

Review

Optimizing Solar–Biomass Pyrolysis: Innovations in Reactor Design and Thermal–Solar System Efficiency

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Abstract: To promote renewable energy sources, we focus on optimizing the design of solar–biomass pyrolysis systems. This study suggests the best reactor orientation that creates effective thermal–solar systems for pyrolysis. Solar–biomass pyrolysis uses solar energy to create valuable products like syngas, tar, and char from biomass. This process promotes energy sustainability. We analyze different solar reactors based on their design, operation, heat transfer rate, efficiency, residence time for biomass retention inside the reactor, and biomass conversion efficiency. A thorough analysis of the existing technologies helps to pinpoint the difficulties and most recent developments in the sector, making decision making more manageable and providing information on the viability and sustainability of biomass conversion technologies.

Keywords: solar–biomass pyrolysis; thermal–solar system design; reactor orientation; heat transfer efficiency; solar concentrators; reactor configuration

1. Introduction

Biomass, obtained from organic substances, including agricultural wastes, forestry byproducts, and organic waste, has historically been a fundamental component of human energy consumption. The historical importance of this resource is derived from its ease of access, ability to be replenished, and wide range of uses, which span from traditional heating to the creation of biofuels [1]. In modern times, biomass is viewed as a renewable energy source that can provide carbon-neutral energy through pyrolysis [2,3]. Pyrolysis of biomass refers to the heat degradation of biopolymers present in organic matter under inertness and the absence of oxygen [4]. Pyrolysis is a very efficient technique for extracting energy from various forms of biomass, such as agricultural and forest wastes, organic waste, and municipal garbage [5]. Pyrolysis is the thermochemical conversion of biomass to gas, solid (char), and liquid (bio-oil) at 450 °C. It occurs without an oxidant or air at a moderate temperature. The reactor's temperature, heating rate, and residence duration significantly impact the product produced during pyrolysis [6,7].

Sun-biomass pyrolysis refers to using sun energy for the thermal conversion of biomass into valuable bioenergy products [8,9]. In addition to providing an environmentally benign alternative to existing energy sources, solar energy and biomass pyrolysis address the world's growing energy demands. Research and innovation in various fields have increased in response to the rising demand for clean and renewable energy sources [10]. In this regard, combining solar energy with biomass pyrolysis has shown to be a viable method of generating biofuels and renewable energy [11]. Utilizing solar energy from the sun's limitless brightness is essential to pursuing clean and renewable energy. Photovoltaic



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cells and thermal–solar systems are examples of solar technologies that have advanced dramatically and now account for much of the world’s renewable energy capacity [12]. Solar energy is essential to pursuing a sustainable energy future as the focus on lowering carbon footprints and moving away from fossil fuels grows [13]. To generate heat, a collection of thermo-solar panels focuses and transfers solar radiation from a vast area into a smaller one [3,14]. Sun-biomass pyrolysis, the endothermic conversion of biomass in an inert atmosphere, is made possible by concentrated sun energy. The pyrolytic reactor receives direct solar insolation through a focused optical system, which converts biomass into valuable products at the desired temperature [15,16].

Combining solar and biomass technology has enormous promise for combating climate change and switching to cleaner energy sources [17]. According to Dou et al. (2023), this thorough investigation will aid solar–biomass pyrolysis researchers and engineers, and policymakers will also gain crucial help in creating sustainable, eco-friendly energy policies [18]. The emphasis is on harnessing renewable energy sources, and environmentally friendly approaches can help the world achieve its energy needs while providing an extra advantage—the ability to transform waste from agriculture and other agro-allied industries into cash. It deals with waste disposal, which occasionally endangers people’s health [19]. In addition to producing biofuel, the processes involved also yield biogas, bio-oil, and charcoal [20,21]. A combination of hydrocarbon substances consisting of carbon, oxygen, and hydrogen with trace amounts of sulfur and nitrogen is referred to as biomass, according to [22]. Depending on the biomass, these organic and inorganic elements can range from 1 to 50% [23]. Pyrolysis, or the heat reduction of these biopolymers present in biomass without oxygen, is one of the main techniques used in biomass conversion [24,25]. According to [26], biomass components are minerals, polymeric compounds, and extractives. The product yields are influenced by the presence of this component during pyrolysis. At the same time, lignin degrades to produce gas, liquid, and solid biochar products; hemicellulose and cellulose breakdown account for most of the production of liquid biofuels in pyrolysis [27]. On the other hand, biochar contains ash particles in the form of minerals, even though the extractives contribute to producing liquid and gas byproducts through volatilization or breakdown [28].

Thermal reduction is an integral part of the pyrolysis process, which takes place inside the reactor [29]. Plasma-type, fixed-bed reactors, ablative systems, auger types, kilns and drums, microwave reactors, and free-fall reactors are some of the various kinds of reactors that are accessible. These reactors come in multiple configurations and modes of operation [30]. However, the most commonly used reactor types are the fluidized bed and auger reactors, which can rapidly raise feedstock temperatures through good heat and mass transfer [31]. In conventional pyrolysis, there are different types of pyrolysis reactors: one for fast pyrolysis and another for slow pyrolysis. The temperatures at which they operate can range from 673 to 973 K [14], depending on the desired product. This process is further divided into various categories, such as Torre faction, flash, rapid, and slow pyrolysis, based on the operating temperatures. Several evaluations of biomass pyrolysis technologies that use a microwave, plasma, or fossil fuel as a heat source have been published elsewhere [32,33]. Still, there is plenty of space for reviews on solar–biomass pyrolysis, particularly those that address reactor and concentrator design configurations for best outcomes [34,35]. The research delivers its most significant value by thoroughly analyzing optimized solar–biomass pyrolysis systems. Research teams can establish efficient, sustainable conversion systems by combining solar concentrators and multiple reactor systems. Biomass reaction measurements across horizontal and vertical and inclined placements and solar concentrators improve sustainable biomass operations. The sustainable operation and efficiency of biomass processing occur by measuring biomass

reaction points when using solar concentrators at different horizontal, vertical, and inclined positions [36]. Scientists examine various strategies to eliminate solar flux uncertainty and advance research on big-scale storage systems that will lead to sustainable solar–biomass pyrolysis facilities worldwide.

The researchers have directed solar radiation onto a reactor or the material using optical tools [35]. At elevated temperatures, pyrolysis occurs without oxygen; consequently, external energy is required to reach the desired pyrolysis temperature [37]. The feedstock is directly exposed to radiation, which causes it to increase in temperature. At the same time, the reactor remains cold, or the heat from solar light is concentrated in a narrow region through the reactor walls in two ways [38]. Researchers [39,40] have experimented with a thermal–solar reactor system. They arrange the experimental setup with a concentrator collector and, for different levels of efficiency, they used a support architecture to obtain higher efficiency. They used a concentrator to capture the sunlight from a large area and squeeze it into a much smaller spot to obtain a 1000 °C temperature [41]. Pyrolysis occurs without oxygen at high temperatures. External energy is, therefore, necessary to reach the appropriate temperature [42]. Most of the time, fossil fuels provide this thermal energy, which releases greenhouse gases that are bad for the environment. To address this issue, scientists have concentrated solar radiation directly onto the material or on a tubular reactor using optical devices [27]. Refs. [43,44] discovered that rearranging the solar part and concentrating all solar energy at a single point can produce high temperatures of up to 1000 °C. To achieve the high efficiency of solar–biomass pyrolysis, the researcher applied different parts such as a solar collector, concentrator, and other parts to support the angle dependence in the horizontal and vertical directions. In this study, we compile all parts of the thermal–solar reactor system and compare recent trends in the efficiency of solar reactors, as well as compatibility for clean energy for the conversion of biomass into valuable products. Also, we discuss how solar–biomass pyrolysis reactors are essential in fulfilling the clean energy demand.

2. Optimizing Solar–Biomass Pyrolysis

The thermochemical technology known as pyrolysis turns biomass into desirable products, including bio-oil, biochar, and syngas, which enthusiasts view as a promising use of biomass resources [45]. Fast pyrolysis supports lignocellulosic feedstock liquefaction to produce bio-oil at 75 wt% on dry feed weight alongside char and gas that can be used to generate process heat [46]. The best results for bio-oil production through conversion processing come from rapidly heating biomass particles and the subsequent fast cooling of vapor and aerosol products [47].

The undesirable properties of the bio-oil produced include acidity, a low heating value, immiscibility with hydrocarbons, and instability, which require additional upgrading for its use as a renewable fuel or chemical feedstock [48]. The research community has initiated efforts to develop advanced technologies to enhance the sustainability and efficiency of the pyrolysis process, according to [49,50]. Combining thermal–solar energy with the pyrolysis system leads to the formation of a solar–biomass pyrolysis system [51]. The combined application enables a sustainable heat supply while minimizing fossil fuel consumption and strengthening processing operations' financial and ecological aspects [52]. Ref. [53] studies two sources of renewable energy, solar power and biomass, which are clean energy technologies. The pyrolysis provides syngas and liquid tar from biomass feedstock, and the process of solar–biomass pyrolysis produces high-energy-density fuel that provides a sustainable option for clean energy utilization [42]. As a consequence, the process converts solar energy into chemical compounds by making it possible to store the energy as tar or biofuel [54]. Following [27], these created byproducts do not contain any external

combustion fuel contamination. High-powered dish receivers or concentrators can control the heating rate and assist in reaching the initial pyrolysis temperature more quickly (high heat flux) [55,56]. According to [57,58], this method creates chemical compounds from solar energy by allowing it to be stored as tar or biofuel. This contrasts with the heating method performed by fossil fuels [59,60]. Additionally, it has greater reactivity due to a more functional site that shortens the condensation reaction and reduces the time the tar vapor stays in the pores. As a result, more oxygen and hydrogen are achieved due to the low carbon percentage and the higher heating rate during pyrolysis [61,62]. As a result, compared to conventional heating techniques, this pyrolysis technique produces high-heating-value clean syngas [63,64]. In addition to increasing the pyrolysis plant's operating costs due to the large amount of fossil fuel required to transport biomass feedstock, using the same fuel or electricity for heating would reduce business earnings. Thermal-solar heating will, therefore, aid in resolving the issues mentioned earlier [65].

Furthermore, it does not release toxins into the environment or emit any nitrogen gas. The main issues with solar-biomass pyrolysis are the specific drawbacks of biomass processing and solar energy [66,67]. Biomass fuels often have a high initial moisture content and a low energy density and are bulky. As a result, pre-processing biomass before use may be necessary, increasing the initial cost of operation. Furthermore, one of the outcomes of a biomass-based process is the formation of fouling and corroding pollutants from chemical components [68,69]. Because of its high reflectivity, biomass has low absorbing optical characteristics and produces more char than bio-oil [70]. In addition, solar insolation has a poor energy density. Due to its intermittent nature, it necessitates concentrators or additional heat support for the pyrolysis process, which might disrupt the solar system's quick thermal reaction [71]. Figure 1 is used to study orange-peel pyrolysis caused by solar radiation as a novel energy source. Solar pyrolytic technologies might become critical approaches for manufacturing solar liquid fuels because they can transform endless quantities of solar energy into chemical energy. Furthermore, substituting solar pyrolytic activities for other processes will lessen harmful emissions and mitigate greenhouse gases [72].

Consequently, thermal-solar heating will aid in resolving the issues mentioned earlier [73]. Additionally, it does not discharge any toxins into the environment or emit any nitrogen gas. The main problems with solar-biomass pyrolysis are the specific drawbacks of biomass processing and solar energy. The usual drawbacks of biomass as a fuel include its bulkiness, low energy density, and high initial moisture content [74]. As a result, pre-processing biomass may be necessary before it can be utilized, increasing the initial cost of operation. Likewise, one of the outcomes of a biomass-based process is the formation of fouling and corroding pollutants from chemical components [75,76]. In addition, solar insolation has a low energy density. It requires concentrators or additional heat support for pyrolysis, and its intermittent heat supply can impede the solar system's quick transient reaction. A parabolic-trough solar concentrator, as shown in Figure 1, is used to address this challenge.

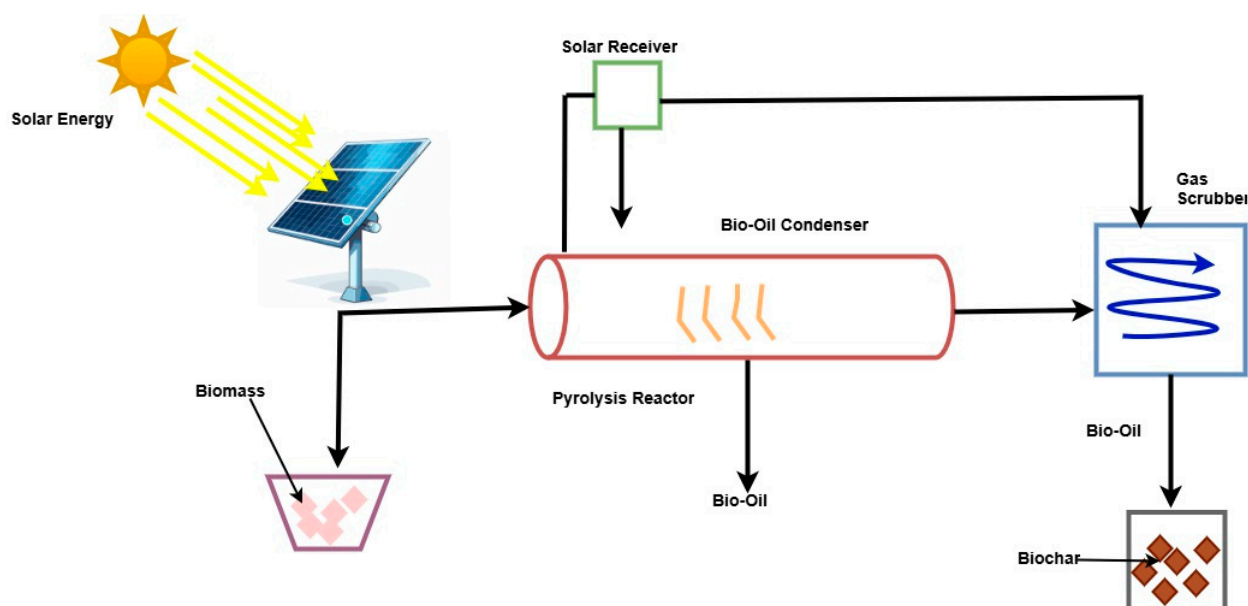


Figure 1. Schematic diagram of the solar–biomass pyrolysis system for the production of biofuels [16,77].

2.1. Solar Thermochemical Looping

Solar thermochemical looping (STCL) is a developing approach that employs solar energy to execute redox-based thermochemical cycles to improve biomass conversion efficiency. Concentrated solar power (CSP) systems combine with thermochemical reactors through this technology to execute the typical gasification and pyrolysis process reactions of cyclic oxidation and reduction [78]. Figure 2 illustrates the principle of solar thermochemical looping, showing the coupling of CSP with a reactor system for metal oxide cycling during biomass conversion.

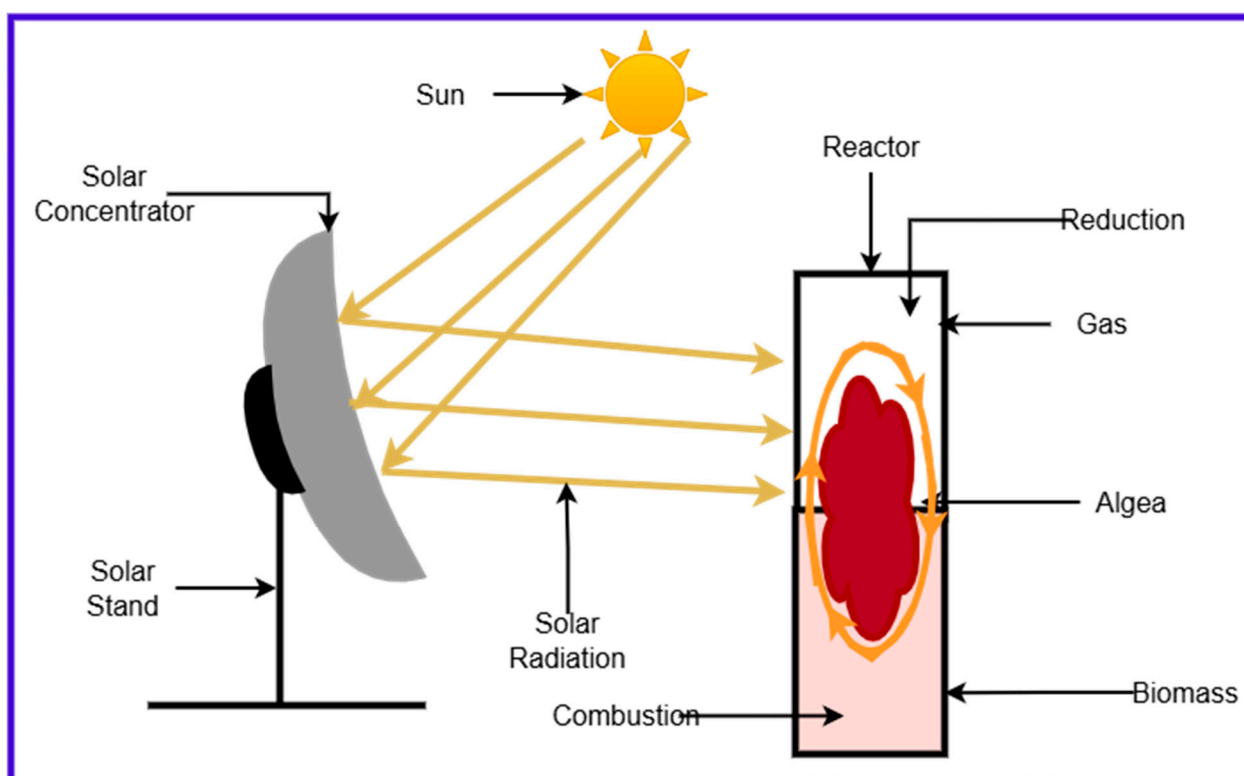


Figure 2. A schematic diagram illustrating the principle of solar thermochemical looping, showing the coupling of CSP with a reactor system for metal oxide cycling during biomass conversion.

The STCL process consists of metal oxide cycles that enable solar radiation to generate sufficient heating to reduce metal oxides and follow an oxide–biomass interaction that triggers syngas production and secondary commodities [79]. STCL achieves efficient biomass processing by using solar energy exceeding 900 °C, lowering dependency on fossil fuels. Implementing STCL in solar–biomass pyrolysis systems has two essential benefits: it enhances process scalability and boosts total energy efficiency through renewable solar power. New reactor designs built with STCL systems present opportunities to minimize operational expenses, decrease environmental harm, and yield better biofuels and chemicals [80].

2.2. Plasma-Assisted Pyrolysis

Biomass conversion receives improved capabilities through the innovative method of plasma-assisted pyrolysis, which operates with non-thermal plasma technology [81]. Plasma-assisted pyrolysis generates plasma through electric fields that apply ionization to gases to break biomass frameworks into bio-oil, syngas, and biochar at reduced temperatures compared to conventional pyrolytic methods [82]. Plasma technology enhances the control of chemical reaction environments during pyrolysis, improving the production of specific desired decomposition products. Figure 3 shows the diagram showing a plasma-assisted pyrolysis system with a plasma reactor, feedstock entry point, and product output.

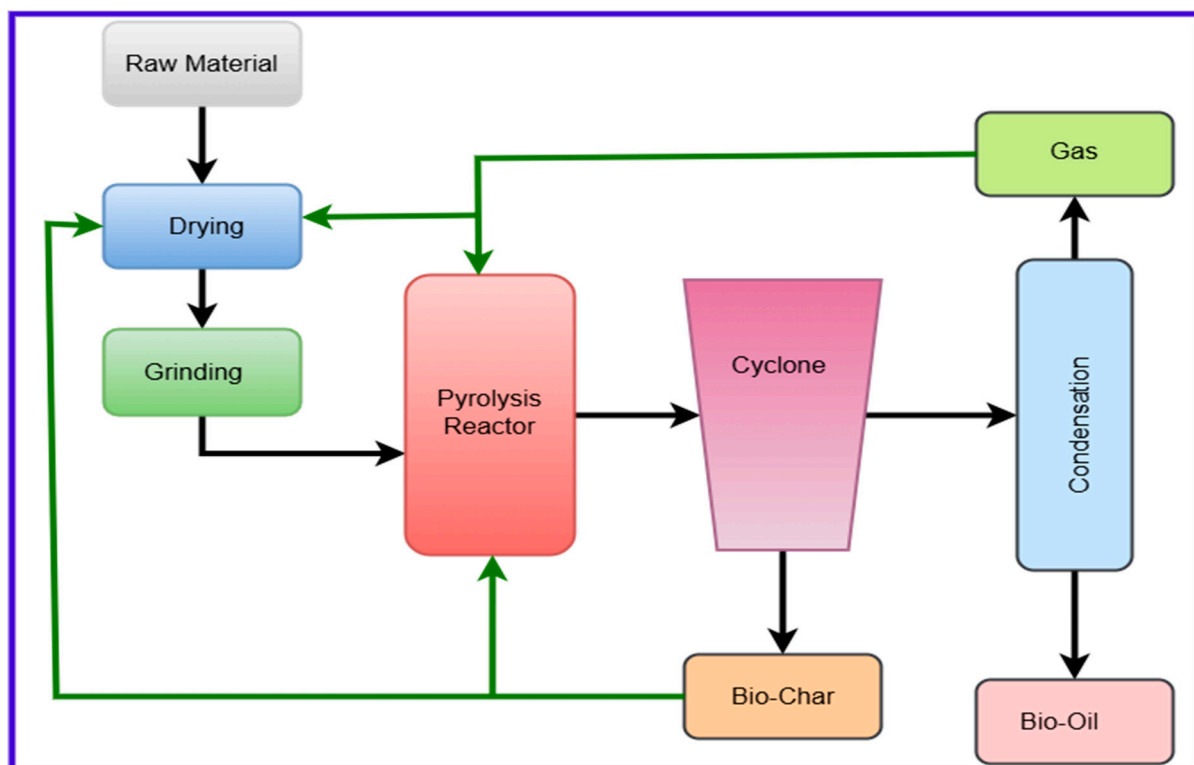


Figure 3. Diagram showing a plasma-assisted pyrolysis system with a plasma reactor, feedstock entry point, and product output.

Plasma-assisted pyrolysis provides specific advantages for bio-oil improvement through its powerful energetic field, which splits large hydrocarbons into valuable smaller fragments. This method raises the bio-oil yield while tar production decreases, a well-known problem in conventional pyrolysis operations [83,84]. Research teams increased bio-oil yields and maintained high-quality output while reducing tar quantities through plasma biomass processing under controlled reaction conditions. Plasma-assisted pyrolysis is being studied for hybrid system applications because it operates with thermal–solar

energy coupled to plasma technology to enhance system performance and product output while lowering environmental pollutants [85,86]. We summarize the product outputs, operational temperatures, and efficiency levels in Table 1 for plasma-assisted pyrolysis compared to conventional pyrolysis approaches.

Table 1. Comparison of pyrolysis methods, i.e., conventional vs. plasma-assisted vs. solar thermochemical looping.

Parameter	Conventional Pyrolysis	Plasma-Assisted Pyrolysis	Solar Thermochemical Looping
Temperature Range	400–600 °C	500–900 °C	900–1000 °C
Product Yields	Bio-oil: 40–70%, syngas: 10–30%, char: 20–40%	Bio-oil: 50–70%, syngas: 15–30%, char: 10–30%	Bio-oil: 50–60%, syngas: 30–40%, char: 10–20%
Efficiency	Moderate efficiency (~50–70%)	High efficiency (~80–90%)	High efficiency (~85–95%)
Environmental Impact	High emissions due to fossil fuels, CO ₂ , and particulate matter	Lower emissions but energy-intensive plasma generation	Reduced CO ₂ emissions, uses renewable solar energy
Energy Source	Fossil fuels, electricity	Electricity (for plasma generation)	Solar energy
System Complexity	Low (standard reactors)	High (requires plasma generators)	Moderate (requires solar concentrators)
Cost	Low (relatively inexpensive)	High (due to plasma generation)	Moderate (solar infrastructure costs)

2.3. Comparison of Pyrolysis Methods

The conventional pyrolysis processing system works from 400 °C to 600 °C [87]. When biomass goes through thermal decomposition without oxygen, three principal products emerge: bio-oil, comprising 40–70% of total output; syngas at 10–30%; and biochar constituting 20–40% of the outcome [88]. The setup process for this method remains basic and affordable, but its efficiency stands at 50–70% because it depends on external power sources, including fossil fuels. The standard thermal decomposition method of pyrolysis amid biomass generates substantial environmental harm since it needs fossil fuels for heating generation, resulting in increased carbon dioxide and parallel particulate matter emissions [89]. The system's structure remains basic yet economical and more efficient than alternative, sophisticated procedures. Table 1 compares pyrolysis methods, i.e., conventional vs. plasma-assisted vs. solar thermochemical looping.

Plasma-assisted pyrolysis functions within an elevated temperature range of 500–900 °C by applying plasma fields to decompose biomass material. The total product yields from this process include bio-oil at 50–70%, syngas reaching 15–30%, and biochar at 10–30% [90]. Using plasma in plasma-assisted pyrolysis produces an 80–90% efficiency rate by providing enhanced energy heating that decomposes complex compounds more efficiently than standard heating processes [91]. Specialized equipment for generating plasma makes the system very complex to operate. The plasma-assisted pyrolysis system has lower emissions than conventional pyrolysis yet calls for the electricity generation of plasma fields that may have greater environmental effects based on energy supplier choice. The expensive nature of plasma-assisted pyrolysis stems from its plasma equipment expenditures and the amount of energy necessary to operate it.

Solar thermochemical looping technology heats metal oxides with solar energy using a redox loop cycle as a biomass conversion process. High temperatures ranging between 900 °C and 1000 °C during this process enable better biomass transformation than general pyrolysis methods [27]. The solar-heated reactor of STCL enables biomass interaction

with reduced metal oxides to generate syngas and bio-oil and biochar in yields of 30–40%, 50–60%, and 10–20%, respectively. The STCL method achieves the highest efficiency rate among the three techniques because its concentrated solar energy system operates efficiently at 85–95% [92]. The transformation of STCL to renewable solar energy power eliminates all CO₂ emissions because this technology functions solely based on solar power. Solar concentrator devices and tracking systems build up a complexity level that falls between plasma-assisted pyrolysis methods. Solar thermochemical looping provides a sustainable carbon-neutral solution to traditional pyrolysis and plasma-assisted processes, even though its solar infrastructure investment may have high initial costs.

2.4. Pilot and Industrial Demonstrations of Solar–Biomass Pyrolysis

Moving solar–biomass pyrolysis technologies into real-world usage represents a necessary step for their future development. Research on lab-scale systems dominates the field, although multiple pilot and industrial demonstrations have occurred throughout the last few years to evaluate scalability aspects for broader applications [93]. These demonstrations offer essential insight into technical barriers and economic and operational constraints during the large-scale implementation of biomass conversion systems linked to solar energy.

Solar–biomass pyrolysis [17] combines solar concentrators and biomass pyrolysis reactor units that transform agricultural waste into biofuels. The successful experimental results proved solar power could heat the pyrolysis reactor while decreasing dependence on fossil fuels. A field test system used parabolic-trough collectors that concentrated solar power toward the reactor to reach the needed temperature levels for optimized biomass transformation. Significant quantities of bio-oil, biochar, and syngas were generated through solar–biomass pyrolysis; however, the researchers faced difficulties controlling the heat input stability and managing fluctuations in biomass feedstocks. Several industrial-scale demonstrations serve to investigate the commercial potential of solar–biomass pyrolysis. The project's implementation by [94] proves that solar–biomass pyrolysis can work for commercial purposes, including biofuel and waste disposal operations. Industrial applications used huge solar collectors through heliostats and parabolic dish systems to aim solar rays at biomass reactors that generated biofuels while decreasing carbon dioxide emissions. The industrial implementation verified solar energy as a suitable power source for large-scale pyrolysis operations and optimized reactor designs for better production efficiency.

The promising outcomes from the demonstration projects have multiple substantial barriers to their industrial production scale. The principal barrier is the sporadic behavior of solar energy because it needs proper energy storage technology alongside hybrid systems that can connect alternative thermal sources during times of limited sunlight availability. Modern research targets improved reactor machinery designs for handling different forms of biomass input materials alongside maintaining sustainable process speeds in pilot and commercial systems. The experimental work has proven that solar–biomass pyrolysis integrated with current facilities could develop into an economical technology for generating sustainable biofuels and combating global warming. The advancing field will probably execute future pilot and industrial demonstrations to achieve better system integration while minimizing costs and expanding scalability. The efforts will concentrate on building thermal–solar hybrid systems incorporating biomass combustion with geothermal heat technologies to maintain uninterrupted operation and increase system stability. Realizing the complete benefits of solar–biomass pyrolysis as an optimized renewable and profitable energy alternative requires the successful advancement of laboratory experiments into commercial deployment methods.

2.5. Innovations in Thermal–Solar System Design

Integrating thermal–solar energy in pyrolysis operations requires different combinations of system designs and reactor configurations [95,96]. Table 2 shows the comparative analysis of reactor designs for solar–biomass pyrolysis: advantages, limitations, and practical viability. Researchers have proposed implementing a hybrid thermal–solar system that combines thermal–solar collectors with biomass pyrolysis reactors for efficient fuel production. The thermal–solar collector uses solar energy to create heat that warms the biomass feedstock flowing into the pyrolysis reactor [96,97]. The solar cavity receiver design allows biomass feedstock to interact with concentrated solar radiation within an enclosed chamber, eliminating the need for separate heat transfer components [98]. Researchers have studied solar-assisted fluidized-bed reactor systems that use hot air and solar-heated particles to fluidize biomass [99,100].

Table 2. Comparative analysis of reactor designs for solar–biomass pyrolysis: advantages, limitations, and practical viability.

Reactor Type	Advantages	Limitations	Practical Viability
Fluidized Bed Reactor	• Excellent heat and mass transfer • High biomass conversion efficiency • Efficient for continuous operation	• It can be challenging to scale for large biomass feedstock sizes • Sensitive to feedstock variability and moisture content • High energy consumption for fluidization	• Suitable for medium to large-scale systems; commonly used in industry • High operational flexibility and uniform heating
Auger Reactor	• Simple design and easy to scale • Can handle larger feedstock sizes • Robust and reliable	• Lower heat transfer efficiency compared to fluidized beds • Can have uneven heating due to limited heat distribution • Requires mechanical components that may wear out	• Viable for small to medium-scale applications • Cost-effective for small-scale or decentralized energy production
Fixed-Bed Reactor	• Low capital cost, easy to operate • Simple to design and operate • No moving parts, reducing maintenance costs	• Lower biomass conversion efficiency, especially at larger scales • Limited by slow heating rates and poor heat distribution • Sensitive to feedstock size and moisture content	• Often used in small-scale or lab-scale systems • Not ideal for industrial-scale unless combined with advanced heat management
Solar Cavity Receiver	• High-temperature capabilities (up to 1000 °C) • Direct coupling with solar concentrators for high heat flux • Excellent for producing syngas, bio-oil, and biochar	• High complexity requires precise solar tracking • Expensive setup with a high initial investment • Requires high-precision equipment and maintenance	• Ideal for large-scale applications, especially in areas with high solar insolation • Demonstrated in pilot plants, but still developing for full commercial viability

2.5.1. Reactor Orientation Optimizations

Reactor orientation systems significantly affect how well the entire system functions. The work of researchers [101,102] has examined numerous reactor arrangements, such as horizontal, vertical, and inclined types, to study biomass conversion along with product yield and energy efficiency. Biomass heating with horizontal reactors leads to superior time distribution control and uniform biomass heating, but vertical reactors have higher heat and mass transfer efficiency [96,103]. The design of inclined reactors combines the optimal qualities from horizontal and vertical configurations, which could enhance biomass transformation alongside product quality improvements [104,105].

The solar reactor features three principal design aspects, which include (1) distinct temperature regions (Figure 4a), (2) fluid dynamics rotation (Figure 4b), and (3) changing pressure from argon gas flow. A graphite crucible contains a wood pellet while black graphite foam encases it for protection, as displayed in Figure 4a. The direct solar radiation

increases the system's temperature. Solar radiation passes through the argon gas base because this gas remains transparent in this light wavelength spectrum. This device's heating method is achieved through direct contact with the sample surface and mixing with resulting volatile products from pyrolysis. Insulating graphite foam surrounds all sides and the bottom of the sample, creating a hot thermal area near the sample's surface [106,107]. Most solar reactors exist in a lower temperature range than the heated crucible section. The high-temperature zone represents the only area where the secondary tar reactions can occur within particle surroundings. A circular tube houses six upward holes near the gas outlet and six downward holes on the opposite wall, enhancing mixing through this system. A simplified version shows the counter-current argon injector system through Figure 4b. Research has proven that the unconventional arrangement of the counter-current argon injector system creates rotational flow dynamics in the solar reactor that both experimental measurements and theoretical computations validate [49].

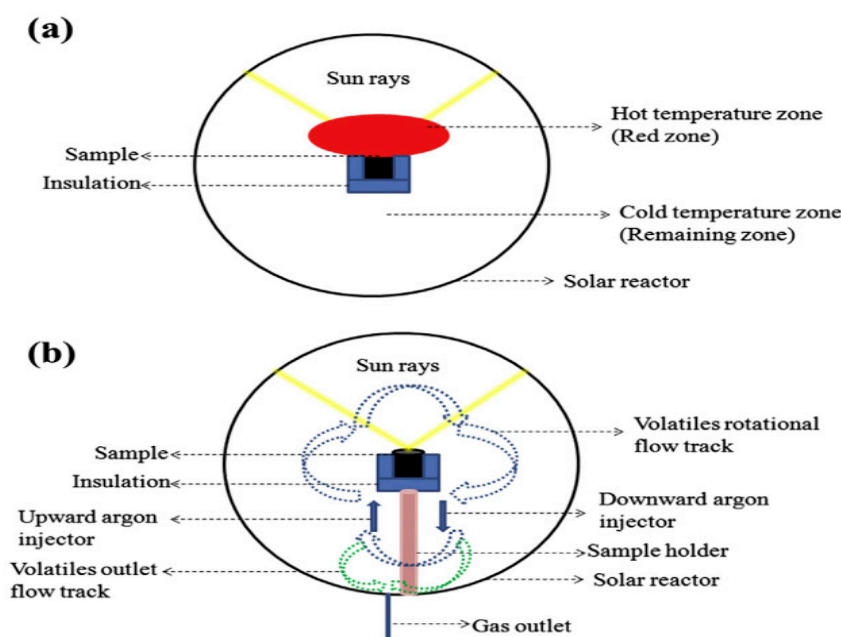


Figure 4. Solar reactor characteristics: (a) two temperature zones and (b) rotational flow field.

2.5.2. Efficiency of Solar–Biomass Pyrolysis

Coupling thermal–solar energy with optimized reactors improves efficiency and sustainability achievements in pyrolysis operations. The synergy between solar power and biomass diversity creates new opportunities to produce sustainable biofuels and chemicals while generating valuable products that build a greener chemical and energy system [108,109]. New thermal–solar system designs and reactor orientation configurations within solar–biomass pyrolysis systems demonstrate strong potential to boost operational efficiency and sustainability for achieving high-quality bio-based product production, displacing fossil-based products and supporting sustainable development [110].

The alignment between reactor systems has received significant research attention because scientists evaluated configurations including horizontal, vertical, and inclined reactor systems [44]. The biomass heating performance, combined with the residence time management aspect, improves in horizontal reactors, while vertical reactors offer superior heating efficiency through enhanced mass transport properties [43]. Compared to horizontal and vertical orientations, the inclined reactor design provides an improved system with superior biomass conversion capabilities and better product quality [40]. The main developments in thermal–solar system design and reactor orientation for maximizing solar–biomass pyrolysis are summarized in Table 3.

Table 3. Delineates the principal changes in thermal–solar system design and reactor orientation to improve solar–biomass pyrolysis.

Innovation Area	Key Innovations	Description
Solar collector efficiency	-	Improved solar panel design for higher energy absorption and conversion rates
Heat transfer mechanism	-	Enhanced heat exchangers using advanced materials for better thermal conduction
Reactor orientation	-	Optimal reactor positioning (e.g., fixed vs. rotating) for maximum solar exposure
Solar tracking technology	-	Automated systems to track the sun’s movement, ensuring constant energy input
Pyrolysis temperature control	-	Precision control systems to maintain consistent pyrolysis
Gaseous emission management	-	Implementation of gas scrubbers and condensers to reduce harmful emission
Biomass feeding mechanism	-	Advanced biomass feeding systems that ensure uniform biomass flow into the reactor
Reactor insulation	-	High-performance insulation reactor to reduce heat loss and improve efficiency
Hybrid solar–biomass energy systems	-	Integration of solar and biomass systems to enhance energy availability
Automation and process control	-	Automated monitoring and adjustment systems to optimize pyrolysis
Advanced materials for reactor	-	Use of durable, high-temperature-resistant materials for the construction of pyrolysis
Post-pyrolysis processing	-	Technologies for refining bio-oil and improving its storage and transportability
Cost-effective design	-	Design innovations that reduce system costs while maintaining efficiency
Modular and scalable systems	-	Designs that allow for easy scalability and facility based on biomass availability
Thermal–solar system design	Integrated solar collectors and pyrolysis reactors Solar concentrators for high-temperature control Heat storage integration	Combines solar collectors with reactors for direct thermal input to biomass. Reduces reliance on external heating Concentrators focus solar radiation to achieve temperatures above 500 °C, enhancing pyrolysis efficiency Thermal energy storage allows for continuous pyrolysis even during cloudy periods
Reactor orientation	Dual-mode hybrid systems (solar and biomass combustion) Vertical reactor orientation Solar tracking systems for optimal orientation Multi-layer reactor design with gradient temperature zones	Utilizes solar and biomass combustion to sustain the system’s operation when solar radiation is insufficient Vertical design enhances heat transfer and promotes better biomass flow for more uniform pyrolysis Automated tracking maximizes solar exposure by adjusting the reactor position relative to the sun Temperature gradients within the reactor optimize the thermal profile for different stages of biomass pyrolysis

The combination of renewable solar power generation with diverse biomass supplies opens possibilities for developing superior bio-based fuel products, chemical compounds, and beneficial products, thus transforming the sustainable chemical and energy sector [39]. Innovations in solar–biomass pyrolysis based on advanced thermal–solar system design and reactor orientation layouts demonstrate significant potential to boost the complete efficiency and sustainability of the pyrolysis reaction [26]. Two essential innovations in this research combine thermal–solar collectors with biomass pyrolysis reactors and solar cavity receivers that expose biomass to concentrated solar radiation within heated cavities [34].

2.6. Mechanisms of Heat Transfer, Radiation, and Convective Heat Transfer

2.6.1. Heating Mechanisms

In the solar pyrolysis system, the mode of heat transfer is a crucial factor; most solar pyrolysis is endothermic, rapid pyrolysis that requires much energy. As a result, many accepted heating methods exist based on resource availability [76]. Solar heating may be used in a hybrid model for solar–biomass pyrolysis, in which other heat sources partially help the heating process [8,10]. According to [17], the average concentrators can achieve temperatures between 100 and 500 °C, which is insufficient for all pyrolysis reactions

because the required temperature is 400–900 °C for complete pyrolysis. As a result, more sunlight is needed for high temperatures to rise further.

The fact that solar applications are defined by both sunny and non-sunny periods is another cause since solar insolation is not constant [19,20]. On the other hand, artificial light simulators (such as tungsten lamps, Super Lasers, halogen lamps, carbon arc lamps, and xenon arc lamps) with emissive powers equivalent to solar radiation and comparable visible spectra wavelengths (400 to 700 nm) were used when there was little or no sunlight [21,22]. Consequently, solar pyrolysis may also be divided into groups according to the artificial and natural sources of light [8]. Another heating method uses solar heat to heat or irradiate the biomass feedstock. There are three types of heat transfer: direct, indirect, or via fluid like molten salt, solid suspension, or supercritical water [24,25]. The reactor's black body helps to absorb the indirect energy and heat transfer to the biomass via conduction.

Furthermore, fluid is heated to transfer the heat to initiate the reaction, and this process continues. The concentrator will pass all the radiation via the reactor wall and focus the whole amount of radiation on a single point [111]. Other researchers utilize sunlight to generate electricity to induce a plasma state in the gaseous. This technique produces high temperatures, increasing solar energy efficiency [27]. In contrast to hybrid heating, continuous solar heating often offers a significantly more ecologically benign heating procedure. Some studies have shown that catalysts may reduce the substantial quantity of CO₂ produced during biomass pyrolysis [112]. You must keep the reactor surface clear of dust envelopes to ensure effective operation. Additionally, if you use indirect irradiation, you must overcome the disadvantage of the black body's temperature range [113,114].

2.6.2. Solar Receivers and Concentrators

Along with sunlight, other power sources are used to obtain the appropriate temperature, increasing the solar flux density [115]. As a result, using optical technologies, scientists have showcased this solar radiation intensity in various energy systems. According to [116], these applications range from power generation using large oval dishes to flat plate collectors for water heating and drying. The desired temperature range determines which optical device is best. Ref. [117] lists the concentrating and non-concentrating optics that are available: linear Fresnel, central dish receivers (≥ 1000 °C), linear mirrors (9 kW thermal power), and parabolic mirrors (100 to 500 °C).

Figure 5 displays various optical concentrating devices. Moreover, elliptical reflectors, also known as mirrors (an image-free visualization), parabolic mirrors with a deep dish, and lamp reflectors have been used by researchers utilizing light simulators in solar-biomass pyrolysis through the reactor window to focus the radiation beam [33,118]. Studies reveal that the number of these concentrators may be increased for a single operation to reach the required temperature, typically 300–900 °C [32]. Effective installation setup is essential for the breakdown of biomass for effective liquid accumulation, regardless of the kind of concentrating equipment used [3].

2.6.3. Thermodynamic Models, Energy Balances, Heat Transfer Analysis, and Fluid Dynamics

Thermodynamic Models

Evaluating solar-biomass pyrolysis system energy efficiency through thermodynamic modeling requires total system energy input and output analysis during biomass conversion. The first law of thermodynamics helps to model system energy flows because the supplied heat ($\dot{Q}$) equals the combined energy used in biomass conversion and the energy that leaves the system. The system uses Equation (1) [119] to evaluate the energy performance where “ $\dot{Q}$ ” represents the solar radiation heat that supplies the system, “ $\dot{W}$ ” indicates the mechanical work functions from biomass handling, and “ $\dot{U}$ ” reflects the

biomass temperature adjustments. At the same time, “ $\dot{H}$ ” shows the enthalpy change linked to biofuel production. During solar–biomass pyrolysis, the solar energy input “ $\dot{Q}$ ” is the primary heat source required for the pyrolysis reaction. The reactor temperature measurement allows scientists to determine the biomass enthalpy change by calculating heat bond-breaking requirements for biomass decomposition. We can compute the total system energy efficiency when we measure the heat released during biomass conversion. The minimization of energy losses and the process reversibility rely on the second law of thermodynamics to achieve these goals.

$$\dot{Q} = \dot{W} + \dot{U} + \dot{H} \quad (1)$$

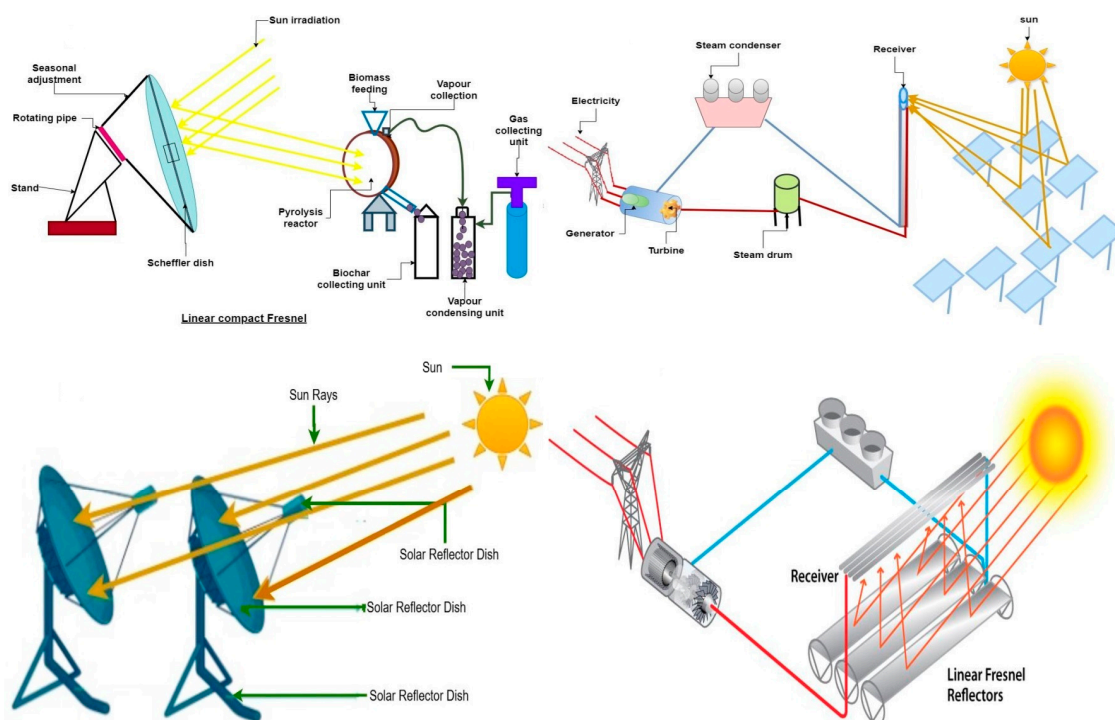


Figure 5. Different optical concentrating devices [35].

Energy Balances

The energy balance of solar–biomass pyrolysis requires analyzing all system energy that enters, exits, and accumulates inside the system. We use Formula (2) [120] when implementing a general energy balance system. The energy balance of this system entails three primary components: “ $\dot{Q}_{in}$ ” stands for total input (combining solar power with supporting sources), “ $\dot{Q}_{out}$ ” measures exhaust and thermal loss from the system, and “ ΔE_{system} ” shows how the system energy changes through biomass heat requirements and chemical transformations as well as thermal storage considerations.

$$\dot{Q}_{in} = \dot{Q}_{out} + \Delta E_{system} \quad (2)$$

Thermal and product yield efficiency should be included in this energy balance system. The energy efficiency formula for pyrolysis operation appears as (3) [121]. The mathematical expression helps to measure the solar energy conversion efficiency into important products, including bio-oil, syngas, and char, while offering suggestions for efficiency enhancement.

$$\eta = \frac{\dot{Q}_{products}}{\dot{Q}_{in}} = \frac{\text{Energy in bio – oil, syngas and char}}{\text{Energy supplied from solar sources}} \quad (3)$$

Heat Transfer Analysis

Heating systems in pyrolysis reactors serve as essential factors to support proper operational conditions. The appropriate analysis of heat transfer stands as vital for improving reactor operational effectiveness. The reactor must efficiently absorb and distribute concentrated solar energy from solar concentrators, including parabolic troughs or heliostats. The reactor operates with heat transfer mechanisms defined by Fourier's law of heat conduction along with radiation rules according to the Stefan–Boltzmann law. The reactor wall heat transfer relies on calculations from Fourier's law.

1. The wall heat transmission speed is described in Equation (4) [122] through Fourier's law. The heat flux value “ q ” (W/m^2) depends on the thermal material conductivity “ k ” divided by the temperature gradient “ dT/dx ” found in the reactor walls. The developed equation determines the heat conduction efficiency of reactor operations.

$$q = -k \frac{dT}{dx} \quad (4)$$

2. The absorbance of heat energy by the reactor from solar concentrators follows the Stefan–Boltzmann law presented as Equation (5) [21]. The model helps to evaluate solar energy utilization efficiency in pyrolysis by measuring the amount of heat the reactor receives. The expression for radiant heat flux uses “ Q_{solar} ” and “ σ ” as the Stefan–Boltzmann constant alongside ϵ representing the reactor surface emissivity and “ T_{solar} ” indicating the incoming solar radiation temperature, alongside A describing the reactor surface area exposure and “ T_{reactor} ” denoting the reactor surface temperature.

$$Q_{\text{solar}} = \sigma \epsilon A (T_{\text{solar}}^4 - T_{\text{reactor}}^4) \quad (5)$$

Fluid Dynamics

The detection of fluid dynamics plays a vital role in fluidized-bed reactors and entrained-flow reactors to successfully process biomass feedstock materials and distribute reactants evenly while facilitating heat transfer. Biomass flow patterns and gaseous movement operate within the Navier–Stokes equation framework that regulates fluid motion. Equation (6) [61] enables researchers to represent the reactor system's flow patterns, particle interactions, and gas-phase movement. The equation consists of fluid density (ρ), fluid velocity vector (v), fluid pressure (P), and fluid dynamic viscosity (μ), as well as external forces represented by (f). By understanding biomass particle motion, researchers study how they engage with reactor gas and heat flow patterns and how to create uniform temperature distribution for successful biomass processing. The reactor design benefits from optimization through visual computation using Computational Fluid Dynamics (CFD) simulations.

$$\rho \left(\frac{\partial v}{\partial t} + v \cdot \nabla v \right) = -\nabla P + \mu \nabla^2 + f \quad (6)$$

Combining sensorimotor analytics with thermodynamic models alongside energy balance equations for heat transfer and fluid dynamic analysis provides complete knowledge about solar–biomass pyrolysis processes. The validated models demonstrate solar-assisted pyrolysis system features and methods to enhance reactor performance, decrease energy losses, and allow system expansion. The complete application of inflexible theoretical frameworks enables scientists to perform precise and comprehensive scientific studies on solar–biomass pyrolysis before advancing its development path.

2.6.4. Thermal–Solar System and Reactor Orientations

The reactor's practical design can help to achieve the system's high efficiency; the best orientation design requires approximately 15% of the total reactor cost [37]. There are many studies on reactor design, and researchers have developed innovative and cost-effective reactor designs for pyrolysis systems [41]. The practical system orientation is significant for smooth pyrolysis and long-term running. Other factors like the product yield, thermodynamic process, optical mirror, and kind of feedstock also influence the solar–biomass system [53]. These concepts included augur kilns, fix-bed, ablative, screw, vacuum pyrolysis, free-fall reactors, circulating fluid beds, entrained flow, bubbling fluid beds, and spinning cones [42].

Nonetheless, fixed-bed reactors dominate solar–biomass pyrolysis, most likely because of their simplicity [27,55], and most research is still conducted in lab settings. Fast pyrolysis is the best option to satisfy industrial requirements, but also brings up many challenges [8]. Once more, many reactors will be needed to scale up to commercial form [10]. In a fixed-bed reactor, the liquid product is not high. However, the high-density liquid product quantity is much higher, which goes through the distillation method for a particular application. The reactor orientation can be either horizontal, with the radiation beam directed onto it utilizing the concentrators, or vertical, with the radiation directed through the heliostat assembly and concentrator [11].

Orientation of Thermal–Solar System

The orientation of a thermal–solar system refers to the direction in which the solar collectors are positioned to maximize the absorption of sunlight. The optimal orientation depends on various factors such as geographic location, seasonal variations in the sun's path, and the specific design of the thermal–solar system [123,124]. Solar collectors should typically face north in the southern hemisphere and south in the northern hemisphere for optimal sunlight throughout the day. This orientation ensures that the collectors are exposed to the sun for the most prolonged duration possible, maximizing energy capture.

However, the collectors' tilt angle is also quite important, and it is typically set to match the location's latitude to maximize solar exposure during the year. Adjustments to the tilt angle may be made for seasonal variations to optimize energy capture during different times of the year. Additionally, factors such as shading from nearby structures or trees should be considered when determining the orientation of a thermal–solar system to avoid obstruction of sunlight. Overall, the optimal orientation of a thermal–solar system involves a balance between maximizing solar exposure and practical considerations based on the specific location and surroundings of the installation.

Tube Configuration in Thermal–Solar System

In a thermal–solar system, the tube configuration refers to the arrangement of tubes or pipes through which a heat transfer fluid flows to absorb solar energy. These tubes are typically part of the solar collectors where solar radiation is absorbed and converted into heat. There are various tube configurations used in thermal–solar systems, including the following:

- **Flat Plate Collectors:** These collectors consist of a flat, rectangular panel with parallel tubes or channels through which a heat transfer fluid (such as water or a heat transfer oil) flows. The tubes are usually arranged in a grid pattern within the collector panel [125].
- **Evacuated Tube Collector:** Individual evacuated glass tubes contain heat transfer fluid in these collectors. Each tube is a separate collector, often arranged in rows or arrays on a support structure.

- **U-shaped Tubes:** Some thermal–solar collectors use U-shaped or serpentine tubes, where the heat transfer fluid flows back and forth within the collector. This configuration can provide efficient heat transfer and is often used in flat plate collectors.
- **Parabolic-Trough Collectors:** These collectors use curved parabolic reflectors to focus sunlight onto a tube running along the center of the reflector. The heat transfer fluid within the tube absorbs the focused solar energy [12].
- **Parabolic-Dish Collectors:** Similar to parabolic-trough collectors, parabolic-dish collectors concentrate sunlight onto a receiver at the dish's focal point. The receiver typically consists of a network of tubes where the heat transfer fluid circulates.

The choice of tube configuration depends on factors such as the desired efficiency, available space, cost considerations, and specific application requirements. Each configuration has advantages and limitations regarding performance, durability, and ease of installation.

3. Concentrated Heated Reactors

Many designs for solar pyrolysis have opted for a vertical reactor orientation, most likely to facilitate the simple collecting and sweeping of the liquid with the help of gravity [18]. To conduct the pyrolysis of tomato waste and agave leaves for solar biomass [19], Mexico used a vertically positioned, borosilicate fixed reactor with a spherical shape. Figure 6 illustrates the thermal–biomass system and the system's orientation [42]. The solar concentrator furnace, which has a concentration area of 8 cm in diameter and is horizontally positioned with a temperature range of 450–1550 °C and a capacity of 25 kW, is directed by the heliostat towards the reactor assembly, situated 3.68 m away [24,111]. The installation's position allowed the biomass to be directly exposed to radiation. Argon gas maintained inert conditions and cleaned the reactor walls [23]. The design aims to increase the amount of biochar produced and describe its physiochemical properties at different heating speeds for one to two hours [111].

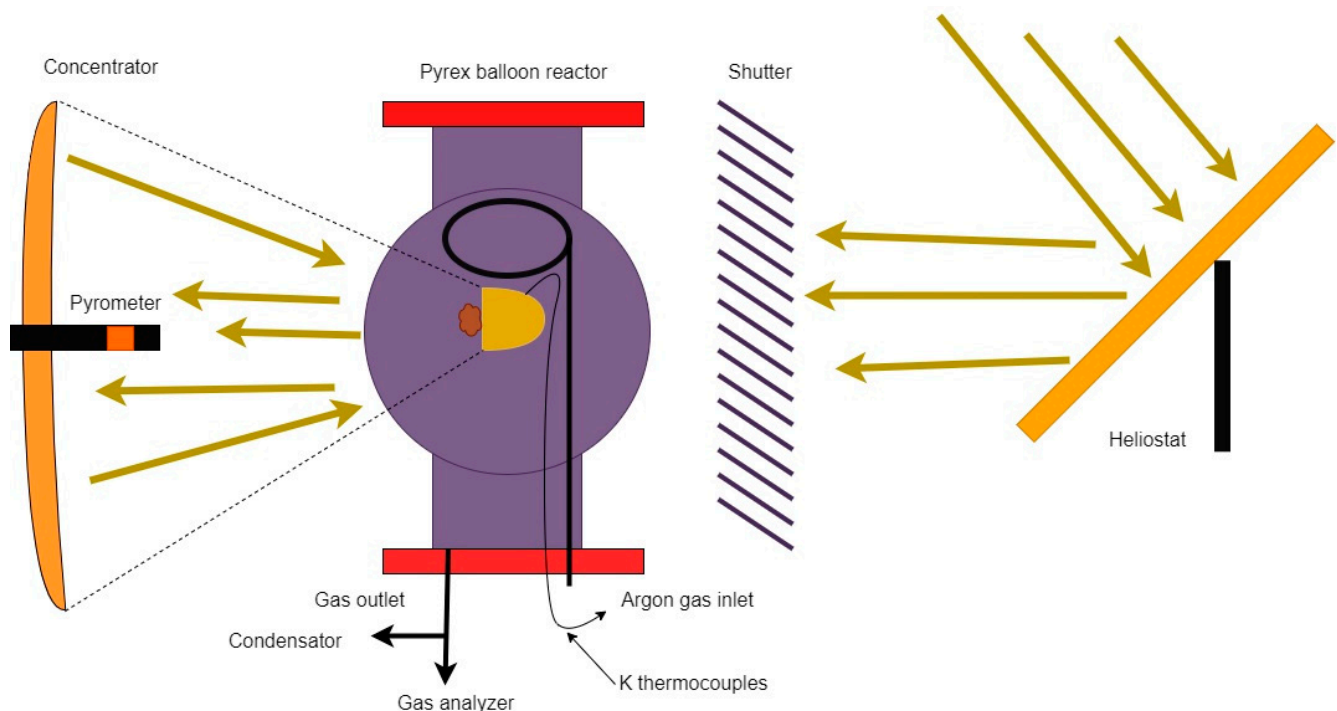


Figure 6. The orientation of solar–biomass pyrolysis. Reproduced from [126] with permission from AIP Publisher, 2025 (License No: 6022910805274).

An orientation of solar–biomass pyrolysis was demonstrated by [127]. The fixed bed, a vertical axis solar furnace, is centered on a Pyrex balloon reactor that has been cleaned and given an oxygen-free atmosphere using argon gas [27]. In a parabolic mirror heliostat tracker (2 m diameter), the sun's rays are concentrated and monitored, then directed directly onto the reactor. To reduce temperature gradients, the biomass pellet was placed in a foam-covered graphite crucible [117]. A water-cooled clamp was used to steady the sample towards the focus of solar radiation, and an additional layer of graphite foam reduced radiation heat loss. The solar furnace's orientation differs from that recommended for solar furnaces [114].

Nonetheless, the reactor's direct radiation was made possible by the placement of the two orientations. High heating rates and final temperatures promote the formation of syngas and the breakdown of tar, according to the results of the influence of lignocellulose content on the product distribution of forestry products, absolute temperature, and heating rate. Using pine sawdust, they produced 63.5 wt% of gas at 50 °C/s and 1200 °C [27]. Ref. [41] used the same reactor setup orientation for their different study goals when they pyrolyzed beech wood. The thermal–solar system's sun-ray-monitoring sensor automatically focuses the heliostats to direct light onto the parabolic mirror that faces down onto the reactor based on the sun's location [35]. Ref. [128] reported a 62% gas yield at a lower heating value of $10,376 \pm 218$ (kJ/kg of wood), with argon flow rates of 12 NL/min, 50 °C/s, 0.85 bar, and 1200 °C, respectively, as well as temperature, heating rate, and pressure. The range of biomass energy upgrading was 38–53% [8]. Ref. [10] provided a schematic representation of a hybrid solar–biomass pyrolysis of date palms using a vertical steel reactor (nitrogen gas was used to provide the inert environment) that was partially heated by a biomass heater (Figure 7).

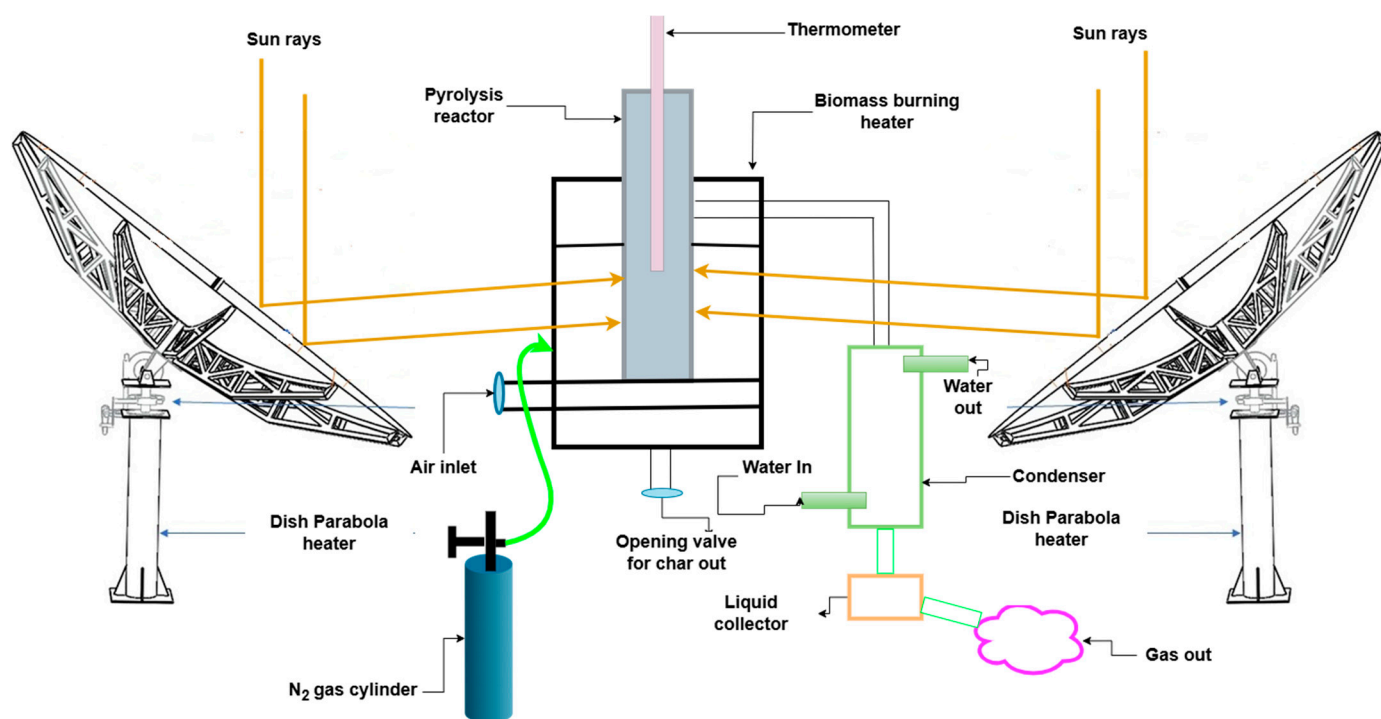


Figure 7. Parabolic solar heater biomass pyrolysis orientation; adapted from (Copyright © 2025. This open-access article is distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited) [129].

The temperature of the steel reactor is raised to around 162 degrees Celsius by the solar reactor, which contains a double parabolic surface that collects sunlight and directs

it onto the surface of the reactor [11]. The experiment's findings demonstrated that 32.4% of CO₂ could be kept out of the atmosphere when liquid oil was used at 500 °C and a residence time of 120 min with a gas flow rate of 6 L/min [17]. Ref. [23] conceptualized and demonstrated indirect solar-assisted biomass pyrolysis. There were tubes of molten sodium and potassium carbonate around the reactor, which might be cylindrical or vertical and used for heat storage. An insulated dome with an aperture to let in sunlight surrounds the setup [117]. The concentrated parabolic trough and heliostat used in the thermal-solar system, which was mounted atop a tower, were designed to focus the beam. Conduction from molten salt (1123 K), which a solar concentrator has heated, transfers heat to the biomass [33,118].

3.1. Heated Reactors with Light Simulators

3.1.1. Vertically Orientated

Many reactor configurations and solar simulator orientations have been used to carry out solar-biomass pyrolysis utilizing solar radiation simulators. Previous researchers used artificial light that mirrored sun rays to begin using a solar-assisted breakdown of carbonaceous material. Because natural sunlight is not continuous, this technology is still being studied today. Some researchers [31] described a fixed-bed reactor with vertical orientation for solar-biomass pyrolysis. The reactor was driven by an elliptical reflector and Xenon arc lamp, with a 2.2 MWm⁻² heat flux density. The superior heat conductivity of the insulated copper reactor led to its adoption as the reactor. Ref. [33] stated that the reactor walls were covered with an absorbent coating to create a black body, and the heat was transferred to the biomass via (indirect heating) conduction when the rays were directed directly onto the reactor walls. This installation features movable light support that allows you to adjust the heating temperature and the lamp's focus distance. Because of the installation's shape, the number of pellets within the reactor varied according to the temperature gradient and the distance from the reactor to the radiation source [3]. Figure 8 represents the schematic view of the solar pyrolysis system and biomass pyrolysis reactor at the focal point of a vertical solar furnace [27].

A customized cinema projector was used as a simulator to mimic the pine sawdust biomass pyrolysis based on the solar system using the deep parabolic-dish surface with the same Xenon arc lamp (wavelengths 850 to 1050 nm) [72]. The vertical position of the reactor is a double-walled quartz reactor with diameters of 29 mm and 58 mm. It may also function as a fluidized bed and the cylindrical reactor inside the wall tapers at the solar simulator's center to hold the biomass [128]. Nitrogen gas was employed to sweep the gas, establish an inert environment within the reactor, and offset the heat loss while the distance between the walls was maintained. The simulator uses movable screw mechanisms to change the focus point's location [76]. As a result, the solar flux changes with distance, changing the input power to control the temperature. Direct sun radiation of the biomass was made possible by the arrangement of the thermal-solar system. Using Xenon lamps (5 kW) fitted with flat glass reflectors (24 in number) and parabolic mirrors (1.5 m in diameter), the simulator replicated solar-biomass pyrolysis [75].

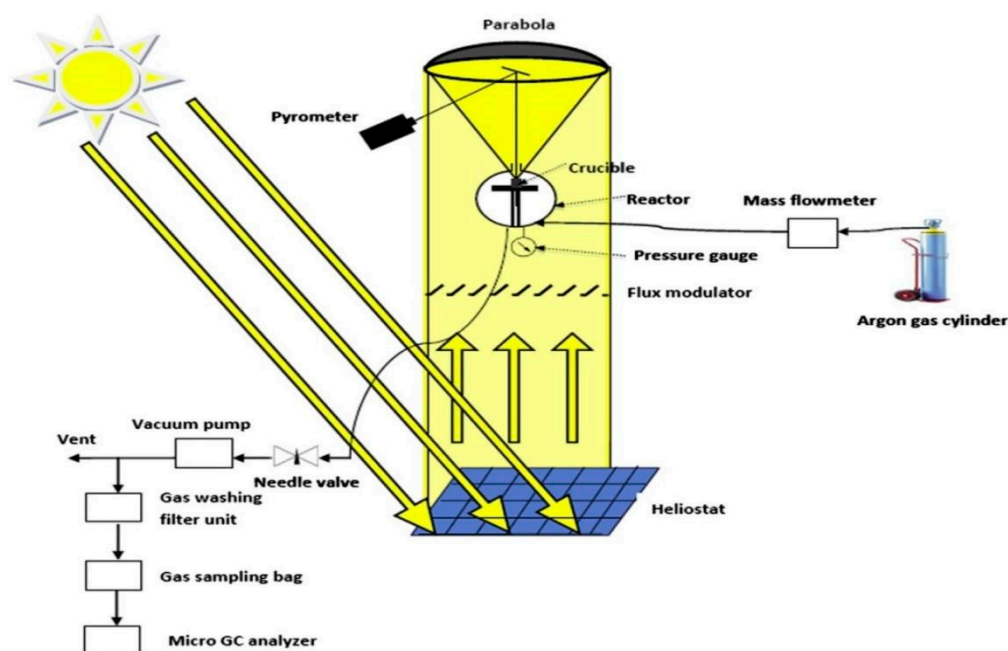


Figure 8. Schematic view of solar pyrolysis system and biomass pyrolysis reactor at the center point of a vertical furnace, Reproduced from [130] with permission from Elsevier Publisher, 2025 (License No: 6032510833145).

The Amersil quartz tube (1.5 mm thick) is a vertical reactor tapered at the base to produce a cone of 20 degrees slant angle. The continual flow of steam in the trapped circular flow sprouting bed and the biomass fed from the top result in pyrolysis [73]. Ref. [131] investigated how pyrolysis biomass created biofuels in a vertical-axis reactor connected to a 1.5 kW solar furnace. The LHV increases (5 times) as temperature increases (600 °C to 1200 °C) because of the variation in the syngas component and the heating rate of 5 °C/s to 50 °C/s. The other pyrolysis product was 28.1% bio-oil, and 10% biochar was considered in the product. This finding shows that solar pyrolysis increases the calorific value of the feedstock [132].

The focus zone receives approximately 150 W of energy from the solar simulator at a flux range of 200 W/cm². About 63% of the cellulose biomass was converted into bio-oil [133]. A similar simulator was used by [55] to assess the optical characteristics in the solar flash pyrolysis of biomass; the light from a xenon lamp passes into the combined sphere containing the pellets, and it is concentrated by a converging lens [27]; the use of an elliptical reflector in a simulator which is based on solar power is attached with a vertical copper tube and a Xenon arc lamp of 1.6 kW (with a heat flux density of 2.2 MWm⁻²) to replicate solar assistance in the pyrolysis of waste biomass. The purpose of using copper material for the reactor is to allow conduction based on biomass heating. Solar-based biomass pyrolysis simulation on spruce, pine, and birch using Xenon lamps was conducted by [54]. A fused silica window on one face of the bell-shaped Pyrex reactor, which maximizes radiant heat transfer, was employed for pyrolysis. For 5 to 10 min, the xenon lamp was pointed straight through the glass at the biomass. Three purge gas outlets for nitrogen gas are located next to the window to keep smoke out. The gas rushed to a cold trap via the outflow outlet at the top. The lamp emits between 80 and 130 kW/m² of heat per square meter. The pyrolysis product for two flux densities for gas, tar, and biochar was 35.9–45.2, 27.9–38, and 26.2–28.7 wt%, respectively [42]. Ref. [41] demonstrated the use of a concentrator-equipped xenon light (5 kW) to replicate the solar pyrolysis of woody biomass. The nitrogen gas increased the temperature in a vertical quartz tube [38]. The product separation occurs in four stages, utilizing four tubes consisting of a heated ethylene glycol

bath at 120 °C; the second stage is a heated water bath at 70 °C, then a room-temperature water bath at 22 °C, and the last stage is a water/ice bath at 0 °C. The overview of biomass pyrolysis with solar assistance and solar simulation is shown in Table 4.

Table 4. Overview of solar–biomass pyrolysis with solar assistance and solar simulation source.

S/No	Biomass	Reactor	Reactor Configuration	Concentrator	Power	Max. Flux Density	Outcomes	Source
1	Orange peel	Borosilicate glass tube	Horizontal	Parabolic trough covered with a silver mirror coating placed according to the angle of sunlight	–	27,088 W/m ²	1.4, 21, and 77.6 wt.% for gas, char, and oil, respectively	[8]
2	Agave leaves and tomato waste	Borosilicate spherical-shape	Vertical	Parabolic	Temperature range 450–1550 °C 25 kW,		Biochar produced at a low temperature of less than 900 °C had a good surface area and capacitance	[10]
3	Date palm	Steel reactor (partial heating)	Vertical	Double parabolic dish	-	-	50 wt.% found for liquid oil at a 500 °C operating temperature, a gas flow rate of 6 L/min, a 120 min residence time, and 32.4% of CO ₂	[11]
4	Rice straw	Cylindrical silica glass tube	Horizontal	Dish concentrator	-	-	-	[17]
5	Wheat straw	Rotary stainless cylindrical kiln	Horizontal retort	Linear mirror II	-	-	Solar carbon of 16.9 MJ/kg energy density	[23]
Solar Simulated Biomass Pyrolysis								
6	Chicken litter	Copper, Indirect (conduction)	Vertical	Elliptical reflector	2.2 MWm ⁻²	0.6 kW Xenon arc lamps	The maximum CO and H ₂ yields were 63 wt.% and 15 wt.%, obtained at 50% CaO in situ loading at 800 °C	[24]
7	Pine sawdust	Cylindrical quartz reactor	Vertical	Deep-dish parabolic concentrator	-	5 kW Xenon arc lamps	-	[25]
8	Waste biomass	Copper, indirect (conduction)	Vertical	Elliptical reflector	2.2 MWm ⁻²	1.6 kW Xenon arc lamp	-	[111]
9	Wood	Quartz tube	Vertical	Direct concentration	-	5 kW arc Xenon bulb	Heavy tar and light bio-oil	[27]
10	Foam material	Solar-driven DRM in a foam reactor	Horizontal	Direct concentration	-	Maximum values of 55.74% and 45.58% are observed at $\phi = 0.9$, $d_p = 1.5$ mm	-	[28]
11	Jatropha biomass seeds	FTIR, TGA, and GC–MS analysis	Vertical	Direct concentration	-	Jatropha seeds biomass consists of 55.8% C, 4.78% H, 7.36% N, 0.93% S, 31.13% O	Three pyrolysis products: (i) bio-oil, (ii) biochar, (iii) pyrolytic gas	[114]

3.1.2. Horizontally Oriented

The literature [134] has few studies employing a horizontal reactor orientation. The horizontal fixed-bed solar-based pyrolysis system for orange peel (Figure 9) comprises many condensation tubes, a hub, a 1.3 m wide parabolic concentrator, and a reactor made of borosilicate glass tubes. The hub is based on a single axis to concentrate the whole structure and is the supporting framework. The gas used in the inert state was helium. The feedstock is the hottest component of the system since the system was built to allow for

direct irradiation of the biomass. Light enters from below the reactor, and the condensation at the reactor exit collects the volatile fluid.

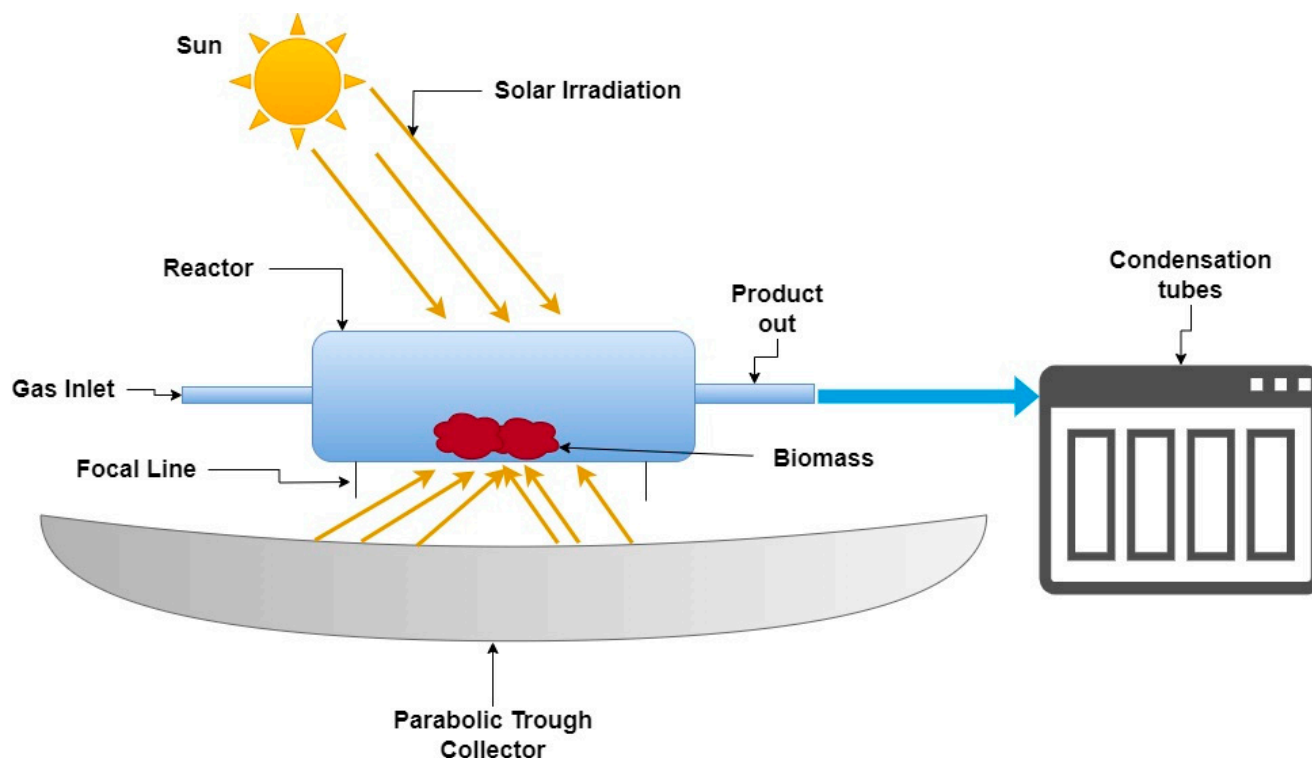


Figure 9. Fixed-bed horizontally oriented solar–biomass pyrolysis reactor. Reproduced from [33]. With permission from Elsevier B.V. All rights reserved.2025, (License No: 6022930342936).

The resulting gas was collected at about 200 °C in a cooling tube dipped in liquid nitrogen. With an average flux of 12,553 W/m², the most concentrated sunlight level obtained was 27,088 W/m², with yields from the orange peel of 1.4, 21, and 77.6 (wt%) for gas, char, and oil, respectively. An inclined hypothetical fluidized-bed horizontal reactor was proposed by [41]. Hot nitrogen injected from one end to the other made the biomass more fluid. A parabolic concentrator aimed directly at the reactor wall helped to maintain the pyrolysis process [131]. A conical flow deflector separated the gas and solid phases, allowing the gas-free solid to pass through an inserted pipe. This separation approach allows for more precise control of the gas residence period while reducing the time spent between the char and the gas after production, which in turn reducing the gas's thermal and catalytic cracking and increasing bio-oil output [54]. The CNRS laboratory in Odeillo, France, used a thermal–solar horizontal reactor for biomass pyrolysis. The concentrating device was a parabolic-trough mirror located at the overhang part of a building, while the heliostat was at the southern position of the structure [22]. The arrangement of the apparatus permitted direct exposure of the feedstock to radiation. The findings demonstrated that while the distribution of sunlight's spectra did not affect gas yield, it did change depending on where the sample was concerning the furnace's focus point [55].

Furthermore, they claimed that yield would rise using the gas-phase pyrolysis of vapor and the two-step pyrolysis of biomass politicization. Ref. [25] introduced a horizontally oriented fixed-bed reactor (silica glass tube) for the solar–biomass pyrolysis of chicken litter waste [24]. The same reactor was utilized for solar pyrolysis rice husk, as shown in Figure 10. With the aid of quartz wool, the biomass was compacted in the middle of the tube. On end of the fixed-bed reactor was linked to an argon carrier gas to provide an inert environment, while the other end was linked to an ice chamber to monitor any byproducts.

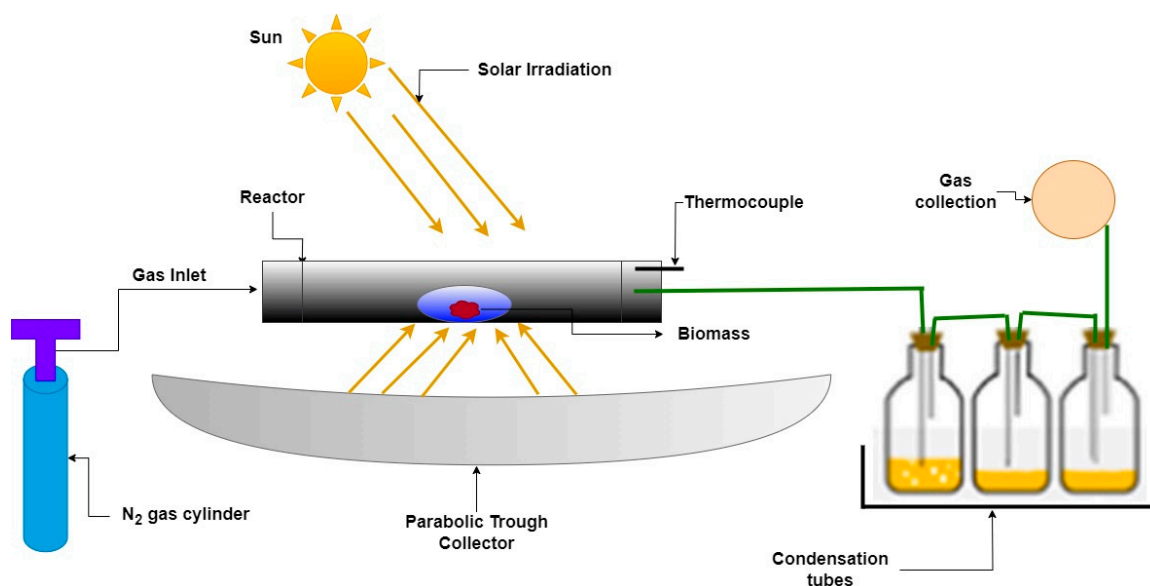


Figure 10. Horizontal-oriented solar-biomass pyrolysis reactor. Adapted from [23].

A 1.8 m diameter parabolic dish concentrator that has 88% reflective aluminum polyethylene terephthalate laminated on its surface was used to harness solar energy. A slow-revolving motor drives a rotational horizontal stainless reactor, also known as a cylindrical retort kiln, as [111] demonstrated. The concentrator was an array of four linear mirrors positioned in two rows with an angle of about 2° that follows the sun. A deflector placed at the mirrors' focal axis helped to divert the concentrated solar radiation toward the reactor. The setup produced 16.9 MJ/kg of the energy density of solar carbon. Figure 11 shows the schematic diagram of the solar-biomass pyrolysis system for producing biofuels. A parabolic-trough solar concentrator was used in investigations [127] on orange-peel pyrolysis caused by solar radiation as a novel energy source. At the center of the focus line, the solar pyrolytic reactor reached a peak temperature of 465°C with a mean irradiation of 12.55 kW/m^2 , and the orange peel lost 79 wt.%.

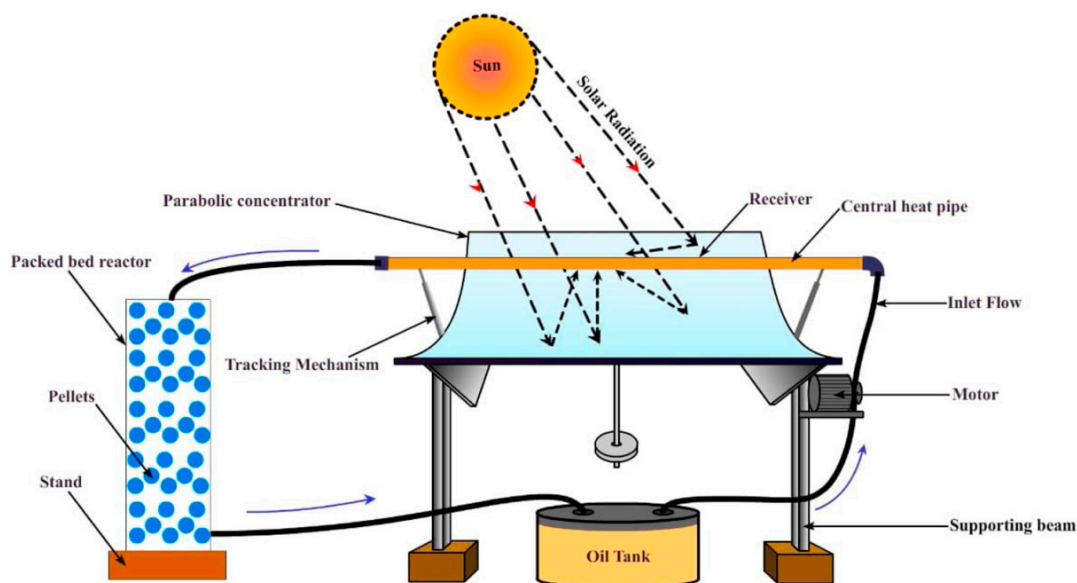


Figure 11. Experimental setup of parabolic-trough collector coupled with packed-bed reactor. Reproduced from [135] with permission from Elsevier B.V. All rights reserved, 2025 (License No: 6022921511008).

4. Economic Analysis of Solar–Biomass Pyrolysis vs. Conventional Pyrolysis

The main expenses for solar–biomass pyrolysis involve purchasing solar concentrators with their corresponding thermal systems since these systems need high-performance solar collectors, tracking systems, and thermal storage technologies. Long-term fuel cost savings can be achieved through solar energy because once it is captured, it becomes available for free instead of having to pay for expenses for conventional energy sources. The maintenance requirements for solar–biomass pyrolysis systems decrease in the long term since solar concentrators need no moving elements and less operational assistance than traditional fossil fuel heating systems. The initial expenditure on the system will eventually pay off because solar energy provides a renewable energy supply ready to sustain operations for extended periods. Table 5 compares solar biomass and conventional pyrolysis based on their cost per unit energy output and Energy Return on Investment (EROI).

Table 5. Comparing solar–biomass pyrolysis and conventional pyrolysis based on their cost per unit energy output and Energy Return on Investment (EROI).

Parameter	Solar–Biomass Pyrolysis	Conventional Pyrolysis (Fossil-Fuel-Based)
Initial Capital Cost	High (due to solar concentrators, tracking systems, and thermal storage)	Low (standard reactor design and fossil fuel infrastructure)
Fuel Costs	Low (solar energy is free once the system is established)	High (dependence on fossil fuels for heating)
Energy Input (per unit energy output)	Low (solar energy)	High (fossil fuel consumption)
Energy Return on Investment (EROI)	High (due to renewable energy input and lower operational costs)	Low (due to fossil fuel input and associated environmental costs)
Operational and Maintenance Costs	Moderate (solar systems are low-maintenance, but initial setup costs are high)	High (continuous fuel purchase, maintenance of fossil fuel infrastructure)
Environmental Impact	Low (carbon-neutral, renewable energy source)	High (emissions from fossil fuels, environmental degradation)
Product Yields	Bio-oil: 50–60%, syngas: 30–40%, char: 10–20%	Bio-oil: 40–70%, syngas: 10–30%, char: 20–40%
System Scalability	Moderate (scaling is possible but requires extensive solar infrastructure)	High (easier to scale with existing infrastructure)
Payback Period	Longer (due to high initial capital costs but savings in fuel costs over time)	Shorter (lower initial investment but higher long-term fuel costs)

The initial expenses of traditional fossil fuel-based conventional pyrolysis systems remain affordable, yet continuous operational costs increase because of fuel purchases, fuel price instability, and environmental compliance requirements. Solar heat and power systems produce greater environmental strain because they emit carbon while burning fossil fuels. The initial low investment costs in fossil fuel-based pyrolysis result in higher long-term expenses because it requires an external fuel supply and incurs rising operational and environmental costs alongside the price volatility of fossil fuels. The EROI of solar–biomass pyrolysis systems surpass fossil-based pyrolysis operations in EROI calculation. The extended energy benefits of solar–biomass pyrolysis emerge from its low solar energy costs even though the process demands high upfront solar infrastructure financing. The constant use of fossil fuels within conventional pyrolysis systems decreases the EROI value because the energy output eventually becomes lower than the initial investment amount. Solar energy allows solar–biomass pyrolysis systems to sustain a remarkably high EROI because solar power is renewable, thus offering better sustainability alongside economic advantages.

5. Conclusions

The examination within this review provides an extensive review of solar–biomass pyrolysis processes to evaluate their potential as a sustainable biomass conversion technology. A detailed evaluation of solar-energy–biomass pyrolysis reactor designs, operational rules, and solar integration methods showed how this system delivers lower emissions with substantial sustainability benefits to the energy output. Technical barriers obstruct the growth potential of solar–biomass pyrolysis systems because they make it hard to control solar flux in real time and integrate energy storage and scale reactor systems effectively.

Our research is directed toward three specific goals that address the technical barriers found in the review. The goals are to focus on solar flux control advancement, combine solar and biomass pyrolysis with energy storage methods, and develop scalable reactor frameworks. These steps represent essential measures for the commercial progress of solar–biomass pyrolysis systems while improving their potential to support sustainable energy transformation.

Future research should focus on developing dynamic reactor designs, incorporating advanced materials, and integrating hybrid systems to overcome existing challenges. By advancing the architecture and operational strategies of solar–biomass pyrolysis, this field can play a pivotal role in meeting global energy demands sustainably. The insights provided in this review offer valuable guidance for researchers, engineers, and policymakers working towards a cleaner, more sustainable energy future.

1. Identifying Technical Gaps:

- ✓ Intermittent solar radiation continues to prove challenging for solar–biomass pyrolysis operations. Researchers should create control algorithms for solar concentrators that respond to current solar conditions.
- ✓ Solar radiation variability causes operational problems in solar power systems. The system requires a large storage capacity to function smoothly through cloudy weather or nighttime conditions.
- ✓ The expansion of solar–biomass systems demands solutions that handle reactor dimensions, biomass conversion methods, and electrical power delivery solutions.

2. Suggesting Research Directions:

- ✓ The research field needs to study solar concentrators that employ feedback loops and dynamic logic to sustain stable solar flux despite varying weather patterns. Intelligent materials that detect flux require implementation as an integral component for success.
- ✓ Scientists must create inexpensive thermal storage systems to accumulate solar energy when sunlight reduces. There is a need to investigate hybrid power systems that unite biomass technologies with solar power generation to achieve reliable heat delivery.

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