Review

Solar Thermal Technologies for Biofuel Production: Recent Advances and Future Prospectus

Amit Kumar Sharma [1,2]

[1] Department of Chemistry, Applied Sciences Cluster, School of Advance Engineering, University of Petroleum and Energy Studies (UPES) University, Dehradun 24806, India; amitsharma@ddn.upes.ac.in or amit.orgchemistry@gmail.com

[2] Centre for Alternate Energy Research, R & D University of Petroleum and Energy Studies (UPES) University, Dehradun 24806, India

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Abstract: Solar thermal biomass conversion technologies are gaining significant interest due to their cost-effectiveness and eco-friendly nature. In these systems, solar thermal heating replaces the traditional electrical heating source as the reactor, as used in conventional thermal technologies. This approach generates higher-calorific-value products with reduced CO_2 emissions compared to standard thermal methods, effectively capturing intermittent solar energy and storing it in the form of solar fuels. This review discussess the integration of solar energy with conventional bioenergy production methods through thermal processes, including torrefaction, pyrolysis, gasification, and hydrothermal liquefaction. Recent advancements have highlighted the effective use of solar collectors, including Scheffler dishes, heliostats, and Fresnel lenses, in solar thermal bioconversion applications. Therefore, we comprehensively describe the advances in solar thermal biomass conversion technologies. The design and operational parameters for efficient solar thermal technologies are also discussed. Furthermore, the challenges and future prospectus of these technologies has are summarized. In conclusion, this review shows that the production of biofuels from various carboneous biomasses through solar thermal technologies represents a sustainable option for various energy applications.

Keywords: solar thermal energy; pyrolysis; gasification; torrefaction; hydrothermal liquefaction; catalyst; Bio-oil; sustainability

1. Introduction

The rapid growth of the global population, rising living standards, and continuous expansion of the automobile industry have increased the demand for energy. Climate change remains a critical global issue, necessitating a shift towards clean energy sources. Biomass is widely recognized as a promising clean and ecofriendly energy source for mitigating greenhouse gas emissions, with significant potential to address environmental and economic challenges affecting the modern society [1,2]. Agricultural waste, municipal waste, forest waste and aquatic waste are some common examples of biomass that is utilized for biofuel production [3]. Fermentation, transesterification, and anaerobic digestion are the common techniques used to extract biofuel from biomass. Among them, thermal technologies are considered superior to biochemical technologies (fermentation, transesterification) [4] because biochemical approaches require a specific part of biomass (e.g., lipid for biodiesel, carbohydrate for ethanol) while thermal technologies utilize the whole biomass. However, these processes are highly energy-intensive, requiring significant heat input typically supplied by non-renewable energy sources. However, being an endothermic reaction, it consumes high energy which is a major drawback of thermal biomass conversion technologies. In conventional processes, the required heat is supplied by electric energy which increases the production cost and environmental damage due to reliance on fossil fuels. To address this limitation, a number of strategies have been proposed to generate the heat through renewable sources including wind energy, solar photovoltaic and solar thermal energy. In recent years, the integration of solar thermal energy with biomass conversion technologies has yielded promising results [5]. This approach not only improves sustainability but also enhances the overall viability of biomass as a renewable energy solution [6]. Solar energy can be harnessed and stored as chemical energy or fuels, known as solar fuels, for later use and convenient transportation. Integrating solar energy into biomass conversion via thermochemical processes is anticipated to greatly improve the overall efficiency and sustainability of the biofuel production cycle [7]. A major advantage of integrating solar thermal technologies in biofuel production is its ability to reduce CO_2 emissions. Joardder el al. reported that solar thermal technologies can reduce CO_2 emissions by about 32.4% and fuel costs by nearly one-third [8]. Recent advancements indicate that Scheffler dishes, heliostats, and Fresnel lenses are applicable in solar thermal biomass conversion technology [9]. Furthermore, various biomasses, including Jatropha seeds, Beechwood, date seeds, agricultural and forestry residues, were investigated for their use in the thermochemical biomass conversion process [10]. However, several technological barriers exist in the implementation of solar pyrolysis. These include the initial costs of setting up solar collection systems, the efficiency of solar-to-thermal energy conversion, and the consistency of solar energy availability. Addressing these challenges requires advanced solar collector technology solutions, improvements in thermal energy storage, and the development of more efficient reactor designs.

Hence, in this study, we reviewed advances in the development of solar thermal biomass conversion technologies to enhance biomass utilization and conversion processes. It also summarizes the potential of solar-assisted thermochemical conversion methods, highlighting various solar concentrating technologies capable of harnessing solar heat to drive these processes efficiently. Additionally, the research examines factors influencing solar thermal biomass conversion technologies. By synthesizing existing knowledge and recent advancements in solar thermal applications for biomass conversion, this paper aims to provide insights for enhancing energy efficiency, reducing environmental impact, and advancing sustainable practices in biomass utilization.

2. Potential of Solar Thermal Biomass Conversion Technologies

Biomass is considered a cost-effective, ecofriendly and clean source of energy and contributes to the global carbon cycle. The annual production of biomass is estimated at approx. 181.5 billion tons. Currently, around 0.2% of the world's total land area (about 25 million hectares) is used for growing bioenergy feed stocks [6]. This ample availability of biomass makes it a viable option for the production of biofuels and bio-chemicals, which can potentially replace fossil-based counterparts. A variety of technologies, including physical, thermal, chemical, and biological ones, can transform biomass into gas or liquid fuels. Thermochemical conversion techniques such hydrothermal carbonization, pyrolysis, and gasification are frequently employed [11–14]. Such techniques rely on processes that are based on the type of feedstock, the oxidation environment (partial or anaerobic), and the final product (gas, liquid, or solid). Integrated renewable energy systems offer several advantages over single-resource-based systems, including increased energy storage capacity, reduced biofuel production costs, improved biofuel quality, and enhanced overall energy conversion efficiency [15,16]. One promising approach is the integration of solar energy with biomass conversion technologies. Incorporation of solar thermal energy in these processes will reduce the reliance on fossil fuels and greenhouse gas emissions significantly. Additionally, thermal energy storage solutions ensure a continuous and stable heat supply, mitigating the intermittency of solar radiation and improving system reliability. This integration presents a promising pathway towards sustainable energy production and a circular bio-economy.

3. Green Energy Solar Thermal Technologies for Biomass Conversion

Solar thermal biomass conversion technologies provide an efficient and sustainable route to transform biomass into liquid, solid or gaseous fuels with reducing dependency on fossil fuel and mitigating greenhouse gas emissions. Concentrated solar energy is commonly used to generate the heat required for biomass conversion, which improves the overall process efficiency and reduces carbon emissions. Some common examples of solar thermal technologies include are solar thermal pyrolysis, Solar gasification, solar hydrothermal liquefaction and solar assisted torrefaction (Figure 1).

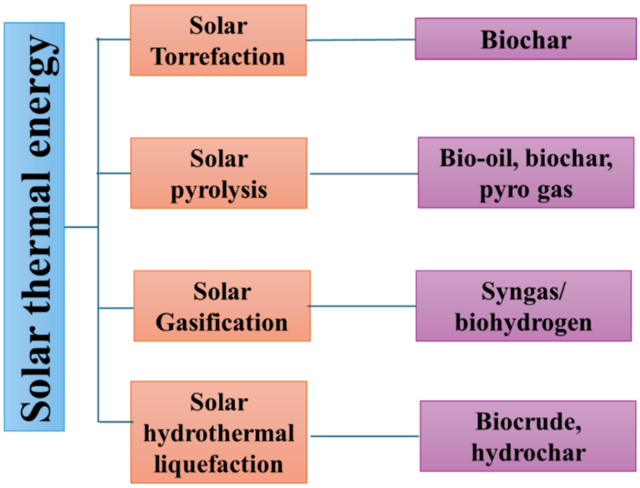

Figure 1. Classification of solar thermal biomass conversion technologies.

3.1. Solar Thermal Pyrolysis

Solar thermal pyrolysis is an innovative and clean technology that is increasingly being investigated for its potential to transform biomass into bio-oil, pyrogas and biochar. Unlike conventional pyrolysis, where heat is typically supplied by electric heaters or external burning of fuels, solar pyrolysis utilizes concentrated solar radiation to heat the reactor [5,16]. This process involves the thermal decomposition of biomass in an inert environment, without the presence of an oxidizing agent, leading to a series of complex exothermic and endothermic reactions [17]. Different types of solar concentrator are shown in Figure 2 and 3.

Initially, feedstocks are preheated or dried to temperatures between 100–200 °C, causing the release of water vapor, CO and CO as molecular bonds begin to break. The primary stage of pyrolysis, occurring around 250–500 °C, involves exothermic reactions where organic matter breaks down into smaller fractions. As temperatures increase to 500–700 °C, heavier compounds convert into gaseous products, and further breakdown into secondary products occurs through endothermic reactions [18,19].

The theoretical representation of the pyrolysis reaction can be described as:

$$\mathbf{C_xH_yO_z \xrightarrow{\text{Solar energy}} \Sigma C_aH_bO_c\ (liquid) + \Sigma C_dH_eO_f\ (gas) + C_gH_hO_i\ (char) + C(char)} \tag{1}$$

Numerous studies have investigated the potential of solar thermal biomass pyrolysis technologies. For instance, Chintala et al. used solar schefflor concentrator to perform pyrolysis of jatropha seeds [5]. Similarly, Wu et al. conducted pyrolysis of mallee wood powders using solar assisted pyrex reactor at varying temperature and reaction time [20]. Xie et al. performed the solar assisted pyrolysis of cotton stalk in molten salt reactor heated with solar energy and obtained up to 29% bio-oil [21]. Zheng et al. performed solar assisted pyrolysis of beech wood and observed that solar thermal pyrolysis increased biomass energy by up to 38–53% [22]. Uzakov and Almardanov examined the solar thermal pyrolysis feasibility of sunflower waste using heliopyrolysis plant which was heated using a parabolic solar energy concentrator. The results showed that 1 kg of pyrolysis gave rise to 10% of liquid 63% of biochar, and 27% of gaseous biofuels [23]. There will be less biochar formed if biomass is efficiently converted by thermochemical processes. Previous studies have shown that the char yield considerably reduces with increasing reaction temperature while the yield of bio-oil increases. A decrease in char yield as temperature rises may be brought on by either a higher rate of primary biomass breakdown at higher temperatures or a secondary breakdown of the char residue.

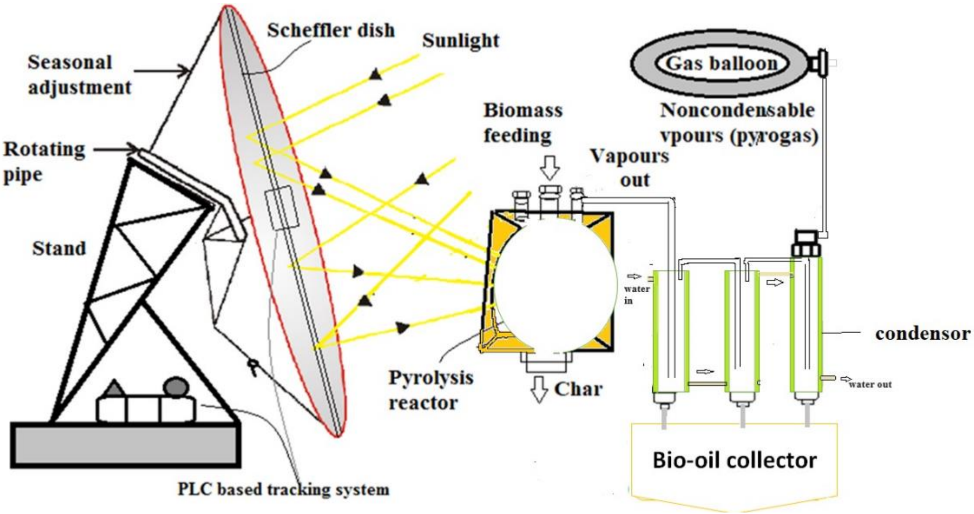

Figure 2. Solar thermal biomass pyrolysis reactor.

3.2. Solar Gasification

To boost efficiency, a technique called solar thermal gasification of biomass is emerging as most promising technique. To supply the required process heat, at least 30% of the initial feedstock is usually burnt in conventional autothermal gasification reactors while solar gasification harnesses solar energy to heat biomass using solar concentrators [24]. This method avoids the contamination of syngas with combustion byproducts, lowers CO_2 and pollutant emissions, and may even result in lower downstream syngas post-processing costs [25]. For powering any high-temperature solar thermochemical process, solar infrastructures like parabolic dishes and solar towers are perfect since they can concentrate solar irradiation over 1000 suns (1 Sun = 1 $kW \cdot m^{-2}$). The reaction heat generated from concentrated solar radiation can be used to transform carbonaceous materials into high-grade syngas, which can then be further processed to create valuable hydrocarbon fuels [28]. The reaction involved is shown below as Equation (2).

$$\mathbf{C_xH_yO_z + (x - z)H_2O + Solar\ energy \rightarrow (y/2 + x - z)H_2 + xCO + C_aH_bO_c} \tag{2}$$

The mechanism of solar thermal gasification can be explained in three steps: The first is pyrolysis, where the thermal breakdown of biomass takes place into chars, tars, and incondensable gases. It usually takes place between 300 and 1000 °C. After pyrolysis, char is injected with an oxidizing agent in the second step of the highly endothermic gasification process, where it functions as a reactant. A third stage includes various gas phase processes as the reforming and Boudouard reactions [27].

Few studies have explored the solar thermal gasification. Ravaghi-Ardebili et al. constructed a solar gasifier for investigating how the performance of gasification was affected by the volumes of injected steam and oxygen, solid fuel and gas-phase residence times, among other factors [28]. The thermodynamics and financial viability of a cogeneration system that coupled solar energy with biomass gasification to produce methanol and electricity were also examined by Bai et al. [29] on the other hand, Zhong et al. performed a 3E analysis of a solar gasification-based biomass-to-liquids production system in order to determine the system's productivity and net efficiency [30]. At the University of Colorado Boulder and Sundrop Fuels, a pilot-scale solar biomass gasification project was demonstrated [31], utilizing tubular solar reactors that can operate at 1 MW at temperatures between 1473 and 1573 K. With this configuration, sunlight-to-hydrogen conversion efficiency for wood waste exceeded 13%.

The production of a range of environmentally beneficial, steady, and continuous resources under certain operating conditions is a confirmed capability of hybrid solar-biomass systems. However, the research on the economic analysis of cogeneration that focuses solely on the production of heat and electricity has been scanty.

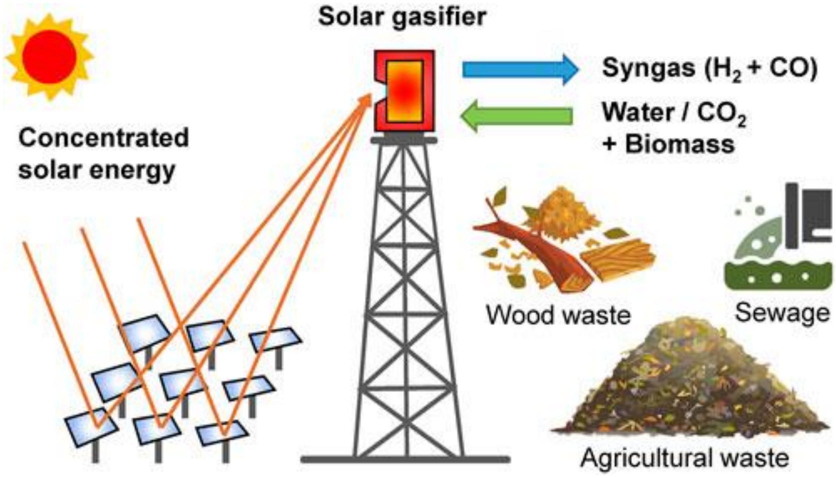

Figure 3. Solar thermal biomass gasification process [28].

3.3. Solar Assisted Hydrothermal Liquefaction

Hydrothermal processes (HTPs) offer a viable way to produce value products from biomass that has a high water content (over 20 wt.%) [32]. Various wet biomass feedstocks, such as algae, agricultural, forest, and food processing leftovers, can be effectively converted into four primary products using hydrothermal liquefaction (HTL): hydrochar, biocrude oil, aqueous phase, and gaseous phase [33]. One major obstacle to HTL is the energy needed to heat the reactants, which are a mixture of biomass and water. This is often accomplished by burning some of the bio-oil output.

Solar-integrated hydrothermal processes are emerging as highly promising technologies as more cost-effective and environmentally friendly. The necessary external heat for the reaction can be supplied by solar energy, thereby enhancing efficiency and reducing CO_2 emissions. [34]. Depending on the solar concentrator, Concentrating Solar Technology (CST) can reach high temperatures and heating rates of between 200 and 3000 °C and 5 to 450 °C/s. Because of these characteristics, CST is a good fit for integrating with hydrothermal processes, which will increase biomass conversion's overall sustainability and efficiency. For example, Tsongidis et al. studied the solar hydrothermal liquefaction (HTL) of food waste, dairy waste, and peach stones during a 30-min period at temperatures between 300 and 350 °C and pressures ranging from 1 to 20 bar [35]. The results showed that maximum bio-oil recovery was 22 wt.% in case of dairy waste when dichloromethane was used as a solvent. Similarly, Cortés et al. demonstrated that solar HTL of agave bagasse at 300 °C produced up to 28% biocrude yield [36]. In addition to this, Giaconia et al. conducted a techno-economic analysis of a hypothetical solar-driven hydrothermal plant, which combines a hydrothermal liquefaction installation with a solar parabolic trough to process 10 kton of biomass annually using microalga [37]. The ultimate selling of bio-oil is very marginally impacted by CST technology, despite the fact that it requires significant capital expenditures—roughly 47% of the plant's capital costs are allocated to the construction and installation of the concentrating solar system.

3.4. Solar Assisted Torrefaction

Torrefaction is a type of thermal treatment that is carried out in anaerobic circumstances (without oxygen) at temperatures usually between 200 and 300 °C. Through thermal conversion, biomass will become more stable, hydrophobic, and energy-dense [38]. This material can then be utilized as a solid biofuel or as a starting point for other conversion processes such as gasification or pyrolysis. Solar assisted torrefaction is similar to solar pyrolysis i.e., the required heat for the reaction process is supplied trough solar thermal energy. The mechanism of solar torrification can be understand as follows: When concentrated solar heat is applied to a reactor, hemicelluloses, cellulose, and lignin break down at various temperature stages. Biomass begins to break down when temperatures rise to between 150 and 200 °C due to dryness and the removal of light volatiles. Then, hemicellulose degrades via a number of processes, such as deacetylation and depolymerization. Deacetylation yields acetic acid, which catalyzes condensation and the breakdown of lignin as well as the following depolymerization of low-order polysaccharides. The amorphous phase of cellulose starts to break down at 200°C, increasing the biomass's relative crystallinity, whereas the crystalline phase of cellulose starts to break down and depolymerizes at 270 °C [39, 40].

$$\mathbf{C_xH_yO_z + Solar\ heat \rightarrow char + CO + CO_2 + H_2O + vapors} \quad (3)$$

Alejandro et al. conducted research on Ashe Juniper biomass waste using a solar-driven torrefaction reactor [38]. In their study, 210 °C was the ideal temperature for torrefaction to produce an energy yield of over 90%, and 360 °C produced the highest energy densification. Cellatoğlu and Ilkan used concentrated solar energy from a parabolic dish concentrator to torrefy solid olive mill residue for 10 min at 250 °C [41]. They discovered that the qualities of the products from solar torrefaction are comparable to those obtained from conventional torrefaction. A lignin-rich residue was subjected to solar-driven torrefaction by Tregambi et al. [35]. The findings demonstrated that when direct solar radiation was used instead of non-solar heating, the degree of torrefaction was pronounced. The solar-driven torrefaction of biomass was first studied in these earlier works. However, more thorough research on solar-driven torrefaction is needed because there are numerous variables, including temperature, biomass species, and treatment duration, that affect the quality of biomass torrefaction [42]. For instance, the correlation between the torrefaction severity index and biomass conversion (decarbonization, dehydrogenation, and deoxygenation).

Table 1. Solar thermal biomass conversion technologies.

S.no.	Biomass	Thermos-Chemical Process	Solar Concentrator Used	Types of Reactors	Reaction Conditions	Results	References
1	Beech wood	Solar thermal pyrolysis	Solar dish		T = 600–2000 °C, Heating rate = 5–450 °C/s	Bio-oil=8%, biochar= 10%, and pyro gases = 62% (H_2, CH_4, CO, CO_2 and C_2H_6)	[43]
2	Jatropha seeds	Solar thermal pyrolysis	Solar Scheffler	Fixed bed	T = 250 °C to 320 °C	Bio-oil = 12%	[5]
3	waste wood	Solar thermal pyrolysis	parabolic trough collector	Fixed bed	solar irradiance = 918 W/m^2,	Bio-oil = 44.58%	[44]
4	waste wood (WW), waste straw (WS), sewage sludge (SS)	Solar thermal pyrolysis	Artificial concentrator of xenon lamp	Fixed bed	WS = 4.51, 5.32, and 5.49 K/min WW = 5.10, 5.19, and 5.37 K/min SS = 3.95, 4.48, and 5.25 K/min	Bio-oil-WW = 69.23 wt%, WS = 62.3 wt%, and ss = 51.68 wt%	[45]
5	Sunflower waste	Heliopyrolysis	Parabolic solar	Heliopyrolysis plant	T = 400–500°C	Biochar=63% Bio-oil=10%, pyrogases=27%	[25]
6	Sewage sludge	Solar steam gasification	Solar concentrator	fluidized-bed	Solar irradiances of 500–1000 W/m^2	H_2 = 61.2–67.6 g/kg(sludge)	[46]
7	Palm waste	Solar gasification	Solar concentrator	directly-irradiated particle-fed solar reactor	T = 1100–1300 °C	Syngas = 81.1 mmol/$g_{\text{dry biomass}}$	[47]
8	Agave bagasse	Solar hydrothermal	Heliostat type concentrator	SS cylindrical	T = 300 °C,	Bio-oil=28% Biochar=29%	[48]
9	Biomass	Solar hydrothermal Gasification	parabolic reflector	cylindrical cavity-type solar receiver reactor	T = 500–650 °C	H_2 = 10–26 mol/kg	[49]
10	Wood biomass	Solar torrefaction	solar dish	Tubular reactor	T = 210 °C	energy densification ~1.51	[50]
11	cotton stalk	Solar torrefaction + pyrolysis	Torrefaction-Fresnel lens Pyrolysis-parabolic-dish	parabolic-dish solar pyrolysis reactor	T = 200–500 °C, Catalyst = HZSM-5	Bio-oil = 36.9%	[51]

4. Factor Affecting Solar Thermal Technologies for Biomass Conversion

Solar thermal technologies may play a crucial to reduce greenhouse emission and make process more sustainable and greener. There are several factors like solar concentrator, reactor design, types of biomasses, and catalyst which influence the final product yield and quality.

4.1. Solar Concentrator

Solar concentrators are instrumental devices designed to concentrate incident solar energy from a large surface area onto a smaller surface, thereby enhancing energy density and temperature. These technologies can capture solar energy for biomass-to-biofuel conversion processes such as pyrolysis, gasification, and hydrothermal liquefaction (HTL) [25].

Several types of solar concentrators are available, each with unique characteristics influencing their suitability for various biofuel production applications. These include parabolic troughs, parabolic dishes, compound parabolic concentrators, flat plates, heliostat fields, box-type concentrators, linear Fresnel reflectors and lenses [29,52,53]. Each concentrator type differs in design, focal point precision, reflective materials, operational features, and application suitability [54]. These distinctions influence their effectiveness in harnessing solar energy for efficient biomass conversion into biofuels, reflecting ongoing advancements in renewable energy technologies.

Each solar concentrator technology offers unique advantages and limitations based on its achievable temperature, focal type, reflective material, operation characteristics, design, and application. For biofuel production, selecting the appropriate solar concentrator is crucial. It generally depends on environmental conditions. Therefore, solar concentrators should be chosen or developed to effectively concentrate solar energy keeping in mind concentrator's orientation and tilt as well as environmental elements including climate, altitude, and geographic location. The system's performance and efficiency can be enhanced by carefully adjusting for the local solar irradiation. This can be accomplished by choosing the ideal concentrator type to meet the site's predicted solar radiation levels based on data and model analysis. Furthermore, to guarantee that the reactor receives the maximum amount of solar radiation, the concentrator's tracking system needs to be built to precisely track the sun as it moves across the sky. It is important to thoroughly assess the tracking mechanism's accuracy while taking the concentrator type and local solar irradiance circumstances into account. Another crucial factor to consider is the duration the reactor will last. The materials that were used to build this component ought to be resilient to challenging environmental factors, such as exposure to the elements and high temperatures. This is necessary to provide a long operating lifespan and low maintenance expenses for the system.

High-temperature processes like gasification and advanced pyrolysis benefit from high-efficiency, high-temperature concentrators such as parabolic dishes and heliostat fields [25,26]. Moderate temperature processes like conventional pyrolysis can utilize parabolic troughs and linear Fresnel reflectors, while low-temperature applications have limited suitability and are typically not aligned with the demands of biomass to biofuel conversion [8,41,54,58].

Table 2. Types of solar concentrator and their suitability for biomass conversion technologies [5,6,9,15,21,25,26,34,36,41,50].

Types of Concentrator	Operating Temperature (°C)	Focal Type	Reflective Material	Operation Characteristics	Technologies Suitability
Parabolic Trough Collectors (PTCs)	Up to 400	linear	Glass mirrors or reflective aluminum	Moderate complexity, suitable for continuous operation with thermal storage options	Used in medium to high-temperature processes like pyrolysis and low to moderate temperature gasification; less suitable for HTL due to lower temperature limits.
Heliostat Fields (Solar Power Towers):	Up to 1500 °C	Point	Flat mirrors	High complexity, capable of achieving very high temperatures, suitable for large-scale operations	Ideal for high-temperature gasification and advanced pyrolysis; less practical for HTL due to the requirement for high pressure and temperature control.
Linear Fresnel reflectors	Up to 450 °C	Linear	Flat or slightly curved mirrors	Simpler and cost-effective, easier maintenance	Suitable for medium temperature processes like conventional pyrolysis and lower-temperature gasification; limited by temperature range for HTL
Parabolic dish	Up to 1000 °C	Point	Parabolic mirrors	High efficiency, suitable for small-scale applications	Excellent for high-temperature gasification and pyrolysis; not commonly used for HTL due to temperature and pressure control challenges.
Compound Parabolic Concentrators (CPCs)	Moderate (200–300 °C)	Linear or point	Reflective aluminum or glass	Non-imaging concentrators, relatively simple design	Suitable for low to moderate-temperature applications; limited for high-temperature biomass

	conversion processes like Tore faction

4.2. Reactor Design

Reactor design is most crucial factor to enhance the efficiency of solar thermal biomass conversion technologies. Types of biomasses, final product quality, reaction parameter like temperature and pressure, reactor material, and integration technique of heat with reactor are some parameters which should be keep in mind during design of reactor. The feedstock is kept inside the reactor and heated with the help of solar concentrator directly or indirectly. During direct heating, the front surface of the reactor where concentrate solar irradiation falls, is generally made of fused quartz or borosilicate glass facilitating effective energy transfer to the reaction site through direct radiation. The solar reactor walls in the directly heated reactor must always be clean to allow the focused rays to reach the feedstock (Figure 4). For indirect heating, first heat is absorbed in a reactor using suitable heat absorbed material and then transferred to reaction site through heat transfer fluid.

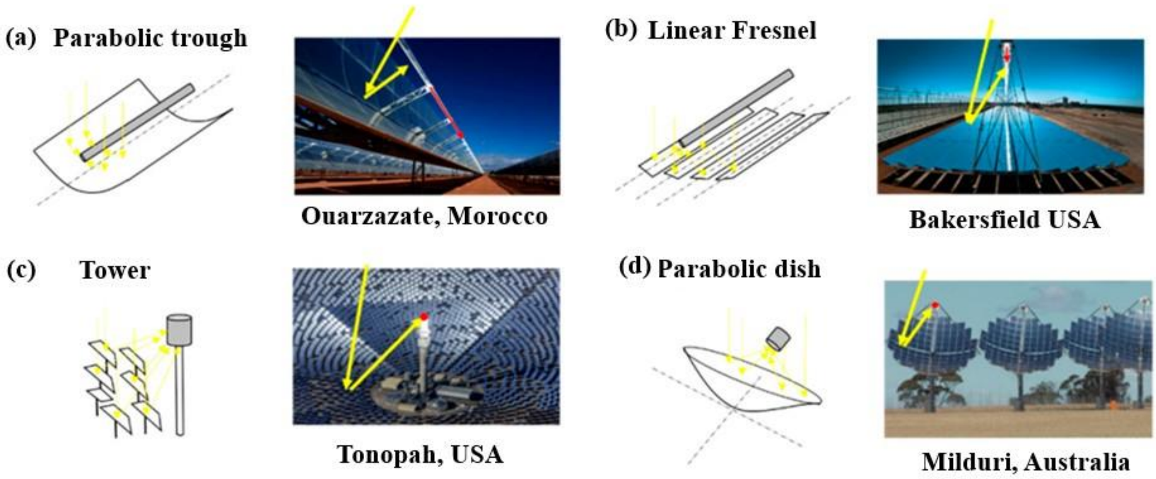

Figure 4. Different types of solar collectors [56].

Fixed bed reactors, augers reactors, and fluidized bed reactors were mostly used by scientists for solar thermal pyrolysis and torrefaction of biomass depending upon reaction temperature, product distribution and heat transfer efficiency [9,20,39,54]. These reactions generally occur 200–500 °C in the absence of oxygen. On the other hand, gasification takes place at higher temperature i.e., more than 700 °C and the gasification reactors must be able to withstand these temperature conditions. They also usually have a gas-solid mixing mechanism to maximize the conversion of biomass into syngas. Fixed bed, entrained flow, circulating fluidized bed, and bubbling fluidized bed are some popular reactor designs used by researchers [24,25,26,57]. Fixed bed reactors are simple in design, energy efficient and suitable for small-scale gasification. However, they often exhibit lower efficiency and higher tar content due to temperature gradient and mass transfer limitations [58]. On the other hand, fluidized bed reactors result into better heat and mass transfer, leading to higher gasification efficiency and better quality of producer gas with lower tar content. However, they are complex and requires higher operational cost due to the need for precise control of fluidization conditions [61,63]. Furthermore, the entrained flow gasifiers are considered for large-scale applications as they operate at high temperatures. High temperature promotes low tar content and better cracking [57]. To gasify maize stover and sorghum entrained with steam passing through the tubes with high residence times, experiments were conducted in a five-tube solar gasifier [59]. Using a high-flux solar furnace for on-sun testing, the average conversion rate from solar inputs to gaseous outputs (namely CO and H_2) was 53.9% for sorghum and 62.8% for corn stover.

Gasifying medium such as air, oxygen, steam and carbon dioxide used in gasification strongly influence the yield and quality of producer/syngas [60]. Air is the mostly used gasifying agent, however it lowers the calorific value due to higher nitrogen content. Oxygen increases the generation of more CO and H_2. Steam promotes the water-gas shift reaction, increasing H_2 production in the gas. The gas yield is high in hydrogen, but the process requires more energy due to the endothermic nature of steam reactions, making it more suitable for high-value hydrogen or syngas production [61]. CO_2 can be used to enhance the gasification of carbon-rich materials through the Boudouard reaction, which can improve CO content in the producer gas [26]. However, this agent is less commonly used due to additional CO_2 costs and lower efficiency.

Hydrothermal liquefaction is high-pressure biomass conversion technology and generally takes place at 200–300 °C and 5–20 MPa pressure. The designs of HTL reactors need to provide effective mass and heat transmission while preserving material integrity in the face of extreme pressure and corrosive environments [39]. Because of their versatility in terms of size and functionality, continuous stirred-tank reactors (CSTRs) and tubular reactors are commonly utilized [34,36,37]. By supplying the necessary process heat with solar thermal devices, advanced reactor designs can be made more energy-efficient and sustainable. Integrating efficient thermal storage technology provides a steady and reliable heat source, mitigating the unpredictability of solar radiation.

Reactor performance can be further optimized by integrating suitable heat exchangers, catalyst beds, and novel materials, resulting in higher yields and higher-quality biofuels.

4.3. Types of Biomass

The product quality and yield are also strongly dependent on types of biomasses used for biofuel production via solar thermal biomass conversion route. The physico-chemical properties like moisture content, cellulose, hemicellulose and lignin composition along with carbon content highly influence solid, liquid of gaseous fuel quality as well as process efficiency [62]. Dry biomass (e.g., forest and agriculture residue) are most suitable for torrefaction, pyrolysis or gasification process depending upon fuel type requirement (bio-coal, bio-oil or syngas) [9,27,39] while wet biomass e.g., fruit and vegetable waste, sewage sludge, algae other aquatic biomass waste is considered suitable for HTL process [38,40].

However, the conversion process is more complex when dealing with different types of biomasses, like mixed trash and municipal solid waste (MSW). Variations in the composition, pollutants, and irregular physical characteristics can create quality fluctuations in biofuel and pose problems for operations. Optimizing conversion efficiency requires efficient sorting and preprocessing of MSW.

The biomass type used in solar thermal conversion systems directly influences the reactor's design, operation, temperature profiles, drying needs, and heat integration techniques, among other factors. To optimize biofuel output, quality, and overall process efficiency, the best biomass and solar thermal conversion method are coupled.

4.4. Catalyst

Catalyst can play a major role to improve the process efficiency of solar thermal biomass conversion technologies. Catalyst allows chemical reaction to happen at lower temperature by reducing the activation energy, thus require less solar energy to create suitable chemical reaction and improve overall sustainability and economy of the process [63]. Additionally, consistent reaction conditions are supported by catalysts, which stabilize the thermal profile and increase the dependability of solar-powered biomass conversion systems. In addition to this, catalysts also improve the final product quality and yield, however, complex composition of biomass makes it difficult to selection of suitable catalyst in different thermos-chemical conversion. For example, the catalyst like metal oxides, zeolites, ZSM and activated carbon highly influenced product distribution and quality of the product [54,64,39]. This reduces unwanted byproducts like tar while increasing the production of useful hydrocarbons. Catalysts, such as nickel-based compounds, expedite the gasification process by converting biomass into syngas and increasing the hydrogen-to-carbon ratio [27,65].

Additionally, hydrothermal liquefaction (HTL) reactions, which involve high temperatures and pressures, require catalysts to transform complex biomass molecules into simpler, energy-dense liquid fuels. Homogeneous acids and transition metal sulfides are examples of catalysts that enhance the efficiency of HTL by accelerating hydrolysis, depolymerization, and subsequent upgrading processes [32,34,66].

5. Perspectives and Challenges in Solar Thermal Biomass Conversion Technologies

5.1. Perspectives

Solar thermal technologies have significant potential to solve the global energy challenges because they provide a reliable and efficient way of producing energy. These technologies harness the abundant and renewable energy available from sun to produce heat, which can either be used directly or converted into fuel or power. The following summarizes the different perspectives on solar thermal technologies:

(1) Integration of thermochemical technologies with solar energy: Solar thermal biomass conversion technologies provide a sustainable and ecofriendly pathway for biofuel production by utilizing available abundant biomass and solar energy both [16]. This integrated process not only help to reduce dependency on fossil fuel but also decreases greenhouse gas emissions combining waste valorization.

(2) Advancement in technology: Continuous advancement in solar thermal biomass conversion technologies such as solar concentrator, thermal fluid and reactor design & material to harness maximum solar energy are the key features to improve the process efficiency and sustainability [27, 54,].
(3) Energy security: The integration of solar energy with thermos-chemical biomass conversion technologies produces a clean and renewable energy resources that can enhance energy security and helps in reduce dependency on fossil fuel [26].
(4) Environmental benefits: It involves adopting local available renewable energy resources, such as solar and biomass to create sustainable energy systems and reducing carbon emission to mitigate climate change [26,54,39].

5.2. Challenges

Solar thermal biomass conversion technologies face several significant challenges which are described below.

(1) Technical challenges: One of the major technical challenges is integration of solar energy with thermos-chemical biomass conversion technologies to improve the efficiency and performance of the process. To harness maximum solar energy and maintain reactor integrity under higher temperature requires sophisticated technology and expert.
(2) Economic challenges: The initial investment for solar thermal biomass conversion technologies is often high. Solar concentrator, sophisticated reactors design for high temperature and pressure, heat transfer technology systems are the key reason for high initial cost.
(3) Environmental and resource challenges: Widespread installation of solar thermal biomass conversion systems may result in changes to land use, increased water use, and possible conflicts with food production. To lessen these effects and ensure sustainable growth, careful planning and stakeholder involvement are essential.

6. Conclusions

This paper offers an in-depth review of solar-integrated biomass thermal conversion, focusing on the recent advancements in solar-driven torrefaction, pyrolysis, gasification, and hydrothermal liquefaction processes. It proposes a sustainable pathway for biofuel production, highlighting the significant potential of this emerging technology. In addition, various solar concentrators are analyzed, detailing their operational conditions and the range of product qualities achievable. Literature indicates that these solar-based technologies provide distinct advantages over traditional methods, including reduced reliance on fossil fuels and lower greenhouse gas emissions. The design of reactors and the selection of solar concentrators play a critical role in optimizing the efficiency and effectiveness of these processes. Advanced solar collectors and innovative reactor designs that promote uniform heat distribution can further enhance system performance. Future efforts should focus on technological innovation and providing policy support to fully harness the potential of solar-thermal biomass conversion.

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