

A Review on Bio-Oil Production from Agricultural Waste Based on Various Processes, Bio-Oil Yield and Energy Recovery

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Abstract

Agricultural waste generated through cultivation of crops, vegetables, fruits, and poultry can pollute the environment and affect the health of both humans and animals. Traditionally, most agricultural wastes are either burned or disposed of in landfills which cause acute environmental pollution. These easily accessible and underutilized agro-wastes remain a potential resource for biofuel production. This review analyses several thermochemical and biochemical methods encompassing pyrolysis, gasification, and hydrothermal carbonization (HTC) and fermentation to convert agricultural wastes including crop stalks, husks, straw, and bagasse into biofuel. The highly accepted method is pyrolysis which results in bio-oil; whereas gasification produces syngas utilized for electric power production as well as conversion to liquid fuels. HTC at lower temperature and pressure produces hydrochar which can act as a solid fuel or be transformed into liquid biofuels. Apart from biofuels, biochar, which is a by-product of pyrolysis, HTL and gasification processes, is also useful in the enhancement of soils as well as for carbon storage. Based on energy recovery, the processes are ranked as follows: Fermentation>Pyrolysis>HTL. Despite its potential, geographical diversity causes feedstock variability necessitating process optimization, technology advancement, economic feasibility toward sustainable implementation. Additionally, scalability and environmental concerns, including pollutant emissions, need to be addressed for large-scale commercial biofuel production.

Keywords: Agricultural waste, bio-oil, production process, yield of bio-oil, energy recovery

INTRODUCTION

The global demand for production of environmentally friendly alternate fuel surged in recent years, as the depletion of finite resources became a severe problem to the world [1]. On the other hand, the Indian Council of Agricultural Research (ICAR) estimated in 2020 that, annually India generates more than 350 million tons of agricultural waste, with a trend of 5–10% annual growth [2, 3]. Conventionally, these residues have been disposed, burned, or used for low-value purposes, which can come up with environmental pollution. According to estimations provided by the Ministry of New and Renewable Energy this trash can provide over 18,000 MW of electricity annually aside from producing green fertilizer for use in agriculture [4].

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Thermochemical conversion methods, such as pyrolysis [5, 6], gasification [7], and hydrothermal carbonization (HTC) are the most widely accepted techniques for converting agricultural waste into biofuel. These processes not only generate biofuels, such as bio-oil, syngas, and biogas but also produce

biochar and hydrochar – carbon-rich materials that can use in multiple sectors [8]. The high surface area and porosity of biochar and hydrochar also make them suitable for various industrial applications, such as adsorption of pollutants from wastewater and air [9, 10]. In addition, biochar is also used as a soil fertilizer to enhance soil fertility [11]. Pyrolysis is a common method for producing biochar and bio-oil. This process can be defined as thermal decomposition of organic materials in the absence of oxygen. Gasification, on the other hand, involves partial oxidation of organic matter at high temperature to produce syngas (mixture of carbon monoxide, hydrogen, and methane) which can be further converted into vehicle fuels or used for electricity generation [12]. Hydrothermal carbonization (HTC), a recent method, is particularly well-suited for wet feedstocks, such as food waste and agricultural residues with high moisture content. This process is conducted under moderate temperature and pressure to produce bio-oil and hydrochar [13]. HTC is advantageous due to its ability to process wet biomass without requiring the energy-intensive drying step typically needed for other thermochemical processes like pyrolysis [14].

Despite the considerable potential of agricultural waste for biofuel production, several challenges remain. These include feedstock variability, as the chemical composition of agricultural residues can vary significantly depending on the crop type, growth conditions, and geographical region [15]. Variations in the lignocellulosic content of feedstocks can affect the yield and quality of the biofuels produced. Additionally, the economic feasibility of large-scale biofuel production from agricultural residues is influenced by factors, such as feedstock collection, transportation, and processing costs. While agricultural residues are widely available, their utilization for biofuel production may not always be economically competitive with fossil fuels without technological advancements to lower processing costs and improve efficiency [16]. Furthermore, environmental concerns related to pollutant emissions during thermochemical conversion processes, such as tar formation and the release of volatile organic compounds (VOCs), need to be addressed through improved emissions control systems [17]. Despite these challenges, ongoing research and technological innovations offer promising solutions to optimize the transformation of agricultural waste into high-quality biofuels, making this approach a viable and sustainable option for energy production.

VARIOUS TECHNIQUES OF BIO-OIL GENERATION

The various conversion ways of bio-oil generation from agro-waste are given in Figure 1. Recent studies focused on thermochemical conversion over biochemical conversion as huge waste can be managed by producing a variety of fuels and useful chemicals. Bio-oil is produced through pyrolysis (fast, slow, and intermediate), which thermally decomposes biomass without oxygen, hydrothermal liquefaction (HTL) processes wet biomass under high temperature and pressure, Gasification and Fischer-Tropsch synthesis convert biomass into syngas, then into liquid fuels [18, 19]. Solvent liquefaction uses organic solvents, and microwave-assisted pyrolysis to enhance the process efficiency. Whereas fermentation process is a biochemical conversion process. The thermochemical methods vary in temperature, pressure, and catalysts to optimize bio-oil yield, quality, and energy efficiency based on feedstock type. Whereas the yield of bio-oil depends on the microbes used. A comparison study of these process is given in Table 1.

The slow pyrolysis process due to its long residence time the production of biochar is much more efficient than bio-oil. Whereas fast pyrolysis, catalytic pyrolysis and microwave-assisted pyrolysis (MAP) gives notable bio-yield [20, 21, 23]. However, the MAP process necessitates specialized reactors which leads to high capital investment. In case of catalytic pyrolysis, selection of catalyst, its cost and regeneration are the challenging part [22]. HTL is suitable for wet feedstock, therefore, the operating cost is low compared to the pyrolysis process. But, due to the presence of water in feedstock the energy recovery and bio-oil yield are notably low [23]. Though fermentation process is natural process, the proper selection of microbes is a challenging part to achieve adequate yield. Thermochemical methods, like fast pyrolysis and HTL, excel in scalability and yield, while fermentation offers eco-friendly pathways for specific waste types [24–27].

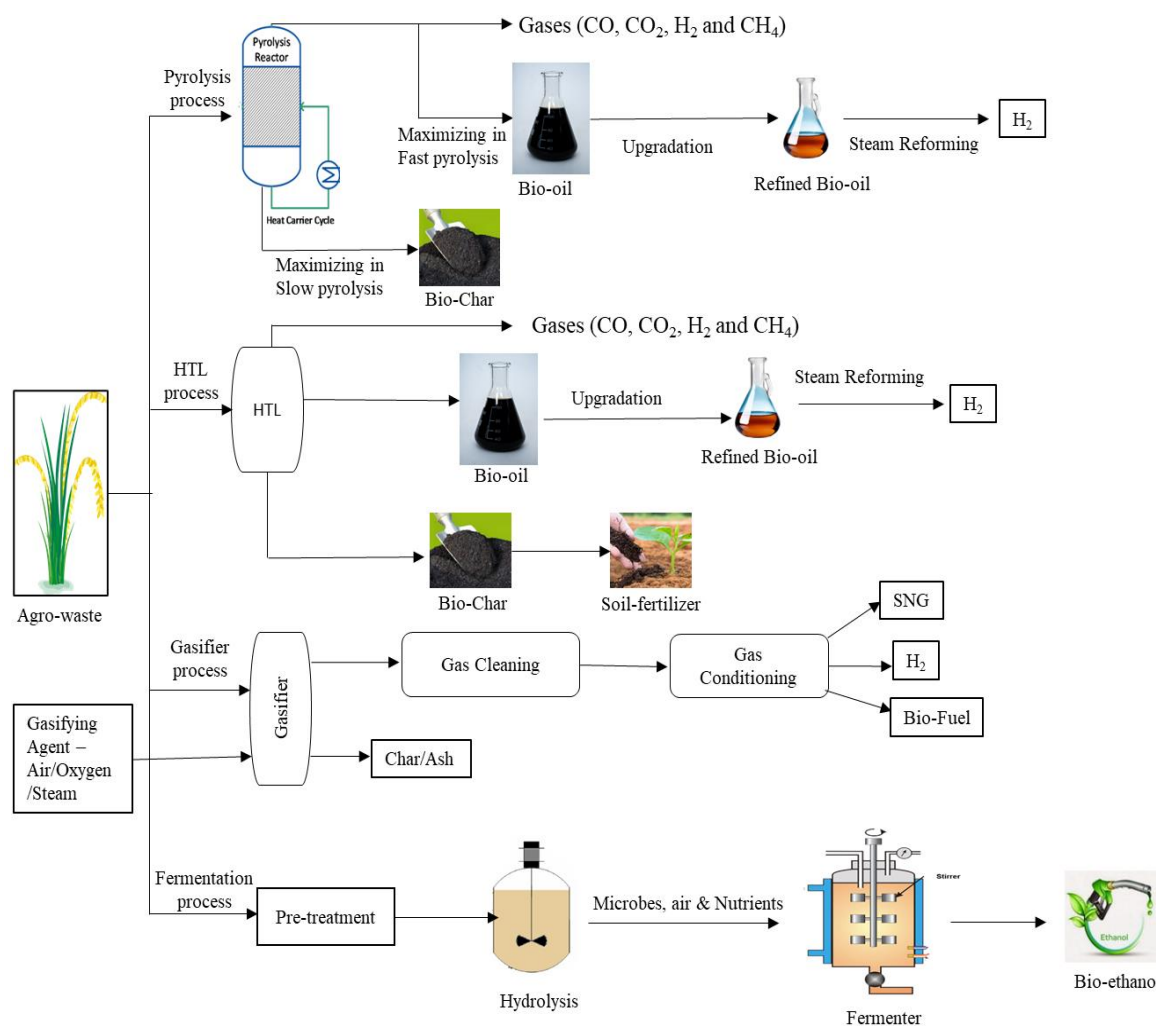


Figure 1. Different routes of transformation of agro-waste to biofuel.

Table 2 indicates that the yields can vary significantly based on the composition of the feedstock, its moisture content, reactor types and the specific parameters of the pyrolysis process. For example, bio-oil yields from rice straw can achieve levels of 40–60%, while similar yields are observed for wheat straw and sugarcane bagasse. In contrast, denser materials, such as coconut shells generally result in lower bio-oil yields, approximately 35–38%, due to their higher lignin content, although they also produce biochar, which is a valuable by-product [28–32]. Though both are high lignin content material, palm Kernel shell and coconut shell, bio-oil yield from palm kernel shell in fluidized bed found 57% which is higher than that of the coconut shell in fixed bed reactor. These agricultural residues represent promising feedstocks for bio-oil production, given their widespread availability and their potential role in advancing renewable energy and waste valorization initiatives.

STUDY OF BIO-OIL YIELD FROM SOME AGRICULTURAL WASTE

Bio-oil production from agricultural residues, including rice straw, oat straw, sawdust, wheat straw, coconut shells, sugarcane bagasse, and palm kernel shells, primarily utilize pyrolysis as the main processing method. This technique involves the thermal decomposition of biomass in an oxygen-free environment, typically conducted at temperatures between 300°C and 600°C [18]. Fast pyrolysis, characterized by elevated heating rates, is favored for optimizing bio-oil yields [19]. Moreover, the use of a catalyst reduces the oxygen level and increases oil stability. The results demonstrate the potential of bio-oil as a renewable energy source that provides sustainable waste management and the generation of biofuel. Yields can be further increased by optimizing the process conditions.

Table 1. Comparison table of bio-oil production through different routes.

Techniques	Reaction Condition	Products	Advantages	Disadvantages	References
Pyrolysis-Slow	Lower Heating Rate (5–30°C/min) and Higher Residence Time (>30 min).	Biochar (High yield) Bio-oil and Biogases.	Can handle diverse feedstocks.	Low bio-oil yield, long residence time.	[18]
Pyrolysis-Fast	High heating rate (10–1000°C/S) and Shorter Residence time (<20 s).	Bio-oil (High yield) Biochar and Biogases (Methane, Hydrogen).	High-quality bio-oil with low tar, High efficiency, short residence time.	Complexity in operational, Cost effective.	[19]
Pyrolysis-Microwave assistant (MAP)	Electromagnetic radiation heating (frequency 300 MHz–300 GHz and wavelength of 0.1–100 cm) Fast pyrolysis-temp-(450–650°C) and residence time (0.5–10 s).	Bio-oil, Biochar and syngas	Selective and instantaneous on/off control heating, shorter reaction time, Energy efficient, Eco friendly.	Higher power requirement for poor microwave absorbing materials, uneven heating, more complicated reactor design.	[20]
Pyrolysis-catalytic	Temperature: 400–500°C, Catalyst: acidic (Zeolites, Al ₂ O ₃), Time: milliseconds to seconds A modified pyrolysis process that uses catalysts to enhance bio-oil yield and reduce the oxygen content.	Bio-oil (high yield), Biochar and syngas.	Improved bio-oil quality, reduces oxygen content, can produce hydrocarbons directly.	High cost of catalysts, Catalyst deactivation due to coke formation, more complex operational requirements.	[21, 22]
Hydrothermal Liquefaction (HTL)	Temperature: 250–350°C, Pressure: 5–25 MPa, Time: 30 minutes to 1 hour, using water as a solvent improving fuel quality.	Bio-oil (major part), Biochar and syngas.	Direct conversion of wet biomass (no drying needed), Produces high-quality bio-oil.	High pressure and temperature requirements, Corrosive environment, High capital and operational costs.	[23, 24]
Gasification	Temperature: 800–1000°C, Pressure: 1–10 MPa, with limited oxygen for partial combustion of biomass.	Syn Gas, Biochar, Bio-oil from syngas can be produced through subsequent process.	Produces syngas, which can be converted to bio-oil or other fuels, Reduces feedstock volume significantly.	Requires high temperature, Low bio-oil yield, Complex gas cleaning processes.	[25]
Fermentation	Enzymatic hydrolysis of sugar fibers, fermentation of derived sugar to convert ethanol. Temperature: 30–35°C, pH: 4.5–5.5, Anaerobic conditions, in presence of microbes, Time: 24–48 hours.	Bioethanol.	Utilizes low temperatures, Converts sugars to bio-oil precursors, environmentally friendly.	Requires pre-treatment for lignocellulosic biomass, Limited to specific feedstocks with high sugar content, Long process time.	[26, 27]

Comparison Study of Bio-Oil Yield from Rice Husk Through Different Production Techniques

A comparison study of various bio-oil production techniques from rice husk is investigated based on process efficiency, bio-oil yield given in Table 3. Slow pyrolysis process is less energy intensive, but bio-oil yield is lower due to higher content of water and oxygen. Fast pyrolysis produces bio-oil of better quality with higher heating rate and uniform heat distribution. Microwave-assisted catalytic pyrolysis, an energy efficient method, enhances quality product with improved hydrocarbon fractions. Thermochemical liquefaction yielding a denser, lower-oxygen bio-crude suitable for refining. Fermentation-based bio-oil production, a bio-chemical conversion to produce bioethanol, offers sustainability benefits using mild reaction conditions [33, 34].

RICE HUSK

Rice Husk is a waste byproduct of rice grains for the time of the shelling and milling processes (Figure 2), from which white and polished grains without husk are produced. Rice husk is composed of 25–33% cellulose, 18–21% hemicellulose, and 25–31% lignin, with 43–58% silica content [35, 36], making it unique among agricultural residues. It has a high carbon content, making it suitable for bio-oil production through pyrolysis and hydrothermal liquefaction while also generating biochar and silica-rich ash as byproducts. Due to its low bulk density and high ash content, proper pre-treatment is necessary for efficient conversion. Besides bio-oil, rice husk is used for biochar, silica extraction, and energy generation, contributing to waste valorization and sustainable biofuel production.

Comparative Study Energy Recovery (ER) of Pyrolysis, Hydrothermal Liquefaction (HTL) and Fermentation Process

Energy recovery can be defined as the fraction of energy contained in the feedstock that is converted into usable energy forms, such as fuels, electricity or heat through a process. In this section energy recovery is calculated by using the Equation (1) [37–42] to identify the most efficient and sustainable process among pyrolysis, HTL and fermentation process for bio-oil production from rice husk.

$$ER = \frac{HHV_{\text{Bio-oil}} \times Y_{\text{Bio-oil}}}{HHV_{\text{biomass}}} \times 100\% \quad (1)$$

where HHV represents the High Heating Value (MJ/Kg) and Y represent the Yield Fraction.

Table 2. A brief informative table of bio-oil production considering few agro-waste examples.

Agricultural Waste	Process	Bio-Oil Yield	References
Rice Straw, Oat Straw, Saw Dust	Pyrolysis in a fixed-bed reactor	40–60% depending on conditions (temperature, particle size)	[28]
Rice straw, corn sticks, palm leaves	Hydrothermal liquefaction	17.49% (light oil from palm leaves) to 24.7% (heavy oil from corn sticks)	[29]
Wheat Straw	Fast Pyrolysis in a Fluidized Bed Reactor	28–42% as temperature increases from 400–500°C	[30]
Coconut Shell	Catalytic pyrolysis (HZSM-5 zeolite catalyst) in fixed-bed quartz reactor	35.10–38.93% as temperature increases from 450–550°C	[5, 31]
Sugarcane Bagasse	Pyrolysis in fixed bed reactor with CO ₂ activation	41.1% at 850°C after 4.5hr.	[32]
Palm Kernel Shells	Fast Pyrolysis in a Fluidized Bed Reactor	57% at 550°C	[33]

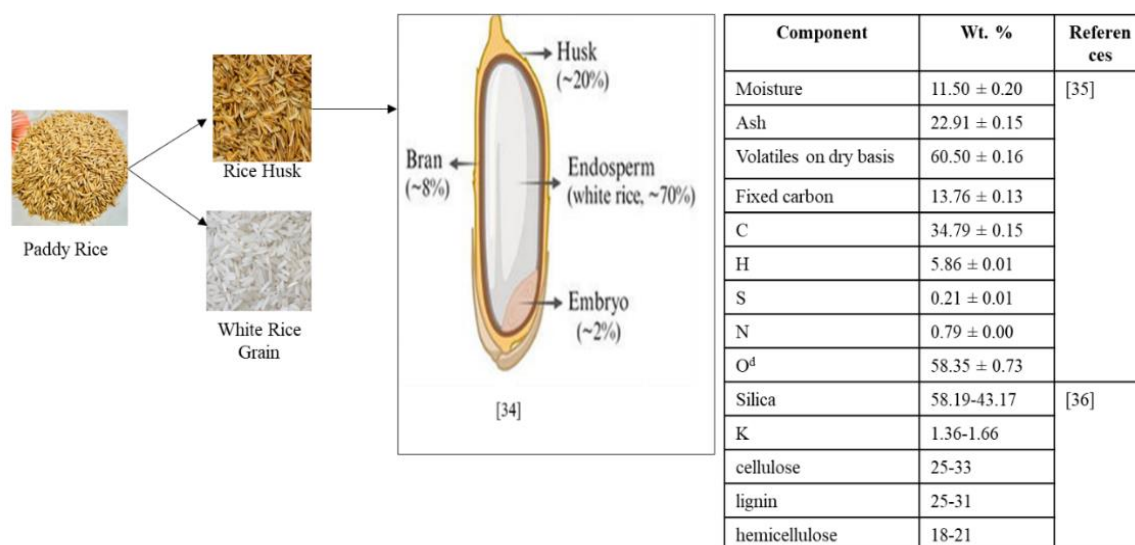


Figure 2. Component of rice husk.

Table 3. Comparison study of various techniques of bio-oil production from rice husk as feedstock.

References	[35]	[37]	[38]	[39]	[40]	[41]
Bio-Oil Characteristics	FTIR Analysis: Wave number 3000–3500 cm ⁻¹ and 1000–1750 cm ⁻¹ indicates presence of C=O, C=C, C-O, C-H, O-H groups.	Physical properties: Water content: 34.71 ± 3.14 Wt.%, Viscosity: 5.6-19 cP. Heating value: 14.285 to 21.742 MJ/kg	FTIR Analysis: % Yield: Acids: 8.46, Aldehydes:2.18, Ketones:7.93, Phenols:9.31, Ethers: 2.72, Carboxylic Anhydrides: 0.98, Furans: 4.19	%Yield: Acids: 7, Ketones: 10, Phenols: 8, Alcohol: 7.8, Hydrocarbons: 28	HV- 27.04 MJ/kg, Ratio: H/C-1.25 O/C-0.07	HPLC analysis confirms the properties of bioethanol.
Properties Of Rice Husk (Wt.%)	Moisture: 11.50 ±0.20, Ash content: 22.91 ± 0.15, Volatile matter: 60.50 ± 0.16, Fixed carbon: 13.76 ± 0.13, C:34.79 ± 0.15, H: 5.86 ± 0.01, S: 0.21 ± 0.00, O ^d : 58.35 ± 0.73.	Moisture: 9.5 ± 0.1, Volatile matter: 62.7 ± 0.3, Fixed carbon: 15.1, Ash: 12.7 ± 0.1, C: 37.86 ± 0.21, H: 5.24 ± 0.01, O: 35.32 ± 2.15, N: 0.68 ± 0.06.	Moisture: 1.1, Volatile matter: 70.5, Fixed carbon: 16.6, Ash: 12.9, C: 42.0, H: 5.4, O: 39.3, N: 0.4, HHV: 16.8 MJ/kg	----	Moisture: 8.38, Volatile Matter: 76.85, Ash:14.77, N 4.26, C: 43.06, O: 46.60, H:6.08	----
Yield (%)	Bio-oil: 38.13	Bio-oil: 53.2, Char: 30.0, Gas: 16.8	Bio-oil: 70, Char: 26	Bio-oil: 47.6, Char: 24.1	Bio oil: 20%	Bioethanol: 85.4 %
Process Condition	Temperature (650 °C), heating rate (9750 °C/hr), and holding time (1800 s)	Temperature- (560 °C), Feeding rate (2.1 ton/hr)	Temperature (450 °C), Feeding rate (200 g/ h)	Ratio of Rice Husk & Catalyst (HZSM-5/MCM-41)-1:1, Power: 1500 W, frequency: 2.45 GHz, Temp: 550°C	Autoclave temperature 533 K, Pressure 30 MPa, retention	pretreatment at 80°C with (0.1 M of FeCl ₃ , HCl, and NaOH), Enzymatic (Saccharomyces cerevisiae) Hydrolysis at 40-60°C for 24 hours.
Process	Slow Pyrolysis	Fast Pyrolysis (Fluidized bed reactor)	Fast Pyrolysis (Fast Pyrolysis) (Conical Spouted Bed	Micro-wave assisted Catalytic Pyrolysis	Hydrothermal liquefaction	Fermentation

Again, HHV can be calculated from equation (2) [42]. Carbon, Hydrogen and Oxygen contained feedstock can be obtained by proximate analysis, whereas that of bio-oil can be achieved from GC-MS analyzer.

$$\text{HHV} = 0.3383\text{C} + 1.422 \left(\text{H} - \frac{\text{O}}{8} \right) \quad (2)$$

The Table 4 indicates that if the suitable bacteria is selected, the fermentation process is most sustainable process. In fermentation process using *Saccharomyces cerevisiae* with rice husk as feedstock gives 85.4% bioethanol, whereas *Pichia occidentalis* with rice straw produce bioethanol with only 23.7% yield. In addition, 24–48 hours required for completion of fermentation process. These drawbacks make this process highly contentious. In contrast, pyrolysis and HTL both processes are very

fast conversion processes. In comparison of these two processes, pyrolysis is more energy efficient than HTL, as wet biomass feedstock is used in HTL process, which reduces the bio-oil yield. So, based on present values, the energy recovery is ranked as follows: Fermentation>Pyrolysis>HTL. In summary, the choice of process depends on feedstock characteristics, desired product quality, and economic constraints.

Table 4. Energy Recovery comparative Study.

Production Process	Bio-oil Yield %	HHV Of Rice Husk (MJ/Kg)	HHV Of Bio-oil (MJ/Kg)	ER % (Based On Bio-oil Yield)	References
Pyrolysis	30	15	22	44	[43]
HTL	23.8	16.19	26.12	38.40	[42]
Fermentation (<i>Bacteria-Saccharomyces cerevisiae</i>)	85.4	15	27	47.4	[44]
Fermentation (<i>Bacteria-Pichia occidentalis</i>) with rice straw as feedstock	23.7	15.09	27	13.24	[44, 45]

ADVANTAGES OF BIO-OIL

Bio-oil is applied as transportation fuel, power generation and precursors of various chemical industries. The bio-oil includes valuable chemicals, such as phenol, cresol and furfural can be utilized further in different sectors. Phenol and its derivatives serve as important chemicals in the production of phenolic resins, bisphenol-A and caprolactam, which are precursors for synthetic fibers nylon adhesives and plywood manufacture [46]. In addition, bio-oil can also be used as a binder to produce pellets of combustible organic waste. Bio-oil is now broadly applicable as a fuel source for combustion, electricity generation, transportation, and the generation of chemicals.

Future Perspectives, Challenges, and Recommendations

Bio-oil production from agricultural waste is getting more popular as a renewable energy source. Advances in catalytic cracking, hydrothermal liquefaction (HTL), and pyrolysis processes are increasing energy recovery and yield. The integration of biorefinery concepts with bio-oil upgrading could enable large-scale commercialization [19]. Additionally, emerging techniques, like microwave-assisted pyrolysis, offer improved efficiency, better quality bio-oil, and lower emissions [47].

The main issues are that bio-oil is unstable and has a low heating value due to its high oxygen and water content. Also, the variability in feedstock in agricultural residues impacts process effectiveness and the composition of bio-oil [48, 49]. Moreover, Commercial implementation is also inhibited by scalability problems, high capital costs, and poor catalyst efficiency. Energy recovery also depends on optimizing process parameters to maximize bio-oil yield and selectivity. Therefore, catalytic upgradation, process integration and feedstock optimization through pretreatment can enhance bio-oil yield, stability, and selectivity.

CONCLUSIONS

Agricultural waste represents a valuable energy resource, exhibiting significant potential as a source of solid, liquid or gaseous energy. Pyrolysis is the most common technique to transform lignocellulosic agro-waste into renewable energy. Though based on the operating cost, hydrothermal process is advantageous over pyrolysis as this process can deal with wet material so no pre-treatment is required for drying the raw materials, but the presence of water in feedstock reduces the yield subsequently reduces the energy recovery. Despite the eco-friendly process, the long conversion time and proper selection of bacteria make the fermentation process challenging. Thus, through gradual upgradation of techniques would enable transforming waste into valuable products in a sustainable as well as economically viable way.

Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. Díaz-Padilla VT, Travar I, Acosta-Rubio Z, Parra-López E. Tourism Competitiveness versus Sustainability: Impact on the World Economic Forum Model Using the Rasch Methodology. *Sustainability*. 2023 Sep 14;15(18):13700.
2. Sharma S, Soederberg S. Redesigning the business of development: The case of the World Economic Forum and global risk management. *Rev Int Polit Econ*. 2020 Jul 3;27(4):828–54.
3. Riseh RS, Vazvani MG, Hassanisaadi M, Thakur VK. Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. *Ind Crops Prod*. 2024 Feb 1;208:117904.
4. Channi AS, Bains HS, Grewal JS, Chidamburanathan VS, Kumar R. Tool wear rate during electrical discharge machining for aluminium metal matrix composite prepared by squeeze casting: A prospect as a biomaterial. *J Electrochem Sci Eng*. 2023 Feb 19;13(1):149–62.
5. Agrizzi T, Oliveira MA, Faria EV, Santos KG, Xavier TP, Lira TS. Assessing coconut shell pyrolysis: Biomass characterization, activation energy estimation, and statistical analysis of operating conditions. *Bioresour Technol Rep*. 2024 Jun 1;26:101831.
6. do Nascimento VR, dos Santos MB, Diehl L, Paniz JN, de Castilhos F, Bizzi CA. Microwave-assisted pyrolysis of pine wood waste: system development, biofuels production, and characterization. *J Anal Appl Pyrolysis*. 2024 Oct 9:106799.
7. Borges FC, Du Z, Xie Q, Trierweiler JO, Cheng Y, Wan Y, Liu Y, Zhu R, Lin X, Chen P, Ruan R. Fast microwave assisted pyrolysis of biomass using microwave absorbent. *Bioresour Technol*. 2014 Mar 1;156:267–74.
8. Kostas ET, Durán-Jiménez G, Shepherd BJ, Meredith W, Stevens LA, Williams OS, Lye GJ, Robinson JP. Microwave pyrolysis of olive pomace for bio-oil and bio-char production. *Chem Eng J*. 2020 May 1;387:123404.
9. Ighalo JO, Rangabhashiyam S, Dulta K, Umeh CT, Iwuzor KO, Aniagor CO, Eshiemogie SO, Iwuchukwu FU, Igwegbe CA. Recent advances in hydrochar application for the adsorptive removal of wastewater pollutants. *Chem Eng Res Des*. 2022 Aug 1;184:419–56.
10. Enaime G, Baçaoui A, Yaacoubi A, Lübken M. Biochar for wastewater treatment—conversion technologies and applications. *Appl Sci*. 2020 May 18;10(10):3492.
11. Rombel A, Krasucka P, Oleszczuk P. Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. *Sci Total Environ*. 2022 Apr 10;816:151588.
12. Zheng JL, Zhu YH, Zhu MQ, Kang K, Sun RC. A review of gasification of bio-oil for gas production. *Sustain Energy Fuels*. 2019;3(7):1600–22.
13. Younas R, Hao S, Zhang L, Zhang S. Hydrothermal liquefaction of rice straw with NiO nanocatalyst for bio-oil production. *Renew Energy*. 2017 Dec 1;113:532–45.
14. Liu Z, Balasubramanian R. Upgrading of waste biomass by hydrothermal carbonization (HTC) and low temperature pyrolysis (LTP): A comparative evaluation. *Appl Energy*. 2014 Feb 1;114:857–64.
15. Guddaraddi A, Singh A, Amrutha G, Saikanth DR, Kurmi R, Singh G, Chowdhury M, Singh BV. Sustainable biofuel production from agricultural residues an eco-friendly approach: a review. *Int J Environ Clim Change*. 2023;13(10):2905–14.
16. Gheewala SH, Damen B, Shi X. Biofuels: economic, environmental and social benefits and costs for developing countries in Asia. *Wiley Interdiscip Rev Clim Chang*. 2013 Nov;4(6):497–511.
17. Mohanty A, Ajmera S, Chinnam S, Kumar V, Mishra RK, Acharya B. Pyrolysis of waste oils for biofuel production: An economic and life cycle assessment. *Fuel Commu*. 2024 Mar 1;18:100108.
18. Patra BR, Nanda S, Dalai AK, Meda V. Slow pyrolysis of agro-food wastes and physicochemical characterization of biofuel products. *Chemosphere*. 2021 Dec 1;285:131431.
19. Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. *Biomass and bioenergy*. 2012 Mar 1;38:68–94.

20. Ge S, Yek PN, Cheng YW, Xia C, Mahari WA, Liew RK, Peng W, Yuan TQ, Tabatabaei M, Aghbashlo M, Sonne C. Progress in microwave pyrolysis conversion of agricultural waste to value-added biofuels: a batch to continuous approach. *Renew Sustain Energy Rev.* 2021 Jan 1;135:110148.
21. Xue Z, Zhong Z, Zhang B, Xu C. Performance of catalytic fast pyrolysis using a γ -Al₂O₃ catalyst with compound modification of ZrO₂ and CeO₂. *Catalysts.* 2019 Oct 12;9(10):849.
22. Czernik S. Catalytic pyrolysis of biomass. *Adv Biofuels Bioproducts.* 2012 Jun 7:119–27.
23. Gollakota AR, Kawale HD, Kishore N, Gu S. Corrigendum to “a review on hydrothermal liquefaction of biomass” [*Renew Sustain Energy Rev* 81 (2018) 1378–1392]. *Renew Sustain Energy Rev.* 2018 Dec 1;98:515–7.
24. Biller P, Ross AB. Production of biofuels via hydrothermal conversion. In: *Handbook of biofuels production 2016* Jan 1 (pp. 509–547). Woodhead Publishing.
25. Devi GS, Vaishnavi S, Srinath S, Dutt B, Rajmohan KS. Energy recovery from biomass using gasification. In: *Current developments in biotechnology and bioengineering 2020* Jan 1 (pp. 363–82). Elsevier.
26. Rastogi M, Shrivastava S. Recent advances in second generation bioethanol production: An insight to pretreatment, saccharification and fermentation processes. *Renew Sustain Energy Rev.* 2017 Dec 1;80:330–40.
27. Muktham R, Bhargava SK, Bankupalli S, Ball AS. A review on 1st and 2nd generation bioethanol production-recent progress. *J Sustainable Bioenergy Syst.* 2016 Jul 8;6(3):72–92.
28. Nuraini N, binti Osman N, Astuti E. Bio-Oil Production Using Waste Biomass via Pyrolysis Process: Mini Review. *J Bahan Alam Terbarukan.* 2022 Jun 20;11(1):37–49.
29. Mohamed OA. Production of bio-oil from agriculture waste. *Biochem Anal Biochem.* 2018;7(348):2161–1009.
30. Paul AS, Panwar NL, Salvi BL, Jain S, Sharma D. Experimental investigation on the production of bio-oil from wheat straw. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects.* 2024 Dec 31;46(1):9777–92.
31. Fardhyanti DS, Chafidz A, Triwibowo B, Prasetiawan H, Cahyani NN, Andriyani S. Improving the quality of bio-oil produced from rice husk pyrolysis by extraction of its phenolic compounds. *J Bahan Alam Terbarukan.* 2020 Dec 17;8(2):90–100.
32. da Cunha Gonçalves G, Pereira NC, Veit MT. Production of bio-oil and activated carbon from sugarcane bagasse and molasses. *Biomass and Bioenergy.* 2016 Feb 1;85:178–86.
33. Asadullah M, Ab Rasid NS, Kadir SA, Azdarpour A. Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell. *Biomass and Bioenergy.* 2013 Dec 1;59:316–24.
34. Shafie NH, Esa NM. The healing components of rice bran. *Functional Foods: Wonder of the World. Evidence-Based Functional Foods in Health & Disease.* 2017:341–68.
35. Wakatuntu J, Olupot PW, Jjagwe J, Menya E, Okure M. Optimization of pyrolysis conditions for production of rice husk-based bio-oil as an energy carrier. *Results Eng.* 2023 Mar 1;17:100947.
36. Kordi M, Farrokhi N, Pech-Canul MI, Ahmadikhah A. Rice husk at a glance: from agro-industrial to modern applications. *Rice Sci.* 2024 Jan 1;31(1):14–32.
37. Cai W, Liu R, He Y, Chai M, Cai J. Bio-oil production from fast pyrolysis of rice husk in a commercial-scale plant with a downdraft circulating fluidized bed reactor. *Fuel Process Technol.* 2018 Mar 1;171:308–17.
38. Alvarez J, Lopez G, Amutio M, Bilbao J, Olazar M. Bio-oil production from rice husk fast pyrolysis in a conical spouted bed reactor. *Fuel.* 2014 Jul 15;128:162–9.
39. Li Z, Zhong Z, Zhang B, Wang W, Zhao H, Seufitelli GV, Resende FL. Microwave-assisted catalytic fast pyrolysis of rice husk over a hierarchical HZSM-5/MCM-41 catalyst prepared by organic base alkaline solutions. *Sci Total Environ.* 2021 Jan 1;750:141215.
40. Liu Y, Yuan XZ, Huang HJ, Wang XL, Wang H, Zeng GM. Thermochemical liquefaction of rice husk for bio-oil production in mixed solvent (ethanol–water). *Fuel Process Technol.* 2013 Aug 1;112:93–9.
41. Chavan S, Mitra D, Ray A. Harnessing rice husks: Bioethanol production for sustainable future. *Curr Res Microb Sci.* 2024 Oct 26:100298.

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42. Shi W, Li S, Jin H, Zhao Y, Yu W. The hydrothermal liquefaction of rice husk to bio-crude using metallic oxide catalysts. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 2013 Nov 17;35(22):2149–55.
 43. Unrean P, Fui BC, Rianawati E, Acda M. Comparative techno-economic assessment and environmental impacts of rice husk-to-fuel conversion technologies. *Energy*. 2018 May 15;151:581–93.
 44. Song Y, Maskey S, Lee YG, Lee DS, Nguyen DT, Bae HJ. Optimizing bioconversion processes of rice husk into value-added products: D-psicose, bioethanol, and lactic acid. *Bioresour Technol*. 2024 Mar 1;395:130363.
 45. Thinh NV, Thu HN, Thao NV, Vy NT. Rice straw management in Mekong Delta: a case study in Long An Province. In: *The Mekong Delta Environmental Research Guidebook 2025* Jan 1 (pp. 283–301). Elsevier.
 46. Lazzari E, Schena T, Primaz CT, da Silva Maciel GP, Machado ME, Cardoso CA, Jacques RA, Caramão EB. Production and chromatographic characterization of bio-oil from the pyrolysis of mango seed waste. *Ind Crops Prod*. 2016 May 1;83:529–36.
 47. Beneroso D, Monti T, Kostas ET, Robinson J. Microwave pyrolysis of biomass for bio-oil production: scalable processing concepts. *Chem Eng J*. 2017 May 15;316:481–98.
 48. Panwar NL, Paul AS. An overview of recent development in bio-oil upgrading and separation techniques. *Environ Eng Res*. 2021 Oct;26(5).
 49. Bridgewater AV. Biomass fast pyrolysis. *Thermal Sci*. 2004;8(2):21–50.