement of bio-energy generation and the reduction of emissions of harmful gases. The AD CSTRs are commonly used in chemical and biochemical processes due to their ability to provide continuous operation and their good mixing. CSTRs are usually involved in various industrial operations, such as mixing, heat transfer, mass transfer, and chemical reactions [79]. The design of a CSTR involves a tank with an agitator to provide continuous mixing of the reactants. This type of reactor is characterized by a well-mixed environment, with the reactants and the products uniformly distributed throughout the tank. The CSTR process is a multivariable system, with MIMO control configuration [80]. One of the key advantages of CSTRs is their ability to maintain a uniform composition and temperature throughout the tank, which ensures consistent reaction conditions and product quality. The performance of a CSTR can be influenced by several factors, including the choice of agitator design, flow rate, temperature control, and reaction kinetics. According to benchmark studies, CSTRs are highly nonlinear systems and are useful benchmarks for modeling techniques such as neural networks [81].

Despite CSTR's excellent efficacy for organic treatment, it encounters abnormalities at high organic loading rate (OLR) operations, resulting in poor methane generation [82]. Another issue is the quality of digestates produced by AD CSTR when performance is inhibited. A wide spectrum of inhibition from proteins, fat, oil, grease, and high total ammonia has also been recorded in BW and FW with CSTR during AD. Various pre-treatment procedures have been developed in order to improve the ability of the AD CSTR process to convert organic waste into valuable products. These include chemical treatments, fenton, alkalization, thermal, biological, and microwave irradiation. Anammox, the usage of zeolite, carbon fiber textiles, and struvite precipitation are all feasible mitigation approaches for ammonia-inhibition management in the AD process [71]. Some authors stated that pre-treatment techniques are effective, but they rely heavily on additional energy sources that are not cost-effective [82]. The slow startup process of the CSTR may occasionally be a problem deemed unsuitable for industrial-scale operations. As a result, the performance of torrefied biochar as an addition in CSTR might be considered an alternate pre-treatment strategy for CSTR bioprocess-enhanced operations.

Doddapaneni et al. (2022) [14] studied the torrefaction of pulp-industry sludge combined with the AD process to generate biomethane and volatile fatty acids (VFA). The biomethane yield was between 401 and 746 mL/g and between 481 and 772 mL/g. The VFA yield was between 1.5 and 4.7 g/g in the thermophilic environment and between 1.1 and 3.4 g/g in the mesophilic environment. It is clear that AD treatment was more stable in mesophilic conditions, which led to high production of biomethane, whereas the development of VFA was highly favored in thermophilic conditions. In another study, the chemical composition of the torrefaction by-product, which included acetic acid, propionic acid, phenol, and 1-hydroxy-2-butanone, was 36.77%, 0.67%, 3.54%, and 1.76%, respectively; this led to the maximum biomethane production and the optimal generation of methanogenic bacteria [83]. A recent study investigated how to treat organic household waste (BW and FW) with the CSTR bioprocess. BW and FW were found able to be treated in a decentralized system through the integration of technologies (AD and pyrolysis). Biochar made from pyrolysis showed potential for addition to the CSTR for biogas generation (with a 60% increase in methane content) and nutrient-rich digestates for farming [84].

Thus, the by-product of torrefaction can help in the production of organic chemicals such as VFA. Moreover, tor-condensate is regarded as a rich organic compound, as it contains dilute acid. The microbial conversion of tor-condensate from pine wood under the AD technique showed remarkable potential toward the production of biomethane, with 430–460 mL/g volatile solids (VS) and 430–492 mL/g VS under thermophilic and mesophilic conditions, respectively [85]. Furthermore, the increase in torrefaction temperature led to an increase in carbon content and a decrease in hydrogen and oxygen amounts [86]. It is common knowledge that one of the crucial stages of AD is hydrolysis, as VCBW is generally composed of huge organic polymers, and the hydrolysis process breaks polymers into monomers, supporting bacteria that enhance methane growth.

4.2. Facilitate in Biogas Production

It is well known that the thermal decomposition of celluloses and hemicelluloses occurs between 315 and 400 °C and 220 and 315 °C, respectively. This allows partial decomposition of those two aforementioned materials, while torrefaction is around 200–300 °C. It allows thermal decomposition of the long chain of hydrogen bonds in cellulose, depolymerizes lignin in lignocellulosic biomass, and breaks down hemicelluloses, thus leading to optimal conversion and improved methane generation.

Torrefaction alters the structure of biomass; the extent of this alteration is significantly dependent on the intensity of the torrefaction process. Temperature, residence duration, and heating rate all have a significant impact on the torrefaction process in order to obtain the final torrefied biomass features, such as biochar [12]. Further optimization should be undertaken depending on the intended application of the torrefied product. Torrefaction can alter the distribution of several components of biomass; typically, cellulose and hemicellulose degrade between 200 and 400 °C, but lignin degrades more slowly: between 200 and 900 °C [40]. Torrefaction also contributes to a decrease in hemicellulose content from 22% to 4.6% at 300 °C, whereas cellulose degrades slowly, and lignin content increases. The application of biochar produced from torrefied lignocellulosic biomass is largely dependent on its structural properties; thus, it is critical to investigate and comprehend the detailed structural changes that occur during the torrefaction process in order to optimize the product's application, most notably in AD [40].

Li et al. (2018) [87] investigated the effect of cellulose, hemicellulose, and lignin in AD treatment on methane production. The result showed hemicellulose hydrolyzed faster than cellulose, but cellulose had more biomethane potential than hemicellulose, while lignin was difficult to digest. In addition, Hidalgo et al. (2023) [74] studied the effect of biomass torrefaction on AD for vine shoots and barley straw. The result showed significant differences in biomethane production for both raw and treated biomass. The maximal yield of biogas from vine shoots and straw was 213 and 458 mL/g volatile solid, respectively. Also, barley straw that was heated to 100 °C showed a biomethane yield that was 275% higher than that of untreated straw biomass, while vine shoots showed a yield of 210%. In general, the main things that make biomethane production better are changes to lignocellulosic materials and a drop in the amount of hemicellulose present. Using urea and potassium hydroxide (KOH) together in torrefaction makes straw more biodegradable by removing the lignin and other cellulose materials. This leads to 41% more methane production than batch AD straw that has not been treated [73]. Also, using tor-biochar with KOH and urea in AD treatment offers digestate that is rich in potassium and nitrogen. This can be thought of as a great source of organic soil conditional.

4.3. Soil Amendment

Globally, people have been using human excrement for thousands of years for soil fertilization to preserve or enrich the organic properties of fields [88]. The use of fertilizer in the agricultural sector has increased dramatically to meet high global population demands for food and may keep doing so for decades. It is expected to increase by about 100% to 110% in global crop demands between the years 2005 and 2050. Many papers have been published recommending the use of different kinds of biochar as soil amendments. For instance, Thengane et al.'s (2020) [78] study pointed out the effectiveness of tor-biochar from pine shavings and rice husk biomass as organic fertilizer. When tested for soil amendment, the tor-biochar showed great results compared with raw biomass, such as in the pH and in providing nitrogen and phosphorous for crop growth. It was reported that light-torrefied biomass has no significant effect on the green shoot number or germination of the seeds. Relatively heavy tor-biochar demonstrated the highest crop yield and shoot heights, followed by light tor-biochar and control.

Application of tor-biochar as an organic fertilizer not only enhances soil properties but also provides a green and effective method for permanent sequestration of carbon in the soil [76]. Also, the carbon in tor-biochar is biologically and chemically more stable than in untreated biomass. In addition, tor-biomass, as a carbon- and oxygen-rich solid biochar, can be added to soil to sequester carbon and amend the soil's chemical and physical properties. Reactive nitrogen is highly essential in the agriculture sector, and unfortunately, there are many challenges in optimizing nitrogen efficiency within that sector [89]. This high loss of nitrogen fertilizer can be supported by the fact that only 50% of the nitrogen fertilizer is recovered in seeds [90]. Therefore, reactive nitrogen deficiency hinders food production, leading to famine in the developing world [91]. Phosphate (PO_4^{3-}) from wastewater-treatment plants via bio-solids reuse has been equally exploited for nutrients [92]. Some studies examine the recovery of calcium phosphate granules from vacuum BW for phosphorus sustainability in soil fertilization, while digestate is employed as a soil conditioner.

4.4. Adsorbent for Organic and Inorganic Pollutant

The by-products of the torrefaction process have been considered eco-friendly and sustainable products for the elimination of organic and inorganic pollutants. Meanwhile, the application of tor-biochar and tor-condensate in the absorption of contaminants has good technical and economic feasibility, particularly when coupled with AD treatment [72]. Efficiency of the aforesaid by-product in adsorption of pollutants depends on physico-chemical characteristics, for instance, pore size, specific surface area, amount of minerals in tor-biochar, and functional groups such as C=C, -CH, and -OH [93]. Doddapaneni et al. (2018) [77] studied tor-condensate detoxification by eliminating the inhibitory furfural material by employing tor-biochar and then using the detoxified tor-condensate as an additive in AD. The maximal adsorbed furfural from tor-condensate was 60% when using tor-biochar in batch adsorption. Then, detoxified tor-condensate was introduced in the AD process, hence the reduction of the lag phase from 25 to 15 days. Thus, tor-biochar can successfully detoxify tor-condensate for the conversion of microbial communities, and also, torrefaction by-products can be combined for their efficiency. The adsorption capacity of two tor-biochars from orange and coconut waste to eliminate polycyclic aromatic hydrocarbons (PAHs) in aquaculture environments was examined in a solution of benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, and dibenzo(a,h)anthracene. The outcomes indicated that 23.84–84.02% and 47.09–83.02% of PAHs were removed by tor-orange and tor-coconut waste, respectively [94].

Moreover, tor-biochar from olive waste has been used for the adsorption of toxic heavy metals [93]. Tor-biochar showed a high removal capacity towards Cd^{2+}, Pb^{2+}, Ni^{2+}, Zn^{2+}, and Cu^{2+}, and it was greater than 85% when compared to commercial activated carbon (CAC) and other types of biochar. In addition, tor-biochar yield and surface area were 24–35% and 1.65–8.12 $m^2\ g^{-1}$, respectively, as compared to 1100 $m^2\ g^{-1}$ for CAC. This result shows that a specific surface area cannot be considered as the only indicator of heavy metal removal ability. Furthermore, Li et al. (2019) [75] examined and compared pyrochar (biochar from the pyrolysis process) and tor-biochar (biochar from the torrefaction process) for uranium (U (VI)) and methylene blue (MB) adsorption capacity. The result indicated that tor-biochar has a high oxygen content and is richer in oxygen-containing functional groups. Also, the maximum MB and U (VI) adsorption capacities were above 350 mg/g and 100 mg/g, while for pyrochar, they were 192.67 mg/g and 56.21 mg/g, respectively. From these results, it is obvious that tor-biochar was twice as effective as pyrochar. The carrier gas used in the torrefaction process has a significant effect on the tor-biochar properties. For instance, tor-biochar produced in a carrier air environment was effective towards U (IV) removal, while in nitrogen carrier gas, it was much more efficient for the adsorption of MB. As ammonia nitrogen is considered a major inhibitor in the AD-treatment process, Maurice et al. (2021) [95] examined the removal of ammonia nitrogen from AD with biochar. The results showed a 56.85% reduction compared to the control. The route of production of by-product from torrefaction and as an additive in VCBW treatment under AD with a CSTR is shown in Figure 2.

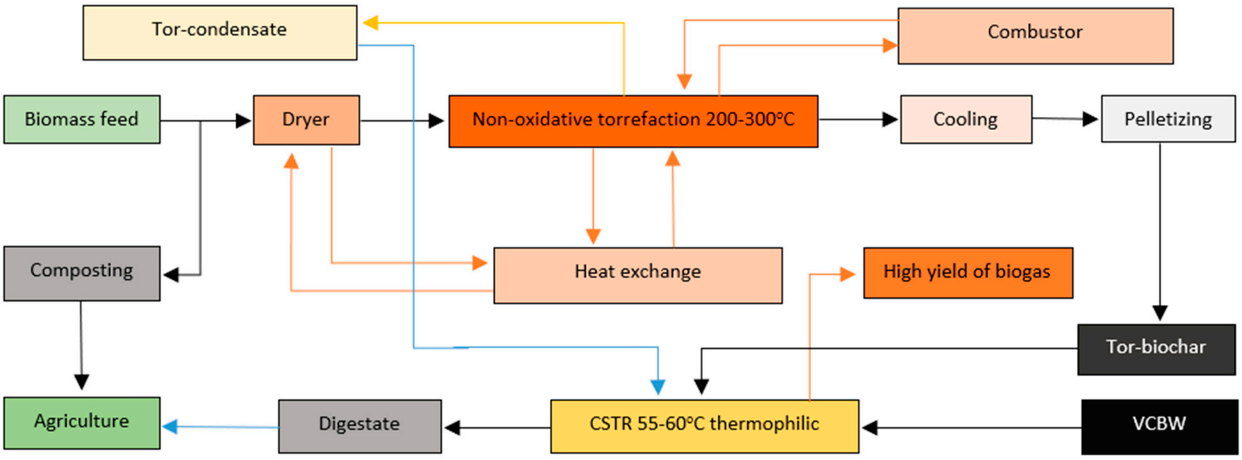

Figure 2. Chart of pre-biomass to tor-biochar as an additive in AD.

Biomass feed can be composted for agriculture or torrefied. Additionally, torrefaction increases the biomass's relative carbon, and the properties of tor-biochar and tor-condensate depend on operating temperature, residence time, and the type of biomass feed [96]. Pelletizing is a high-tech way to make biofuels that are dense, uniform, and contain less water. These biofuels have a higher heating value, a more uniform shape, and burn cleanly compared to raw biomass. This means that they are easier to handle and feed, with less ash content [97]. Moreover, after the use of tor-biochar and tor-condensate with VCBW in the CSTR under the AD process in a thermophilic condition, the production of biogas results, which can be used as an energy source. The digestate from AD also improves soil characteristics in the farming sector. Various thermal processes have generated biochar, and Figure 3 compares tor-biochar with other types of biochar under different operational conditions.

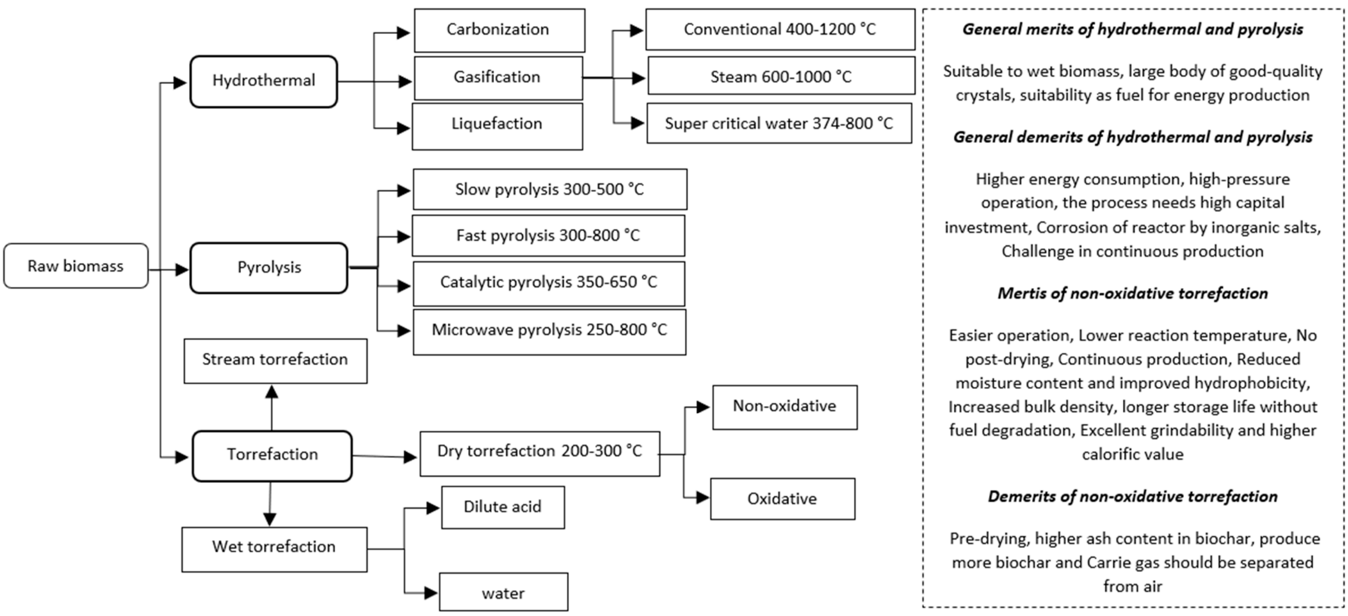

Figure 3. Comparison of tor-biochar with other types of biochar.

Generally, tor-biomasses such as biochar, activated carbon, and other types of biochar are all carbon-based substances that can be used as additives in bioprocesses. In addition, tor-biomass with activated carbon is generally more effective for use in bioprocesses such as AD compared to other types of biochar for increasing adsorption applications due to its porous structure and surface area. It is more cost-effective and can be used as an alternative additive for improving biogas production in the AD process. A large amount of digestate is generated in AD, and it can serve as a soil conditioner for agricultural purposes. However, activated carbon has the highest adsorption capacity, though it is also the most expensive. Therefore, tor-biomass can be an affordable and sustainable additive in bioprocesses for the production of value-added products such as methane gas.

5. Overview of Torrefied Biochar and Blackwater Economic Significance

An economic analysis of the combination of BW and torrefied biomass can provide valuable insights into the financial feasibility of this integration. By assessing the costs and benefits of this combination, decision makers can make informed choices about implementing this technology. The integration of BW, which is wastewater from toilets and domestic sources, with torrefied biomass offers promising opportunities for sustainable energy production as well as valuable chemicals and soil enrichments for agriculture. The torrefaction process, which converts biomass into a valuable commodity, can be used as a nutrient-rich feedstock for sustainable agro-farming. Depending on the treatment parameters and composition of the biomass, torrefied biomass after grinding may resemble various grades of biochar. The increased surface area and porosity of tor-biochar boost its moisture- and nutrient-retention capacity, resulting in reduced water and fertilizer requirements for soil amendment applications, according to Thengane et al. (2020) [78]. They clarified further that tor-biochar is an appropriate conditioner for a range of soils due to its decreased N concentration and considerable compositional variability caused by variations in feedstock and operation circumstances. The solid product formed following torrefaction was found to exhibit enrichment of P, Fe, Mn, and Zn and reduction of K, Ca, S, Cl, Cu, Ni, Si, Sr, Ti, and Br, according to Anshu et al. (2023) [98]. The fixed-carbon content is improved when the degree of process severity is increased. It is necessary to comprehend the impact of process conditions, chemical forms, and elemental interactions on the release of compounds containing nutrients. This is demonstrated by the analysis of variation in nutrient composition in relation to changes in fixed-carbon content, which shows that the variation of nutrients with increasing fixed-carbon content does not follow a uniform trend [98].

In the integration of torrefaction with AD of BW, it is imperative to conduct a comprehensive economic analysis, with consideration of several factors. Firstly, the costs associated with biomass production and torrefaction should be evaluated. These costs may include the procurement of biomass, its quality, and the conversion yield. Cai et al. (2017) [99] investigated the optimization of the combined biomass torrefaction and fuel pellet production process. The results of the study showed that factors such as particle size, torrefaction degree, moisture content, and pelletizing temperature significantly influenced the compression and friction work, pellet dimensions, and strength. Further, it can provide numerous economic benefits, such as reduced grinding costs and improved power plant performance [100]. Studies have shown that integrating wastewater treatment with biomass production can significantly reduce the requirement for freshwater and nutrients, thereby reducing operational costs [101]. Furthermore, the economic viability of the combination of BW and torrefied biomass can be assessed by considering the potential revenue streams. These revenue streams may include the sale of torrefied biomass as a valuable commodity and the generation of renewable energy from the integrated system. Moreover, the economic analysis should also take into account the potential benefits of this integration. It has been shown that the combination of BW treatment with torrefied biomass production can result in cost savings by reducing the need for freshwater and nutrients while simultaneously generating revenue from the sale of torrefied biomass. Integrating BW treatment with torrefied biomass production resulted in a 40% reduction in freshwater usage and a 30% reduction in nutrient requirements compared to traditional biomass production methods. The combination of these two processes resulted in a significant decrease in operating costs and increased revenue due to the sale of torrefied biomass [72]. The combination of these two processes not only provides an efficient and cost-effective method for treating wastewater but also allows for the production of valuable biofuels and other valuable products. This integrated approach has the potential to significantly reduce overall costs, with one study reporting decreases in algal biomass production expenses of 90% and unit energy costs of 20–25% upon usage of wastewater [102].

The research by Doddapaneni et al. (2018) [72] investigated benefits associated with the combination of torrefaction with AD. The researchers presented a case study on the Kristianstad biogas plant in Sweden. This plant has a biogas production capacity of approximately 2.9 million cubic meters per year. It has a digester volume of 8500 cubic meters and can process 75,000 tons of various types of waste, including organic waste from municipal solid waste, industrial organic waste, and manure. The plant also generates electrical energy, producing 1.8–2 megawatts [14,72]. Another plant situated in Werlte, Germany, was claimed to have an installed capacity for electrical energy production of 2.6 MW, together with a digester volume of 6400 m^3. The current plant case study, situated in Werlte, Germany, has the capacity to process 35,640 metric tons per year of torrefaction condensate. It has a digester volume of 7826 cubic meters and can produce 3.04 million cubic meters per year of biomethane and 1.73 megawatts of electrical energy [72].

According to Doddapaneni et al. (2018) [72], it would be better to condense the torrefaction volatiles and produce torrefaction condensate instead of burning them to make heat energy. This approach, although increasing the total capital investment by approximately 8 million euros and the raw material cost by 0.87 million euros, would result in optimal resource recovery and financial gains. However, additional income from alternative products like bio-methane, electricity, and thermal energy offsets this shortfall. An important benefit of combining torrefaction with AD is the potential reduction in the selling price of torrefied biomass pellets. This is as a result of the integrated techniques' relatively higher net revenue generation when compared to a standalone torrefaction process. As an illustration, the lowest price at which standalone torrefaction may be sold to cover costs and achieve a 10% return on investment is 199 EUR/t. Doddapaneni et al. (2018) performed an investigation and found that at a production rate of 10 t/h of torrefied biomass pellets, the bio-methane production from AD was about 369 m^3/h. The economic evaluation shows that the minimum selling price of the torrefied biomass to reach breakeven could be reduced from 199 EUR/t for standalone torrefaction to 185 EUR/t in the case of torrefaction integrated with AD.

Char enhances the levels of inorganic nutrients in AD digestate, which can then be utilized in the farming process as a soil amendment. Still, about 60% of organic substances break down during AD treatment. The digestate that is made can be broken down even more through torrefaction to make it more useful and produce more bioenergy. All of these important by-products can also be sold at a price that makes economic sense. This will make sure that there is no waste from managing biomass and BW, supporting the ideas of the circular economy. There are a lot of things that affect how profitable it is to combine torrefaction with AD of biomass or organic waste. These include the size and capabilities of the processing facility, the costs of electricity and other inputs, the costs of waste management or treatment, and the demand for the products that are made, like syngas or hydrogen, biogas or methane gas, and charcoal, which can be used in other industries [84]. Overall, torrefaction and AD can offer economic advantages when compared to conventional approaches for waste and wastewater management and energy production. The energy produced from these processes can be utilized to operate the treatment facility or sold to the power grid, generating extra income. Nevertheless, it is crucial to acknowledge that the economic feasibility of various technologies will differ based on the particular conditions and geographical position of the treatment facility.

The combination of torrefied biomass with BW also has potential environmental benefits that can contribute to the economic feasibility of biomass production. For instance, the use of BW as a fertilizer for biomass production can reduce reliance on chemical fertilizers. Chemical fertilizers are often expensive and can have negative environmental impacts such as runoff pollution. Replacing chemical fertilizers with BW as a fertilizer for biomass production can help mitigate these environmental concerns and reduce costs associated with purchasing and applying chemical fertilizers [103]. Additionally, the use of torrefied biomass can also contribute to the reduction of greenhouse gas emissions. According to research, torrefied biomass has a higher energy density, better grindability, and more uniform properties than raw biomass. This means that torrefied biomass combined with BW has the potential to produce a higher quantity of bioenergy while reducing the overall carbon footprint.

6. Torrefied Biomass with Vacuum BW Challenges and Recommendation

The utilization of BW combined with torrefied biomass presents slight challenges and abundance opportunities from technical, environmental, and economics perspectives. One of the primary technical challenges is that achieving an efficient combination of both processes might incur higher expenses for both the initial implementation and ongoing maintenance. This encompasses the expenses involved in procuring and setting up the required equipment, together with the continuous costs associated with running and upkeeping the system. Another technical challenge is the removal of tar from the gas produced during the torrefaction process. This is essential because tar can cause issues such as equipment fouling and corrosion as well as a decrease the overall efficiency of the system. Both challenges can be reasonably controlled. The operational processes would require proper control and optimization to ensure high gas yield, low tar content, and high biomass conversion rates. In this case, the application of a two-stage torrefaction [104] or two-stage catalytic torrefaction [105] can be added where it further would enhance degradation of the tar and avert reactors pipeline blockage as well as tube and pipeline corrosions, thus causing higher gas and fuel production. The associated merits, challenges, and recommendations are briefly highlighted in Table 5.

Table 5. The merits, challenges, and recommendations regarding the tor-biomass and anaerobic digestion of blackwater.

Merits	Challenges	Recommendation	Reference
Produces tor-gas and tor-condensates	Tar generation in by-products causing equipment fouling and corrosion	Application of a two-stage torrefaction	[104]
Produces high gas and fuel amounts	Pipeline and tubes blockage	Application of a two-stage catalytic torrefaction device	[105]
High energy density can significantly decrease transport costs	Low bulk density of torrefied biomass	Pelletizing can address this challenge by increasing the bulk density	[106]
Torrefaction with AD is economically feasible	Configuration challenges, including higher maintenance requirements	Process optimization with extensive techno-economic sensitive analysis	[53]
Co-digestion of tor-biomass and VCBW will improve digestate quality and biogas yield	Possibility of AD inhibition during the integration	Co-digestion of BW-torrefied biomass will balance the COD:N ratio of BW with biomass and generate CH_4	[84]
Tor-biomass integrated with AD offers different fuel and energy products (digestates, biogas, biochar, and syngas)	Market value clarity and uncertainty exist in the integrated technology by-products (digestates, biogas, biochar, and syngas)	The energy produced from the by-products of these processes can be utilized to operate the treatment facility or be sold to the power grid, thus generating extra income	[107]

Table 5. *Cont.*

Merits	Challenges	Recommendation	Reference
Ability to immobilize some harmful materials	Challenges with concentrated heavy metals in the solid fragment	Optimization in the process of torrefaction to significantly reduce complex harmful emissions	[108,109]
	Emission of harmful products and ash-related issues	Inserting emission control device; washing pretreatment could be a promising route to reduce pollutant emissions during torrefaction and remove ash in torrefied biomass	[110]
Both torrefaction and AD as standalones and combined could produce energy by-products	Moisture and associated water content could inhibit ignition and lower energy value of by-products	Conducting torrefaction on the BW digestate downstream with other resistant items like wood, cardboard, and certain paper could yield high-calorific products	[111].

Torrefied biomass has a higher calorific value, making it a strong feedstock as biofuel [112], and its high energy density can significantly decrease transport costs [113]. However, there are challenges associated with the use of torrefied biomass. One major challenge is the low bulk density of torrefied biomass compared to raw biomass, which can make transportation and handling economically challenging [114]. Integrating torrefaction with densification processes such as pelletizing can address this challenge by increasing the bulk density and thus enhancing the efficiency of storing and transporting biomass to mix with the BW. Another challenge is the impact of torrefaction on the moisture content of the biomass. Torrefaction removes moisture from the biomass, and this reduction in moisture content can affect the palletizations process [106]. To overcome these challenges, palletizations subsequent to torrefaction has been suggested, as it improves the energy density per unit volume of torrefied woody biomass and facilitates efficient logistics throughout the value chain. Despite the integration methods and their respective merits, numerous challenges remain with such configurations, including higher maintenance requirements due to the abrasive nature of torrefied biomass, safety risks from fine-particle generation during the grinding and pelletizing of torrefied biomass, and the need for hydrophilic binders that lower the pellet heating value and compromise hydrophobicity [106].

AD has been used for various co-digestion and pre-treatment techniques to achieve energy balance and optimize biogas production. If environmental factors are not adequately monitored and balanced, inhibition is possible, and this could affect the bioprocess and hinder production of good-quality digestates and biogas. Therefore, to enhance CH_4 formation and prevent bioprocess failure and its associated inhibitions, it is crucial to take into account substrate compatibility. Co-digestion of BW-torrefied biomass is believed to be a potential solution for balancing the COD:N ratio of BW with the biomass and generating CH_4. This process is similar to the co-digestion of BW and food waste biomass [84]. The digestates produced by the AD include organic matter and nutrients, making them suitable for use as stable agricultural products [103]. Hence, investigations are underway to explore alternate methods of assessing the value of digestate apart from its use on land. One possible option is to utilize digestate liquor as a substitute for freshwater and fertilizers in the process of cultivating algae [84]. Bioethanol combustion, hydrothermal carbonization, and pyrolysis are several biological or thermal methods employed to convert solid digestate into energy. The solid digestate can be converted into valuable products such as char or activated carbons using a pyrolysis or torrefaction method. Under comparable conditions, digestates derived from BW and other biomass materials can be repurposed and transformed into valuable commodities or resource materials. Conducting torrefaction on the BW digestate at the downstream with other resistant items like wood, cardboard, and certain paper could yield high-calorific products [111].

One of the environmental challenges associated with combining BW with torrefied biomass is the potential release of harmful emissions during the torrefaction process.

These emissions are carefully regulated due to their potential environmental and health impacts by integrating emission-control devices into the torrefaction process [110]. Another environmental challenge is the proper disposal of the residual ash generated during the torrefaction process. This ash may contain trace amounts of heavy metals or other pollutants that need to be handled and disposed of in an environmentally responsible manner. Several strategies can be implemented to effectively control emissions in the torrefaction process of biomass with BW. Optimization in the process of torrefaction can significantly reduce complex harmful emissions, concentrating heavy metals in the solid fragment to avoid environmental harm and thereby limiting their release into the environment [108,109]. In addition, one of the key economic advantages of combining torrefied biomass with BW is the reduction in the cost of chemical fertilizers. By using BW as a fertilizer for biomass production, the need for expensive chemical fertilizers is reduced, resulting in cost savings. Additionally, torrefied biomass pellets have a higher volumetric energy density than those made from untreated biomass [115].

One additional economic obstacle is the lack of clarity regarding the market demand and pricing of items produced by the torrefaction and AD method, such as digestates, biogas, biochar, and syngas. However, torrefaction operates at a higher temperature compared to AD, making the combination of the two methods expensive and energy-intensive. Nevertheless, the high quality of the energy by-products generated during operations can offset the cost. The energy produced from these processes can be utilized to operate the treatment facility or be sold to the power grid, thus generating extra income [107]. Furthermore, the by-products of torrefaction, both in solid and liquid form, can undergo additional treatment to yield high-value products such as biochar. This biochar can then be commercially marketed as an inorganic fertilizer or a substance that improves the quality of soil. Nevertheless, it is crucial to acknowledge that the economic feasibility of various technologies will differ based on the particular conditions and geographical position of the treatment facility.

7. Conclusions

This review examines the effects of using torrefaction by-product (tor-biochar) as an additive in the BW AD process and the economic significance of the integration. The by-products generated during the torrefaction process possess significant and promising capabilities to adsorb both organic and inorganic contaminants, which could potentially disrupt the formation of bio-methane in the AD of the BW. The by-products derived from AD have significant potential applications as a substitute for freshwater in the form of digestate liquor as well as biofertilizers and bioenergy. This review emphasizes that both technologies are operated at high temperatures, resulting in a costly and energy-intensive combination (torrefaction and AD). However, the superior quality of the energy by-products produced during the combined activities can compensate for the expense. The energy generated from these processes can be used to run the treatment plant or sold to the power grid, resulting in additional revenue. The combined technical routes have the potential to effectively utilize tor-biomass char and BW for maximum resource recovery and sustainable development in real-life situations. Nevertheless, a thorough examination of the techno-economic aspects requires additional investigation.

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