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Inayat, Abrar, Ahmed, Ashfaq, Tariq, Rumaisa, Waris, Ammara, Jamil, Farrukh, Ahmed, Shams Forruque, Ghenai, Chaouki and Park, Young-Kwon (2022) Techno-economical evaluation of bio-oil production via biomass fast pyrolysis process: a review. Frontiers in Energy Research, 9. ISSN 2296-598X

frontiers
in Energy Research

MINI REVIEW
published: 13 January 2022
doi: 10.3389/fenrg.2021.770355

Techno-Economical Evaluation of Bio-Oil Production via Biomass Fast Pyrolysis Process: A Review

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Specialty section:
This article was submitted to
Bioenergy and Biofuels,
a section of the journal
Frontiers in Energy Research

Received: *03 September 2021*
Accepted: *21 December 2021*
Published: *13 January 2022*

Citation:
Inayat A, Ahmed A, Tariq R, Waris A, Jamil F, Ahmed SF, Ghenai C and Park Y-K (2022) Techno-Economical Evaluation of Bio-Oil Production via Biomass Fast Pyrolysis Process: A Review.
Front. Energy Res. 9:770355.
doi: 10.3389/fenrg.2021.770355

Biomass pyrolysis is one of the beneficial sources of the production of sustainable bio-oil. Currently, marketable bio-oil plants are scarce because of the complex operations and lower profits. Therefore, it is necessary to comprehend the relationship between technological parameters and economic practicality. This review outlines the technical and economical routine to produce bio-oils from various biomass by fast pyrolysis. Explicit pointers were compared, such as production cost, capacity, and biomass type for bio-oil production. The bio-oil production cost is crucial for evaluating the market compatibility with other biofuels available. Different pretreatments, upgrades and recycling processes influenced production costs. Using an energy integration strategy, it is possible to produce bio-oil from biomass pyrolysis. The findings of this study might lead to bio-oil industry-related research aimed at commercializing the product.

Keywords: fast pyrolysis, biomass, bio-oil, economic analysis, production cost

INTRODUCTION

Biomass is becoming the most promising alternative source for producing clean and sustainable products, because of its communal availability, relatively lower price, and zero harmful emissions (Li et al., 2004). According to a report, biomass accessibility is abundant for biofuel production worldwide (Trinh et al., 2020). Bioenergy is the energy derived from the different sources of biomass (Adams et al., 2018). Biomass originates from microbes and vegetation (Boran, 2018). It comprises all the organic and biological constituents from living organisms produced by direct or indirect processing (Nachenius et al., 2013). It can be classified further into agriculture biomass, forestry biomass, crops, wood-based biomass, municipal and industrial waste, food waste, animal and human-generated waste. Biomass is the fourth primary energy source and currently delivers 14% of prime energy (Tabakaev et al., 2019). Biomass can be transformed into biofuels through biological and thermal conversion approaches. On the other hand, the biological conversion approach is unstable at the commercial level because it employs all stresses on food-based raw materials (Naik et al., 2010). On the other hand, the thermal conversion approach, such as pyrolysis, gasification, and combustion, has a wide range of raw materials in a shorter period and deals with multiple and intricate biofuels (Bridgwater, 2012; Shahbaz et al., 2016; Ghenai et al., 2019; Inayat et al., 2020). These biofuels have variations in physicochemical composition and properties, which helps deal with unique practical and economic challenges (Shemfe et al., 2015).

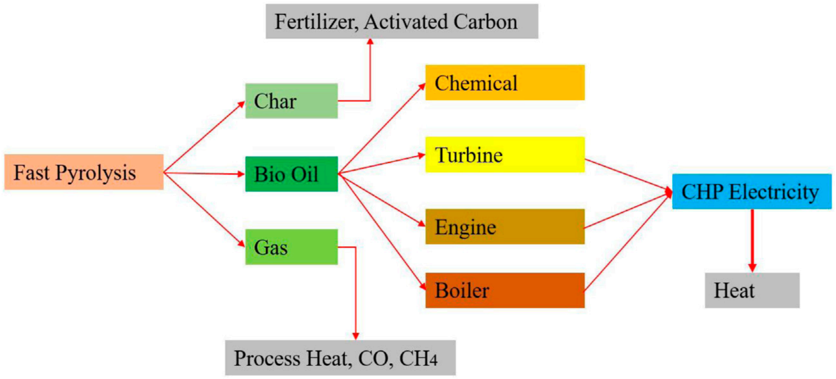

FIGURE 1 | Products of fast pyrolysis of biomass.

Fast pyrolysis is considered the most promising approach to generate liquid fuel, such as bio-oil, at its maximum extent among all these thermal conversion methods. According to an estimate, fast pyrolysis can produce up to 75 wt% bio-oil, which can be used in many applications directly or as an energy carrier after upgradation (Czernik and Bridgwater, 2004). Fast pyrolysis is a suitable process for converting biomass into bio-oil in an inert atmosphere at the medium temperature range from 400 to 600 C using a short residence time of approximately 2–10 s and higher heating rates. Various conditions, such as raw material, reactor type, temperature, additives, catalysts, residence time, and pressure, greatly influence the performance and quality of the product (Zhang et al., 2011). Bio-oil obtained from fast pyrolysis contains oxygenated organic compounds and water, making it unstable and corrosive. Therefore, upgrading is necessary for deoxygenation to make it compatible with refinery fuels (Sorunmu et al., 2020).

Many research articles have been published on optimizing bio-oil production from various biomass using a fast pyrolysis process under different operating conditions (Chen et al., 2019; Nzihou et al., 2019; Marathe et al., 2020). On the other hand, there is a lack of information on economic analysis comparison on fast pyrolysis process to make it commercially stable. The commercial practicability of bio-oil is based on reducing the manufacturing cost, enhancing the product quality, and improving accessibility to an abundant and sustainable source of biomass. Economic analysis is a helpful strategy to assess the potential of the process to scale up using product cost prediction (Kim and Parker, 2008). Economic analysis can be done using different approaches with an experimental study and developed mathematical models to make any process feasible at the market level (Zhang et al., 2013). Literature showed many research papers and case studies published on the economic analysis of pyrolysis used for bio-char and bio-oil production. There is a need to provide a platform specifically for economics analysis and cost of the bio-oil output using a fast pyrolysis process. This work aims to provide valuable information on the economic evaluation of bio-oil produced by different biomass via the fast pyrolysis process.

BIO-OIL PRODUCTION VIA FAST PYROLYSIS

Fast pyrolysis is a technique of changing different biomass types in the absence of air or O_2 to generate three types of products based on their nature, i.e., solid char, liquid oil, and volatile gas, by thermal breakdown of the material. Pyrolytic gas is generated in this process. A dark brown homogenous liquid is produced with a high heating value known as bio-oil upon cooling and condensing. **Figure 1** shows the schematic diagram of biomass pyrolysis (Bridgwater, 2017). Three main products (biochar, bio-oil, and syngas) are produced from the fast pyrolysis of biomass. Bio-oil can be used as a fuel in engines and boilers, used further for electricity and heat production via combined heat and power (CHP) plants. This temperature range of this process is typically 350–600°C, but the temperature for the maximum yield is most commonly around 500°C; the residence time is shorter, approximately 2 s, and the heating rate is higher (Wang and Jan 2018). The biomass should be dried to the level of less than 10% moisture and ground to fine particles for optimal yield and improved bio-oil quality. Bio-oil produced from fast pyrolysis usually contains 15 to 30 wt% water, reducing its viscosity and making it capable of combustion engines. The carboxylic acid of bio-oil has a significant effect on pH (Zhang et al., 2007). The acidity with pH = two to three makes the bio-oil corrosive, which imposes additional costs during the upgrading process of bio-oil before it can be used as a fuel in the transport industry.

The heart of the pyrolysis process is the reactor, where all biomass conversion reactions occur. Many reactors are used in the pyrolysis process, such as entrained flow reactors, fluidized bed reactor, fixed bed reactor, autoclave, rotating cone reactor, and plasma reactor (Garcia-Nunez et al., 2017). These reactors can be classified into subcategories according to the flow of material and phenomena, such as circulating, co-current, counter-current, and crossflow. The amount of bio-oil depends on the type of reactors being used and the operating conditions (Peacocke et al., 1994; Abu Bakar et al., 2020).

Table 1 lists the experimental work conducted by different researchers using different temperature ranges for bio-oil production from the fast pyrolysis of biomass. Chandran et al.

TABLE 1 | Experimental work on the fast pyrolysis of biomass for bio-oil production.

Sample	Reactor	Temperature range	Bio-oil yield	References
Palm kernel cake	Bubbling fluidized bed reactor	350–600°C	63% at 401°C	Jeong et al. (2020)
Prosospis juliflora	Continuous blade type reactor	350–800 C	50.2% at 450 C	Chandran et al. (2020)
Sawdust, Empty fruit bunch, Miscanthus	Circulating fluidized bed reactor	400–600 C	60% at 500 °C	Park et al. (2019)
Pomegranate marcs (PM) and grape marcs (GM)	Fixed bed reactor	400–600 C	43.7% at 500 C	Ateş et al. (2019)
Rape straw	Continuous bubbling fluidized bed reactor	450–550 C	41.39% at 480 C	Gómez et al. (2018)
Sugarcane bagasse	Batch pyrolysis reactor	653–1053 K	50.89% at 753 K	Al Arni, (2018)
Sewage sludge	Conical spouted bed reactor	450–600 C	77% at 500 C	Alvarez et al. (2016)
Saccharine japonica alga	Fixed-bed reactor	350–550 C	40.19% at 500 C	Ly et al. (2016)
Corn cob, Corn Stover, Sawdust Rice straw	Microwave-assisted reactor	400–500 C	42.1%	Ravikumar et al. (2017)
Pinewood, oak wood, rice husk	Rotating cone reactor	550–700 C	70%	Wagenaar et al. (1994)

(2020) examined the effects of temperature on the bio-oil product of a unique biomass Prosospis Juliflora. They tested its performance as a blending agent using a 35% bio-oil blended with diesel at the diesel engine's fully loaded condition. Borges et al. (2014) reported a maximum 65 wt% and 64 wt% of bio-oil yield achieved at a temperature of 480°C and 490°C, respectively, with 0.9–1.9 mm size feed of wood sawdust and corn stove in microwave-assisted pyrolysis and applying a vacuum of less than 100 mmHg. Chen et al. (2017) examined the influence of temperature and catalyst amount in the fast pyrolysis of cotton stalk using a fixed bed reactor. The results showed that the percentage of ketone in bio-oil increases as the CaO amount as catalyst increases. Furthermore, as the temperature was increased above 600°C, the amount of bio-oil decreased, and the gaseous product increased. The bio-oil yield was higher between 500 and 600 C despite using different types of biomass and reactors (**Table 1**).

ECONOMIC ANALYSIS FOR BIO-OIL PRODUCTION

Economic analysis involves checking or testing the economic practicability of a process or product under a progressive stage, which helps track future research, expansion, and investment (Sharma et al., 2019). Financial analysis is related to determining the price of manufacturing, selling, investing, and marketing. Furthermore, the calculated values can help predict the future cash flow and return on investment. Different types of sustainability and business models, such as the triple bottom line analysis model and pay as you go model, are available for analyzing sustainability development (Sharma et al., 2019). Economic analysis is based on methods, size of the plants (laboratory, pilot, or commercial), availability, and continuous feedstock supply. Feed supply and product cost analysis are critical challenges to making the product market compatible—several factors are involved in the economic analysis. Fixed capital investment (FCI) refers to funds used to purchase manufacturing and plant infrastructure, while working capital refers to funds used to maintain factory operations. The total capital investment is the sum of the fixed capital investment and the working capital. Manufacturing fixed capital investment (direct cost) and non-manufacturing fixed capital investment may be separated into two categories (indirect cost). Capital needed to complete the process operation, such as site preparation, piping, instrumentation and auxiliary equipment, is included in manufacturing fixed-capital investment. In contrast, non-manufacturing fixed-capital investment includes construction overhead and components unrelated to the process operation (Inayat et al., 2017). Furthermore, the total direct production cost is calculated based on feedstock and utility costs. Total product cost highly depends upon both fixed capital and total product cost.

Using a blended feedstock (mixture of two or more different biomass) is beneficial because of the massive variety in biomass selection, lower risk, and lower carriage costs (Oasmaa et al., 2010). Bio-fuel upgrading is another suitable technique for making a product commercially feasible. Fast pyrolysis and upgrading of crude bio-oil can be carried out with or without the catalyst. Several kinds of catalysts used for the bio-oil upgradation (N_i, zeolite, Al_2O_3, P_d, P_t, TiO_2, etc) (Mortensen et al., 2011; Miandad et al., 2019; Farooq et al., 2021). The catalytic bio-oil has less acidic and oxygen compounds than non-catalytic bio-oils. These properties prove that the scale-up of catalytic pyrolysis is more favorable from an economic point of view because of the lesser requirement of additional equipment (Sorunmu et al., 2020). Recycling is another route to enhancing economic potential. Research has been conducted on rape straw, corn stalks, and camphor wood, in which gases produced during the pyrolysis process are recycled (Yang et al., 2018).

Table 2 lists the techno-economic analysis presented by several researchers for bio-oil production using the fast pyrolysis of biomass. The final percentage yield of bio-oil is one of the most substantial constraints affecting process economics. Meyer et al. (2020) conducted an economic evaluation of six lignocellulosic biomass. The maximum bio-oil yield was obtained through pine, while switchgrass provided the minimum product. Wang et al. (2019) performed a techno-economic analysis of the products obtained from the cotton stalk. They concluded that the production capacity could reach approximately 18,000 tons per year with a manufacturing cost of \$3/kg. The research was conducted to determine the potential economic use of rice straw in thermochemical conversion techniques. The results showed that bio-oil production through pyrolysis from rice straw is economically viable. Usually, only 46–65% of the biomass is converted (Diehlmann et al., 2019).

TABLE 2 | Techno-economical analysis of bio-oil produced from fast pyrolysis.

Sample	Plant size or feed rate	Process	Software	Economic analysis findings	References
Pine Tulip poplar Hybrid Poplar Switchgrass Corn stover Oriented strand board	2000 tons per day	Bubbling fluidized bed reactor pyrolysis oil upgrading	CHAMCAD	Capital cost: 30–40% Feedstock cost: 30% Hydrotreating catalyst cost: 13–18% Labor cost: 12–15%	Meyer et al. (2020)
Forest residue	5 kg/h	Continuous rotatory kiln reactor	Aspen Plus	The minimum selling price of upgraded bio-oil was more than double that of crude bio-oil	van Schalkwyk et al. (2020)
Corn cob	96.5 ton per hour	Fluidized bed reactor and hydrotreating	PYROL HYSYS	The least tolerable product prices for the economic feasibility of pyrolysis route US$ 1.47/gasoline-gallon-equivalent bio-oil	Brigagão et al. (2019)
Sugarcane bagasse	10 tons per hour	Pyrolysis reactor and hydrotreating	Aspen Plus	Fluctuating tax charges and capital costs can not disturb the least selling price as much as conversion ratios	Ramirez and Rainey (2019)
Eucalyptus	2000 metric ton per day	Tail gas reactive pyrolysis (TGRP) and electricity generation plant	Pro/II simulator	The results specified that pyrolysis of eucalyptus for power in a single facility is not good with the current electricity cost	Pighinelli et al. (2018)
Rice husk	1,000 tons per day	fluidized-bed fast pyrolysis	Aspen Plus	The least bio-oil selling price was intended as $ 0.55/L	Wang and Jan (2018)
Wheat straw Corn cob Sawdust	100 kg/h	Internally interconnected fluidized bed reactor and pretreatment unit	Aspen plus	The mobile pyrolysis system has a better long-term economy than the fixed plant due to the higher turnover	Chen et al. (2018)
Pinewood	72 tons per day	Pyrolysis reactor with catalytic cracking	Aspen plus	The outcomes deliver indication to the provision of biofuel production’s economic viability via zeolite cracking of pyrolysis-derived bio-oil	Shemfe et al. (2017)
Rice husk	4,000 kg per hour	Pretreatment Pyrolysis reactor	Aspen Plus	The production cost of liquid fuel is less than the expected selling price of pyrolysis liquid with 6 years payback period	Ji et al. (2017)
Sugarcane bagasse	1,000 tons per hour	Fast pyrolysis and hydrotreating	Financial and risk analysis simulator	Fisher-Tropsch synthesis is the more efficient option than the fast pyrolysis approach	Michailos et al. (2017)
Forest residue	2000 dry metric tons per day	Pyrolysis reactor hydrothermal treating	Lab experiment and Aspen Plus	With a 30-years project life, a minimum fuel selling price was determined to be 6.25 $ per gallon	Carrasco et al. (2017)
Empty fruit bunch	400 tons per day	Fast pyrolysis reactor and upgrading unit	A four-level economic potential approach	The bio-oil plant is the most economical due to the highest economic potential for the rate of interest and return rate	Do and Lim (2016)

BIO-OIL PRODUCTION COST AND LIFE CYCLE ANALYSIS

Economic analysis is mainly based upon capital cost and cash flow analysis, as shown in **Figure 2** (Mohammed et al., 2019). This analysis will help determine the investment required to run a plant every year and the production cost of bio-oil (Rogers and Brammer, 2012). The cost can be calculated by capacity factored (heat and mass balances, power supplies, size) and equipment-based assessment and quotation from vendors (Uslu et al., 2008). Sensitivity and uncertainty analysis is dependent on the fluctuations of the price rate of different parameters, such as feedstock, labor, electricity, taxes, and total plant running time (Oudenhoven et al., 2016). The additional economic analysis leads to the production cost of bio-oil, which can be compared with fuel produced from other sources and methods (Jaroenkhasemmeesuk and Tippayawong, 2015). This can be reduced by applying different pretreatments, upgrading, and recycling techniques. The sale of by-products produced in biomass pyrolysis, such as biochar, can reduce the bio-oil production cost by 18% (Rogers and Brammer, 2012).

Operations cost, payback period, and break-even analysis are used to examine the link between anticipated project cost and the rate of return. Entire revenue and total costs must be equal for a company to break even, which is known as the breakeven point. A point at which the projected selling revenues plus the anticipated sale proceeds after upgrading are equal to production costs

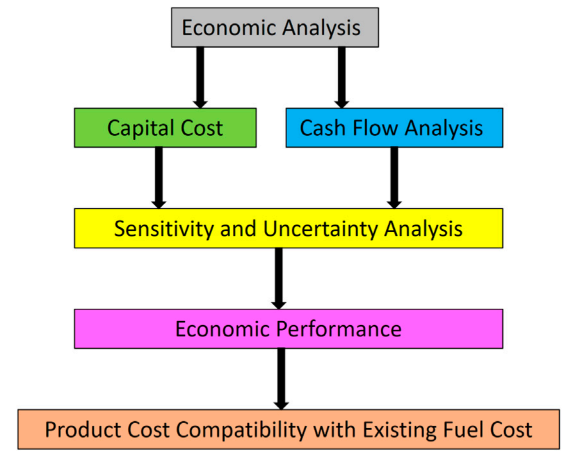

FIGURE 2 | Methodology flow chart of economic analysis.

(Jaroenkhasemmeesuk and Tippayawong, 2015). The plant's lowest break-even selling point may be attained by employing the most inexpensive biomass available. The minimal feasible price for a given plant size was the risk event with the most significant break-even selling point (Rogers and Brammer, 2012).

Table 3 lists the cost of bio-oil produced from the fast pyrolysis of diverse types of biomass. Patel et al. (Patel et al., 2019) examined bio-oil production cost from the fast pyrolysis of 2000 tons per day woodchips and reported 1.09 $/L. They also tested the feasible plant size optimization from 500 to 5,000 tons per day and determined that a 3,000 tons per day capacity is well suited based on economic analysis. Xin et al. (2016) performed an economic analysis to determine the cost of bio-oil and co-products using a unique approach (cultivating, harvesting, dewatering, fast pyrolysis, and bio-oil utilization of water-based waste algae and estimated a price of $ 2.23/gallon bio-oil, which is an almost acceptable level. The return rate could surge to 18.7% if three grave mechanisms, such as cultivation, harvest, and conversion, can be advanced. Li et al. (2015) conducted a cost analysis of biomass in *in-situ* and *ex-situ* catalytic pyrolysis. The least fuel-selling price of bio-oil from the *in situ* process was $1.11 per liter, whereas the *ex-situ* process was $1.13 per liter. Heat integration application in pyrolysis leads to the sustainability of the process via energy recovery and reduces the overall process's utilities cost. The overall pyrolysis process is endothermic, and heat is required for the complete the significant reactions. The combustible gases produced as a co-product during fast pyrolysis can also provide the process heat. These approaches reduce the overall utilities and operation cost, which positively affect

TABLE 3 | Cost of bio-oil produced from fast pyrolysis.

Source of bio-oil	Process	Capacity	Cost of bio-oil	Ref
Municipal sewage sludge	Pyrolysis, Gas Chromatography, Mass Spectroscopy Aspen Plus	50 kg/h	3.130 (€/kg)	Shahbeig and Nosrati (2020)
Napier grass bagasse	Pyrolysis *In situ* hydrodeoxygenation	49 kg/h	$ 5.81/gallon ($ 1.45/L) gasoline equivalent	Mohammed et al. (2019)
Sludge Scum	Integrated system with pyrolysis	3.5 wet tons of scum, 265 dry tons of sludge daily	$ 1.85/gallon	Xin et al. (2018)
Horse manure	Tail gas reactive pyrolysis (TGRP)	200 metric dry ton per day	($ 1.35–$ 1.80 L^{-1}) of jet fuel by upgraded bio-oil	Sorunmu et al. (2017)
Pine	Pretreatment Fast pyrolysis Catalytic upgrading Heat integration	1,000 dry metric ton per day	4.01–4.78 $/gal for the heat-integrated process 4.70–6.84 $/gal without heat integration	Winjobi et al. (2017)
Sorghum bagasse Corn stove Palm kernel Switchgrass	The regression-based chemical process model	2000 metric tons per day (MT/d)	$ 2.5 to $ 5 per gallon	Li et al. (2017)
Beechwood	Pre-treatment Catalytic circulating fluidized bed reactor	500 MT/day	2.32–3.08 $/gallons	Vasalos et al. (2016)
Pinewood	Fast pyrolysis Hydro processing Economic analyzer	72 MT/day	£ 6.25/GGE	Shemfe et al. (2015)
Red oak	Fast pyrolysis Five-stage fractionation system	2000 dry metric tons per day	$ 3.09/gallon	Hu et al. (2016)
Microalgae	Pretreatment Catalytic Pyrolysis Chemical process modeling	2000 MT per day	$ 1.49 and $ 1.80 per liter	Thilakaratne et al. (2014)

the bio-oil production cost. Economic analysis showed that the operating cost of the process was decreased using blended feedstock. Catalytic upgrading contributes to the operational cost and can be reduced using a less expensive catalyst. Furthermore, pyrolysis plants with a higher capacity can produce less expansive bio-oil than smaller plants. In addition, downstream methods, such as solvent addition, emulsification, electrolytic, and electrochemical processes for upgrading bio-oil should be developed for a cost-effective process (Kumar and Strezov, 2021).

Bio-oil is used as a feedstock for boiler and heavy-duty engines. Furthermore, bio-oil is also used as a feedstock to produce several products, such as hydrogen, chemicals, binder for electrodes, and plastics. Bio-oil is commonly used for boilers as an alternative to furnace oil because of the advantages of low emissions (Hou et al., 2016). From an economic point of view, the direct burning of bio-oil in boilers for heating is considered competitive with fossil fuels (Brammer et al., 2006). Co-firing bio-oil with conventional fuels is energy-efficient and cost-effective. Particular burner technologies, such as duel block systems, have been adopted in commercial plants for bio-oil burning (Lehto et al., 2014). Bio-oil is also considered a potential candidate for hydrogen production via catalytic cracking commercially (Wang et al., 2013). In addition, several chemicals and solvents can be produced from bio-oil on a commercial scale via distillation. In bio-oil applications, the cost is considered the main barrier to the commercialization of bio-oil on a large scale.

For biomass conversion pyrolysis processes, life cycle assessment (LCA) is widely accepted as a valuable framework for analyzing environmental, human, and natural resource effects (Iribarren et al., 2012; Opatokun et al., 2017). For long-term strategic policy and environmental sustainability, it delivers scientific proof data. The LCA professionals and decision-makers have to find the paths to environmental sustainability and energy efficiency while considering the concepts simulated in the research (Osman et al., 2021). Han et al. (2013) performed LCA for the pyrolysis process using a well-wheel approach. The greenhouse gases (GHG) emissions were reduced to 112% using the pyrolysis process. Meyer et al. (2020) studied the LFA with the effect of feedstock composition on the fast pyrolysis process and evaluated the GHG and economic analysis. Field to wheel approach used for data generation. Pyrolysis oil upgrading, electricity used in the pyrolysis process, energy used in biomass harvesting and processing are the essential variables in GHG emissions. GHG elimination may not always be in the best interest of the economy.

CONCLUSION

Fast pyrolysis is the most beneficial method to extract bio-oil products from biomass feedstock. Bio-oil and its properties differ considerably depending on the feedstock configuration and structure, residence time, and temperature. Several research articles have been published on optimizing bio-oil production from various biomasses using a fast pyrolysis process under different operating conditions. Few reports on economic analysis of the fast pyrolysis process make it commercially stable. This review article evaluated fast pyrolysis's technical and economic routine to produce bio-oils from various biomass. A series of aspects, such as plant life expectancy, raw feed, technological parameters, and biomass price, regulate the economic stability of bio-oil production from fast pyrolysis. The temperature range from 500 to 600 C produces a higher bio-oil yield, reducing overall production cost. The production cost of bio-oil is the critical factor for evaluating the market compatibility with other biofuels available. The cost can be affected by different pretreatments, upgrading processes, and recycling techniques. The torrefaction of biomass as a pretreatment and upgrading of bio-oil using a less expensive catalyst will lead to cost-effective biomass pyrolysis for bio-oil production. A self-sustained pyrolysis process can reduce the bio-oil production cost and is most economical on a commercial scale. This review can aid future studies on bio-oil production in terms of the commercial sector's economic benefits. Furthermore, there is a need to develop systematic autonomous algorithms required for the prediction of minimum bio-oil production cost based on the parametric study.

AUTHOR CONTRIBUTIONS

AI and AA developed the conceptualization and methodology of the study. RT and Y-KP managed resources, provided supervision and valuable research insights into the study. FJ, and SA provided literature resources and helped in analysis. CG contributed to the writing and provided valuable research insights. All authors have read and agreed to the published version of the manuscript.

FUNDING

The authors would like to acknowledge the financial support from the University of Sharjah, United Arab Emirates, through the Competitive Research Project (1602040654-P). Also, the support from the National Research Foundation of Korea under the projects (NRF-2020R1I1A1A01072793, NRF-2020M1A2A2079801) is gratefully acknowledged.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.