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Production of Biochar from Lignocellulosic Biomass Obtained from Paddy Straw

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Abstract

The pressing issues of fossil fuel depletion and environmental degradation have spurred the search for sustainable solutions in energy production and carbon management. This research delves into the eco-friendly prospect of generating biochar from lignocellulosic biomass, specifically paddy straw. Given the undeniable contribution of contemporary fossil fuels to greenhouse gas emissions, air pollution and climate change, a shift towards cleaner alternatives like biofuels becomes imperative. Paddy straw emerges as a promising feedstock due to its abundant availability and favorable attributes for biochar production. Its high lignocellulosic content and low ash levels render it particularly suitable. Various conversion methods, such as pyrolysis, gasification and hydrothermal processes can transform paddy straw into biochar, reaping multiple benefits. Biochar enhances soil fertility, sequesters carbon and mitigates methane emissions. Moreover, it offers a sustainable energy source and contributes to effective waste management. This abstract offers an encompassing view of paddy straw biochar production techniques, its inherent qualities, and its wide-ranging applications, underscoring its potential as a sustainable alternative to conventional fuels. By leveraging the distinctive features of paddy straw, we can simultaneously tackle energy and environmental challenges while promoting a circular economy.

Keywords: Fossil fuels, sustainability, biofuels, biochar, lignocellulosic biomass (LB), paddy straw, pyrolysis

INTRODUCTION

The rapid growth of technology and the simultaneous rise in the population and transportation, driven by swift industrialization, have led to a substantial surge in the demand for petroleum-derived fuels [1]. These fuels serve as vital, sustainable energy sources in the modern age. Unfortunately, the extensive reliance on fossil fuels and petroleum-based alternatives has brought about numerous adverse repercussions on the global ecosystem [2]. This has led to heightened emissions of greenhouse gases and several impacts on human health. The elevated concentration of greenhouse gases in the atmosphere, stemming from the combustion of fossil fuels, has triggered climate change, excessive air and water pollution, habitat degradation, loss of biodiversity and environmental contamination on a worldwide scale [3]. Moreover, given the finite nature of fossil fuels, their extraction entails significant ecological ramifications and often necessitates damaging mining techniques. These practices lead to soil erosion, deforestation and habitat destruction, resulting in resource depletion [4]. This jeopardizes energy security, drives up energy costs and presents socio-economic challenges. To tackle these issues, concerted endeavors are underway to shift towards cleaner and sustainable energy sources like solar, wind, hydroelectric and geothermal power [5]. It is imperative to prioritize augmented energy efficiency, conservation and the adoption of sustainable methodologies to counteract the detrimental consequences of fossil fuel consumption on the ecosystem. These renewable sources of energy are widely harnessed for power generation and play a pivotal role in mitigating energy scarcities [6].

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BIOFUELS

Biomass, one of Earth's most abundant carbon reservoirs, serves as a sustainable source for biofuels, offering a renewable and eco-friendly energy alternative. Biofuels like biodiesel, bioethanol, biogas, and bio-hydrogen are derived from biological sources, including first-generation crops like corn and sugarcane, and second-generation lignocellulosic biomass, such as agricultural residues and forest waste [7, 8]. Second-generation biofuels minimize food competition, reduce carbon footprints, and utilize renewable feedstocks like sugarcane bagasse and wheat straw.

Lignocellulosic biomass (LB), composed of cellulose (30%–50%), hemicellulose (15%–35%), and lignin (10%–20%), is ideal for biofuel production due to its high cellulose content [9]. However, lignin hinders enzymatic hydrolysis, necessitating pre-treatment methods to enhance sugar yield and reduce inhibitory byproducts [10]. LB is also widely used for biochar production because of its availability, low cost, and simpler composition compared to other biomass sources [11].

Paddy straw, a fibrous lignocellulosic material, is a promising biochar source but is often burned, causing environmental and health issues [12]. Converting paddy straw into biochar addresses these concerns and offers applications, such as soil improvement, greenhouse gas mitigation, biodiesel production, and water purification [13]. Biochar's porous structure enhances its adsorption properties, making it suitable for activated charcoal production and other uses [14]. Further research is essential to explore and optimize biochar's potential applications [15].

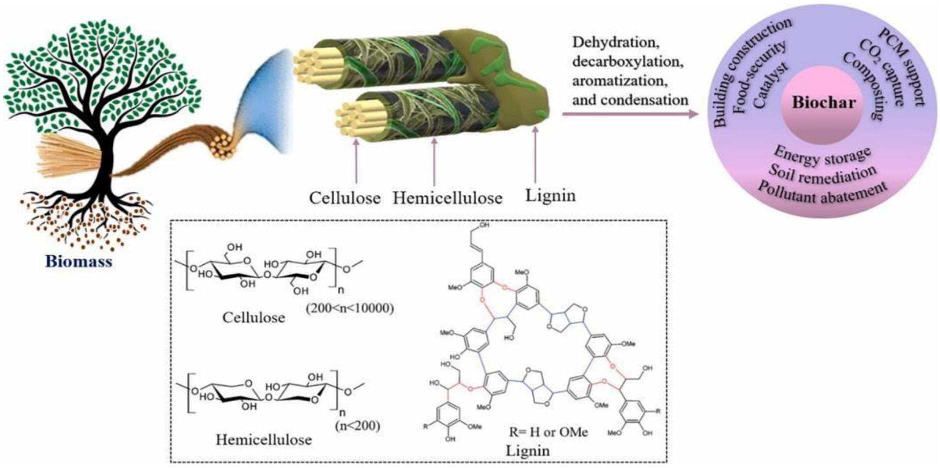

Figure 1. Chemical composition of Lignocellulosic biomass and Biochar application.

Biochar Production from Lignocellulosic Biomass

Lignocellulosic biomass, a sustainable and abundant energy resource derived from cellulose, hemicellulose, and lignin, is utilized for biochar production through various thermochemical processes (Figure 1) [16]. Cellulose, a crystalline glucose polymer, provides high energy potential, while hemicellulose is a branched polymer composed of xylose. Lignin, an aromatic polymer, enhances biomass rigidity and contributes significantly to biochar yield during pyrolysis [17, 18].

Biochar, a carbon-rich material with high surface area and functional groups, is produced via pyrolysis at temperatures between 400°C–1200°C (Figure 2). Pyrolysis methods vary slow pyrolysis uses lower temperatures (300°C–800°C) and longer residence times, while fast pyrolysis operates at higher temperatures (400°C–1400°C) with shorter durations [19]. Torrefaction, conducted at 200°C–300°C, and gasification, exceeding 700°C, also generate biochar alongside other by-products [20, 21].

Hydrothermal carbonization, suitable for high-moisture biomass, produces hydro-char at temperatures below 300°C in water, yielding 40–70 wt% solids [22]. Lignin-rich biomass generates more biochar (~65%), making it suitable for long-term carbon sequestration. Optimizing biochar production, activation, and reprocessing enhances its economic and environmental viability, supporting sustainable energy solutions [23].

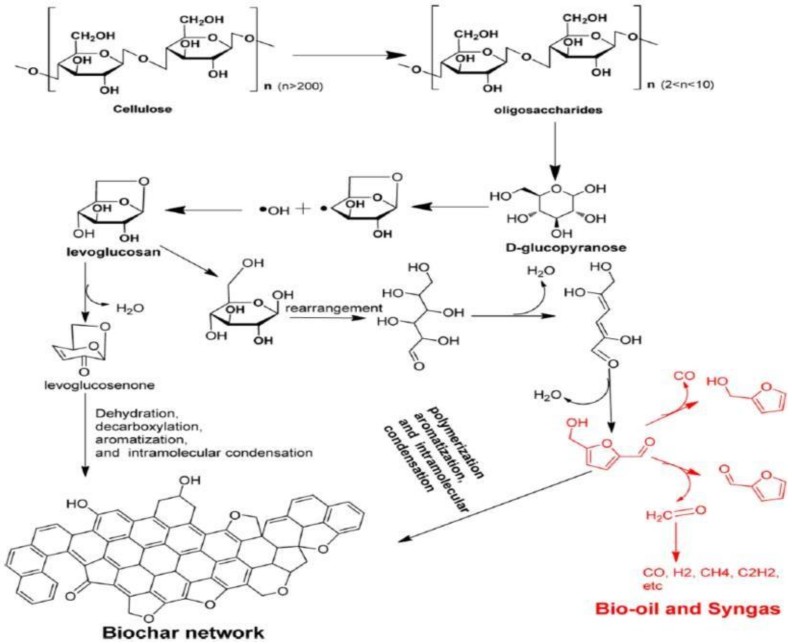

Figure 2. Cellulose pyrolysis and biochar production mechanisms.

Biochar Production from Paddy Straw

Utilizing climate-smart technologies to generate bioenergy from crop residues offers a sustainable solution to address environmental challenges. Agricultural remnants like paddy straw (PS), often discarded or burned, can be converted into renewable energy, reducing pollution and combating climate change [24]. As a lignocellulosic biomass, paddy straw contains approximately 25% hemicellulose, 38% cellulose, and 12% lignin, along with high silicon dioxide (SiO_2) and other mineral contents [25].

The production of biochar from paddy straw presents an eco-friendly alternative to crop burning, offering added value to agricultural waste. Paddy straw biochar features traits like high surface alkalinity, substantial cation exchange capacity, and macronutrients like potassium and phosphorus, making it ideal for improving soil quality [26]. Additionally, biochar effectively remediates organic and inorganic contaminants, including herbicides and heavy metals, contributing to environmental sustainability [27]. Transforming paddy straw into biochar represents a valuable and sustainable approach to addressing environmental and agricultural challenges.

Rice straw's calorific value, along with its proximate and ultimate analyses and the ash properties of rice straw are shown in Tables 1 and 2, respectively.

Table 1. Rice straw's calorific value, along with its proximate and ultimate analyses [28].

	HHV MJ/kg	Proximate analysis (% dry fuel)		Ultimate analysis (% dry fuel)								Sources
		Fix C	Volatiles	Ash	C	H	O	N	S	Cl	Ash	
	15.09	15.86	65.47	18.67	38.24	5.2	36.26	0.87	0.18	0.58	18.67	Jenkins et al. (1996)
		11.10	69.70	19.20								Braunbeck (1998)
	14.57				35.94			1.18			22.00	Munder (2013)
	14.08				33.70	4.0		1.71	0.16	0.32	29.10	Guillemot et al. (2014)
	15.03	13.21	64.24	13.26	44.40	7.40	47.07	1.13				Duan et al. (2015)
	14.39	16.75	60.55	22.70	35.35	3.91	37.35	0.71	0.03			Migo (2019)
Range	14.08	11.10	60.55	13.26	33.70	3.91	36.26	0.71	0.03	0.32	18.67	
	−15.09	−16.75	−69.70	−22.70	−44.40	−7.40	−47.07	−1.71	−0.18	−0.58	−29.10	

Table 2. Ash properties of rice straw [28].

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O_3	SO_3	P_2O_5	Sources
% of ash (d.b)	75.00	1.40	0.02	2.00	1.50	1.90	1.90	10.00	0.90	2.70	Liu, et al. (2011)
	74.67	1.04	0.09	0.85	3.01	1.75	0.96	12.30	1.24	1.41	Jeng, et al. (2012)
	82.60	1.10	0.60	1.00	3.30	1.70	0.30	6.30	0.90	1.70	Guillemot (2014)
	67.78	1.54			2.08	1.11	1.48	11.87			Migo (2019)
Range	67.78	1.04	0.02	0.85	2.08	1.11	0.30	6.30	0.90	1.41	
	–82.60	–1.54	–0.6	–2.00	–3.01	–1.90	–1.90	–12.30	–1.24	–2.70	

APPLICATION OF BIOCHAR AS BIOFUELS

The adoption of biofuels contributes to economic stability, mitigates global oil price fluctuations, safeguards foreign currency reserves, and creates job opportunities. As renewable energy sources, biofuels play a pivotal role without exacerbating health conditions caused by fossil fuels. Biomass conversion into liquid, solid, and gaseous forms through thermochemical and biological routes has broadened biochar's applications due to its distinctive attributes [29, 30].

Biochar-based catalysts are gaining prominence for biofuel production, reducing carbon footprints and offering advantages like superior physicochemical properties, structured active frameworks, and enhanced reusability [31, 32]. In biodiesel synthesis, biochar catalysts outperform conventional catalysts, ensuring higher efficiency, easier separation, and reusability [33]. Biodiesel is produced via trans-esterification of triglycerides using alcohol, with catalysts improving yield, efficiency, and reducing reaction time [34].

Hydrogen, a clean fuel, faces high production costs but is produced from biomass using nickel- and iron-based catalysts to enhance yield and quality while reducing tar content [35, 36]. In biogas production, biochar boosts methane output, enhances substrate utilization, and stabilizes anaerobic digesters through CO_2, NH_3, and H_2S removal, along with pH buffering and microorganism support [37, 38].

Biochar-based catalysts, with adjustable surface chemistry and porosity, present a sustainable approach for biofuel production, paving the way for efficient and environmentally friendly energy systems (Figure 3) [39].

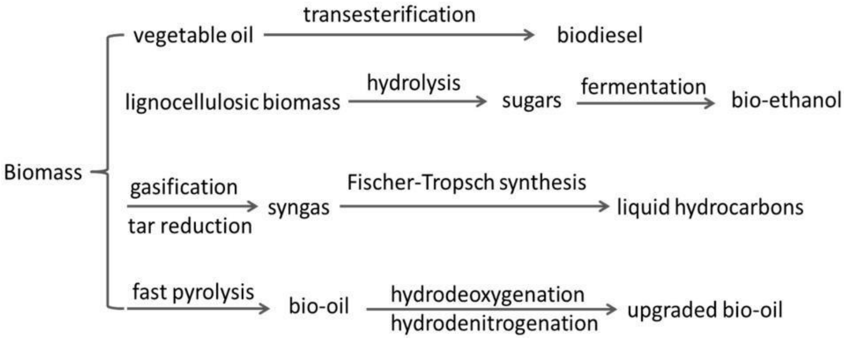

Figure 3. Conversion routes of biomass to biofuel.

CONCLUSIONS

To sum up, this study delivered into the creation of biochar from paddy straw, shedding light on its potential as an eco-friendly and sustainable solution for waste management and soil enhancement. The biochar production process from paddy straw brings forth a host of advantages, including carbon sequestration, nutrient preservation and improved soil fertility. The investigation explored various fabrication methods, such as pyrolysis and gasification and their respective merits and limitations were discussed. Furthermore, the research emphasized the significance of fine-tuning production parameters to achieve desired biochar characteristics. The findings underscore the considerable potential of paddy straw biochar as an asset in tackling climate change, fostering agricultural sustainability and addressing waste management issues. Continued research and the widespread implementation of biochar production methods have the potential to make substantial contributions towards cultivating a more sustainable and resilient agricultural sector.

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