DOI: https://doi.org/10.59983/s20230101010
AgroEnvironmental Sustainability, 2023, 1(1), 76-85

REVIEW

Biochar as a Versatile Resource for Achieving Sustainability in Agri-food Chains

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ARTICLE HISTORY
Received: 13 May 2023
Revised: 29 May 2023
Accepted: 31 May 2023
Published: 26 June 2023

KEYWORDS
agricultural waste
biochar
bioenergy
climate change
soil pollution

EDITOR
Bashir Adelodun

Abstract

The agriculture sector generates a significant quantity of waste. These wastes, when mismanaged, can cause environmental issues like air, water, and soil pollution. Thus, the upcycling of agricultural wastes especially for bioenergy production would be highly advantageous. Biofuels, including biochar, biogas, biodiesel, and bioethanol, are eco-friendly fuels owing a significant contribution to the bioenergy industry. Biochar, a carbon-rich substance prepared from a wide range of feedstocks, can be produced from agricultural wastes via pyrolysis and has numerous applications. When added to soil, biochar enhances soil fertility by acting as a soil conditioner. It can also be used to purify air and wastewater and/or used for carbon sequestering, in the textile and construction industries. Moreover, biochar can also be used in the food products such as charcoal-based ice cream, and cookies besides being an animal feed improver. Furthermore, biochar has potential applications in the cosmetic industry and can address issues such as climate change, energy shortages, and food security. The use of agricultural wastes for biochar production can be a tool for low-cost bioenergy production, which could improve the financial status of local farmers. The current review emphasizes the potential of biochar as a versatile resource for achieving sustainability in agri-food chains by recycling generated waste.

Citation: Kumari, S., Širić, I., & Abou Fayssal, S. (2023). Biochar as a Versatile Resource for Achieving Sustainability in Agri-food Chains. *AgroEnvironmental Sustainability*, 1(1), 76-85. https://doi.org/10.59983/s20230101010

Statement of Sustainability: This review article aims to provide a comprehensive understanding of the potential benefits of biochar as a versatile resource for waste management in the agri-food industry. The article explores different forms of agricultural wastes, the challenges associated with waste management, and the potential of biochar to address these challenges by converting waste into a valuable resource.

1. Introduction

The agricultural sector generates a significant quantity of wastes, especially during the harvesting season, which has become a management issue. Agricultural wastes include unwanted materials produced during agricultural operations such as growing crops and raising animals, including rice straw, wheat straw, poultry waste, and cattle manure. Unfortunately, the most common practice of such waste management is burning, which results in environmental (air, water, soil) pollution (Ippolito et al., 2020). In some Indian regions, such as Punjab and Haryana, wheat and paddy straws are extensively burned during winter season leading to numerous environmental issues. Such act liberates harmful gases that contribute to the decrease of atmospheric visibility, particulate matter release especially particulate matter 2.5 (PM 2.5), global warming, acid rain, and air pollution (Jain et al., 2014). This adversely affects air quality and causes health problems, especially respiratory issues in the elderly (Yang et al., 2018). Therefore, there is a need for efficient management of biomass, such as agricultural residues, to mitigate environmental issues caused by agricultural waste burning (Xing et al., 2016; Khanna et al., 2018). Figure 1 demonstrates the contribution of various crop categories to residue generation.

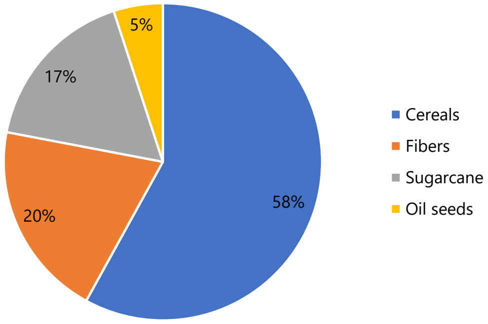

Figure 1. Contribution of various crop categories in residue generation (Jain et al., 2014).

The conversion of agricultural wastes into environmental energy sources like biofuels is a good solution for such an emerging issue. Biofuels are carbon-neutral fuels made from a wide variety of wastes such as agricultural, commercial, domestic, and/or industrial wastes. Biofuels include biochar, biogas, bioethanol, biodiesel, etc. (Rodionova et al., 2016). On a daily basis, fossil fuels are used globally and the demand is in a continuous increase. Fossil fuels account for about 86% of the world's energy demand, which is ultimately contributing to the emission of carbon dioxide (CO_2) (Abas et al., 2015). Moreover, natural events like forest fires are also big contributors to CO_2 emissions (Aponte et al., 2016). CO_2 is a potent greenhouse gas emitted from natural sources (e.g., volcanic eruptions, forest fires) as well as anthropogenic sources (e.g., deforestation, cement manufacture. It also contributes to climate change that needs proper mitigation (Valavanidis, 2017). Biochar has the potential to address many challenges such as energy lack, poverty, food insecurity, low agricultural productivity, and climate change (Abeydeeraet al., 2019).

Biochar is a dark-colored carbonized substance produced from organic materials like biomass. Pyrolysis, carbonization, and gasification of dry biomass and thermal carbonization of slurry under pressure are mainly used to produce biochar. The latter contains high amounts of carbon (around 50%) besides nitrogen, oxygen, sulfur, hydrogen, and ash found in variable proportions (Wijitkosum and Jiwnok, 2019). The properties of biochar formed depend on the kind of feedstock used as well as on the production conditions like pyrolysis temperature, oxygen (O_2) supply, and heating rate. An increase in pyrolysis temperature from 500 to 950 °C improves the surface area of biochar (increase from 25.7 to 68.9 m^2/g) and its porosity (increase of 0.059–0.1 cm^3/g) (Zhou et al., 2017). Biochar yield can be maximized under low-temperature pyrolysis technique (Singh et al., 2012; Qambraniet al., 2017). A higher temperature improves the ash content of biochar. The pH of biochar also depends on the type of feedstock and the pyrolysis condition. For instance, pH of biochar produced from hardwood was reported as 5.6, while that of biochar produced from orange peel was 12.3 when both pyrolyzed at 700 °C (Qambraniet al., 2017). In their work, Tomczyk et al. (2020) showed the effect of pyrolysis temperature and feedstock type on the physicochemical properties of biochar. A wide variety of feedstocks can be used for the production of biochar like crop residues, animal manures, and forest wastes. Apart from this, microalgae, poultry litter, waste from dairy, food processing industries, municipal waste, and sewage sludge can also be used for biochar production (Ippolito et al., 2020).Various physicochemical characteristics of biochar i.e., porosity, carbon content, cation exchange capacity (CEC), surface area, and catalytic properties govern its wide utility in various fields (You et al., 2017). In this context, Lee et al. (2017a) approved the potential of biochar as a catalyst. The porosity of biochar is responsible for its water-holding capacity which therefore, improves the moisture-holding capacity of soil when amended (Weber and Quicker, 2018). High specific surface area, ion exchange capacity, and high adsorption capacity make biochar suitable for environment-friendly applications. The utilization of crop residues for energy production can reduce fossil-based energy consumption. Also, it can serve as a source of income for farmers. Hence, this review shows that the production of biochar serves the dual purpose of waste management and sustainable energy production.

2. Feedstock for Biochar Production

Biochar can be produced from biomass of organic origin. For instance, agricultural wastes, forest residues, animal wastes, industrial wastes, food wastes, municipal wastes, temple flower wastes, and algal biomass can be used as feedstock for biochar production (Ippolito et al., 2020). Moreover, this use would provide the dual benefit of waste management and energy production. Among all available feedstocks, agricultural wastes such as rice husk, wheat straw, maize straw, nut shells, sugarcane bagasse, coconut shell, and wood chips are the most commonly used for biochar production (Jatav et al., 2020). Since agricultural wastes are free-cost and easily available, especially in agriculture-based countries like India, it would be the most suitable feedstock type for biochar production (Jain et al., 2014). The properties of biochar depend on the type of feedstock used (Cha et al., 2016). Figure 2 shows various types of feedstocks used for biochar production.

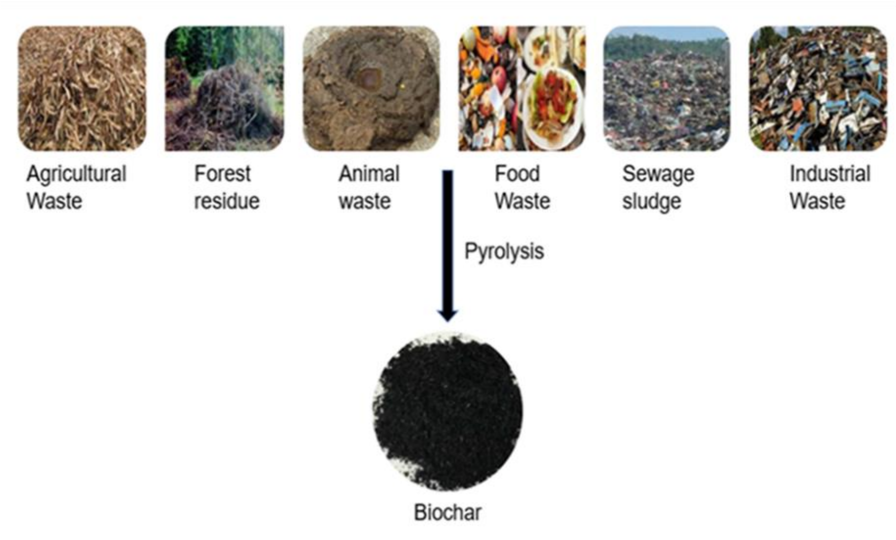

Figure 2. Various feedstocks used for biochar production.

3. Biochar as a Source of Energy

The increasing population brings about several challenges, and energy consumption is one of them. For instance, it has been estimated that in Saudi Arabia, electricity demands can increase up to 120GW by 2032 (Ouda et al., 2015). Biochar applications in the power industry depend on its various properties like calorific value, moisture, carbon content, and volatiles. The calorific value of biochar produced from good quality biomass is high and comparable to that of fossil-based coal. It has been estimated that by using biochar as a substitute 14% of coal, demands can be met which will reduce coal demands (Cheng et al., 2020). The high heating values (HHV) of biochar, which is in the range of 23.08-24.0 MJ/kg, make it worth to be used as an energy source (Waqas et al., 2018). In a study carried out by Suman (2020), it was found that biochar produced from corn cob and coconut shell biomass can be effectively used for energy production. In their work, Suman and Gautam (2018) showed that pyrolysis temperature outlines a difference in the quality of fuels derived from various agricultural feedstocks. Hence, biochar can be used as an eco-friendly electrical energy substitute for coal.

4. Other uses of Biochar

Besides being an energy source, biochar has several other uses such as an adsorbent, soil conditioner, catalyst, animal feed, textile and construction material, and cosmetic industry primary ingredient. Figure 3 shows different uses of biochar produced from biomass.

4.1. Adsorbent

The adsorption capacity of biochar depends on the raw material used for biochar production. The porosity, surface area, and aromaticity make biochar suitable as an adsorbent. Biochar serves as a low-cost means of water and air purification.

4.1.1. Adsorbent for Wastewater Treatment

Biochar can remove heavy metals, organic pollutants, nitrates, and phosphates from wastewater (Michalak et al., 2019). To meet the water requirements of the growing population, biochar can serve as the best treatment agent. Because of its eco-friendly nature, biochar can be useful in wastewater treatment (Lalander et al., 2013). Through their study, Gokulanet al. (2019) achieved greater than 77.5% of dye removal efficiency from dye wastewater using biochar prepared from *Ulva lactuca* (green seaweed) at 300 °C. In a successful study carried out by Ozsoy and van Leeuwen (2010), activated biochar was used for the decolorization of fruit candy waste extract to minimize waste emerging out of the industry.

4.1.2. Adsorbent for Air Purification

Anthropogenic activities have deteriorated the quality of air, thereby impacting the health of living beings, especially humans (Gwenzi et al., 2021). The use of biochar as an adsorbent for air pollutants improves air quality by capturing the gases responsible for global warming e.g., CO_2. Biochar produced at high temperatures has an enhanced surface area and thus, a better adsorption capacity (Creamer et al., 2014). Benzene present in air is harmful if inhaled which requires its removal. Khan et al. (2018), through their work, evaluated the benzene-sequestration ability of biochar derived from biowastes with promising results. A study carried out by Zhou et al. (2018) on biochar showed an ozone removal of up to 55 ppb within 24 hours only.

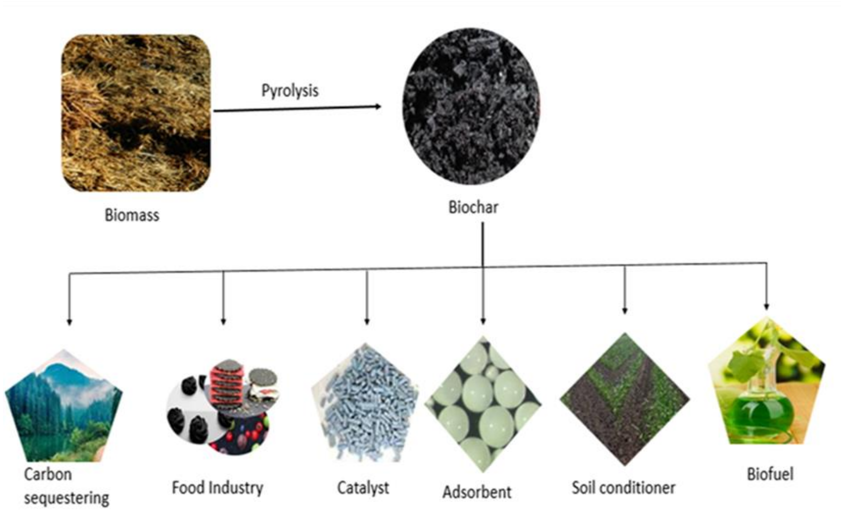

Figure 3. Various uses of biochar produced from biomass

4.2. Soil Conditioner

Biochar is rich in mineral nutrients i.e., N, P, K, and Ca. The application of biochar increases soil pH (Yuan et al., 2011). Biochar improves the physicochemical properties of soil and soil fertility is increased as a result of better nutrient-retaining ability (Chan et al., 2008; Širić et al., 2023). In parallel, the microbial populations are triggered and so their activity for diverse pollutants removal (Singh et al., 2019). The porosity of biochar is responsible for improving soil, water-holding capacity and thereby, improving the overall soil health (Srinivasarao et al., 2013). Therefore, the demand for chemical-based fertilizers can be reduced. Biochar can increase soil resistance against pollutants (Wu et al., 2018). Hence, the addition of biochar in the soil increases crop yield and quality (Macdonald et al., 2014). A study carried out by Sorrenti et al. (2016) showed that the application of biochar in kiwi cultivation improved its nutrient absorption capacity. Table 1 shows the effect of biochar application on the yield of some selected plants.

Table 1. Effect of biochar application on the yield of crop plants.

Crop	Type of Biochar	Dose (t/ha)	Increase in Yield (%) (Compared to the control)	Reference
Cowpea	Wood	68	20	Glaser et al. (2002)
Radish	Poultry litter	10	42	Chan et al. (2008)
Grapes	Woodchips from fruit trees	22	20	Genesio et al. (2015)
Maize	Cattle manure	15	150	Uzoma et al. (2011)
Maize	Hardwood	38	17	Rogovska et al. (2014)
Rapeseed	Wheat straw	40	36	Liu et al. (2014)
Sweet potatoes	Wheat straw	40	54	Liu et al. (2014)

4.3. Catalyst

Due to the adverse environmental impacts caused by the utilization of fossil fuels, renewable energy sources like biofuels are gaining more attention (Gwenzi et al., 2021). Among these, biodiesel is being used as an additive or alternative to fossil-based diesel. Thus, the use of catalysts in the production of biodiesel can be considered as an important aspect. Homogenous catalyst has certain disadvantages. Therefore, the biochar-based catalyst appeared as one of the best homogenous catalysts for biodiesel production (Lee et al., 2017a; Jechan et al., 2017). Likewise, Li et al. (2014) used a solid biochar catalyst prepared from rice husk for the production of biodiesel. In a study carried out by Song et al. (2017), it was revealed that the biochar-based catalyst succeeded in the catalytic hydrolysis of carbon disulfide (CS_2) and carbonyl sulfide (COS). Such catalyst was previously prepared from walnut shell biochar, and colloid solution of $Cu(NO_3)_2$, $NaCO_3$, and $Fe(NO_3)_3$.

4.4. Carbon Sequestration

The application of biochar in the field has numerous benefits other than soil amendment. The emission of greenhouse gases like CH_4, N_2O, and CO_2 from various human activities is the main contributor to climate change. According to a previous report, by burning 1 ton of fossil fuel, more than 3.5 tons of CO_2 are released (Jiang et al., 2010). To mitigate climate change, there is a need to reduce the greenhouse gas (GHG) emissions (Singh et al., 2017). Biochar acts as a carbon sink by absorbing more CO_2 from the atmosphere. It also reduces the amount of other greenhouse gases like methane and nitrous oxide emitted from agricultural fields. In that manner, biochar contributes to mitigating climate change (Gupta et al., 2020). A study by Matovic (2011) showed that the addition of biochar at a rate of 13.5 t/ha can store carbon in the soil for at least two hundred years. Yang et al. (2016), from their work on interfacial behavior between biochar and soil minerals, concluded that the latter can increase biochar stability. This shows the environmental significance of biochar for carbon sequestration.

4.5. Cosmetics

Biochar is being used in the cosmetic industry in an activated form. Traditionally, it was used to cleanse the skin by controlling acne and oil besides improving its color and texture. Looking at the benefits of biochar, it is being nowadays used in soap making, and in skin-care products like creams, facial masks, and scrubs (Narzari et al., 2015).

4.6. Waste Management

Agricultural wastes (wheat straw, corn straw), animal wastes (poultry waste, horse manure), municipal solid wastes, and industrial wastes, can be used for biochar production (Barrow, 2012). The utilization of biodegradable wastes in biochar production is a sustainable approach that reduces the volume of wastes mostly dumped in open areas. It is also an appropriate approach to cope with the problem of environmental pollution and energy crisis (Gąsior and Tic, 2017). In their work, Lee et al. (2017b) showed that the pyrolysis of agricultural wastes for biochar production is an effective means of waste management along with energy recovery. A study carried out by Vithanage et al. (2016) also showed that the production of biochar from various biological wastes helps in environmental sustainability and waste management.

4.7. Animal Feed

The use of biochar as an animal feed additive for ruminants, poultry, pig, and fish is becoming popular. Biochar can improve the egg-laying capacity of poultry (Schmidt et al., 2017b). It also helps in improving immunity, nutrient intake efficacy, and growth rates in animals when orally ingested (Toth et al., 2016; Man et al., 2021). Temperature plays a crucial role in biochar formation and the particle size of biochar is important in ruminant feed supplements (Mui et al., 2006; McFarlane et al., 2017). Edmunds et al. (2016) studied the effect of biochar in horse feed and found that it controlled the toxic substances in foregut and mid gut of horses. In their work, Mabe et al. (2018) found that the addition of 1–4% bamboo biochar to the feed of juvenile common carp resulted in improved fish quality and health with no visible side/negative effects. Table 2 shows the effect of various biochar feeding on some selected animals.

4.8. Textile Industry

Biochar is recently being used in shoe soles and socks as a deodorant to reduce sweating odor. In countries like China and Japan, fabric bamboo-derived biochar is used in textile making to improve the thermal insulation and odor of functional clothing (Lin et al., 2008). Biochar can be also used as a filling material for pillows due to its ability to absorb moisture and odor (Çay et al., 2020).

4.9. Construction Industry

Biochar can be used as a construction material like plaster for walls of wooden houses (Cuthbertson et al., 2019). Because of its micro, nano, and mesopores, biochar has a high moisture-retaining capacity. Air cleaning, insulation, noise control, humidity regulation, anti-bacterial effect, and aesthetic qualities make biochar a good construction material (Schmidt, 2013a). A study by Gąsior and Tic (2017) showed that biochar can absorb toxins and unpleasant smells in smoking areas. In their work, Akinyemi et al. (2020) used rice husk biochar along with cementitious composite and successfully reduced significantly the disadvantages of the latter.

Table 2. Effect of various biochar feeding on animals.

Animal	Daily BC intake	Feedstock for biochar	HT (°C)	Blend	Weight increase (%)	Duration (days)	Remarks	Reference
Cattle	1% feed DM	Rice husk	> 600	-	15	56	15% feed conversion rate increase	Phongphanith and Preston (2018)
Goat	1% of body weight	Bamboo	-	-	20	84	Increase in DM, OM, CP digestibility, N retention	Van et al. (2006)
Pig	0.3% feed DM	Bamboo	> 600	Bamboo vinegar	17.5	42	Improvement in marketable meat quality	Chu et al. (2013)
Poultry	0.2% feed DM	Maize cob	-	-	6	49	Carcass traits improvement	Kana et al. (2010)
Duck	1% feed DM	Bamboo	> 650	Bamboo vinegar	-	49	Increase in intestinal villus height	Ruttanavut et al. (2009)
Flounder	1.5% feed DM	Wood	-	20% wood vinegar	11	56	10% increase of feed efficiency at 0.5% BC	Yoo et al. (2005)
Strip fish	1% feed Dm	Rice husk	> 600	-	36	90	Significant improvement in water quality	Lan et al. (2018)

5. Conclusion and Recommendations

Biochar, a carbon-rich substance produced from various kinds of waste, is emerging as a new source for remediating soil, water, and air pollution. It is also a potential energy source in the present world due to its high carbon content and porosity. The properties of biochar make it suitable for use in various fields such as the pharmaceutical and power industries. Additionally, soil amendment with biochar can reduce greenhouse gas emissions. The cost-efficiency and wide utility of biochar are attracting global interest to increasing its production. To promote sustainability, using agricultural wastes for biochar production is a promising approach. Moreover, the future scope is to explore the potential of biochar in various fields such as medical applications, production of bricks, use as food colorants and/or food preservative, incorporation in electronics (semi-conductors and batteries), paints, and dyes. Therefore, the use of biochar produced from agri-food chain wastes serves the dual purpose to recycle the generated waste and contribute to achieving sustainability in various industries.

Author Contributions: Conceptualization, Sonika Kumari; Methodology, Sonika Kumari; Supervision, Ivan Širić; Validation, Ivan Širić and Sami Abou Fayssal; Visualization, Ivan Širić and Sami Abou Fayssal; Writing – original draft, Sonika Kumari; Writing – review & editing, Ivan Širić and Sami Abou Fayssal. All authors have read and agreed to the published version of the manuscript.

Funding: This review article received no external funding.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data/Supplementary Information Availability: Not applicable.

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