



## Review

# Agricultural Biomass Waste to Biochar: A Review on Biochar Applications Using Machine Learning Approach and Circular Economy

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**Abstract:** Biochar has gained attention as an alternative source of solid energy and for the proper disposal of agricultural biomass waste (ABW). Microwave-assisted pyrolysis (MAP) is a promising approach for the production of biochar. This review article presents the beneficial use of biochar for soil fertilization, machine learning (ML), the circular bioeconomy, and the technology readiness level. The use of machine learning techniques helps to design, predict, and optimize the process. It can also improve the accuracy and efficacy of the biochar production process, thereby reducing costs. Furthermore, the use of biochar as a soil amendment can be an attractive option for farmers. The incorporation of biochar into soil has been shown to improve soil fertility, water retention, and crop productivity. This can lead to reduced dependence on synthetic fertilizers and increased agricultural yields. The development of a biochar economy has the potential to create new job opportunities and increase the national gross domestic product (GDP). Small-scale enterprises can play a significant role in the production and distribution of biochar, providing value-added products and helping to promote sustainable agriculture.

**Keywords:** microwave pyrolysis; agricultural biomass waste; biochar; circular bio-economy; machine learning; technology readiness level



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## 1. Introduction

Climate change and greenhouse gas emissions are the main concerns of the researchers, as well as tackling the rising demand for alternate energy. Toxic gases and emissions from the industrial sectors should be curtailed by the use of renewable resources. The conversion of biomass into useful products provides a solution to inorganic emissions and wastes. Biochar production has recently emerged as a simple, productive, and scalable process. Production of biochar using the steam pyrolysis process is very cost effective and efficient. The production of biochar from agricultural biomass waste will serve society in an economic manner [1]. As biomass is highly carbonaceous, such as rice husks, sugarcane bagasse, corn husks, corn straw, wheat straw, and so on, it is considered one of the sources of excess GHG emissions. Almost all biomass contains more than 78 wt.% carbon [2].

Agriculture is an important sector in several countries, as reflected by its contribution to the national GDP in 2017. Agriculture was identified as a significant economic backbone in Pakistan, Nigeria, India, Indonesia, Malaysia, China, Denmark, and Thailand. Agriculture contributes to approximately 25% of Pakistan's GDP, making it one of the

largest sectors in the country's economy. In Nigeria, agriculture contributed to 21.60% of the national GDP in 2017. Similarly, in India, agriculture accounted for 15.40% of the GDP, which is a significant contribution given the size of the country's economy. In Indonesia, agriculture contributed 13.90% to the national GDP in 2017, making it a vital sector for the country's economy. Similarly, in Malaysia, agriculture accounted for 8.40% of the GDP, which is a significant contribution given the country's level of development. In China, agriculture contributed 8.30% to the national GDP in 2017, which is significant given the size of China's economy. Denmark, a developed country, also relies heavily on agriculture, with the sector contributing 8.30% to the national GDP. Finally, in Thailand, agriculture accounted for 8.20% of the GDP, making it an important sector in the country's economy. Overall, this demonstrates the importance of agriculture in several countries with arable lands and the significant contribution the sector makes to their national economies [3,4]. Each country produces different crops and have become major producers, shown in Table 1.

**Table 1.** Major producers of agricultural crops.

Countries	Major Crops	Agricultural Biomass Waste Generated
Asian countries	Rice	Husk, straw, hull
India, China, Pakistan, and Thailand	Sugarcane	Bagasses
Indonesia, Malaysia, Thailand, and Nigeria	Palm	Kernel shells, palm fibres
Thailand, Indonesia, and Malaysia	Rubber	Roots, barks, leaves, unproductive rubber trees

After the harvest of crop products, there is abundant generation of ABW. It is predicted that Asian countries will produce four to five kilograms of ABW/per capita/per month by 2025 [5–8]. Figure 1 shows the agricultural waste generation in Asian countries, in which Japan tops the other countries with an agricultural waste generation of 5.1 kg/capita/month. A multifold increase in waste can be predicted for the year 2025 exclusively for Thailand. Apart from this, the huge amount of ABW occupies land but also poses a potential threat to the environment. By dumping on the land, it can also cause environmental problems. Natural biodegradation of ABW releases greenhouse gases such as methane and CO<sub>2</sub> and increases global warming [9]. ABW can be frequently loaded with soluble organics, so the unfavorable leaching that takes place in rainy seasons can pollute and clog the waterways. Direct disposal of ABW should be avoided and efficient technologies should be incorporated for its disposition.

Lignocellulosic ABW is a highly available, sustainable, renewable, and affordable source to generate bioenergy. In general, there are six main ways to convert ABW: (a) thermochemical conversion to biofuels, (b) combustion, (c) hydrothermal liquefaction, (d) torrefaction, (e) pyrolysis, and (f) gasification. Among these methods, pyrolysis is an efficient technique to convert ABW into residues, gases, and oil. These products are value-added, which has a huge demand in industry: they produce less NO<sub>x</sub> and SO<sub>x</sub> emissions than combustion techniques [10], less pressure than hydrothermal liquefaction [11], less tar formation than torrefaction [12], and less energy consumption than gasification [13]. ABW can be used as a renewable source of lignocellulosic feedstock for applications such as fiberboard through mechanical recycling, bioproducts through fermentation, and biofuels using thermochemical processes. Exponential population growth necessitates a search for alternate energy sources.

As mentioned above, pyrolysis techniques are effective in the production of biochar. MAP is the most appropriate pyrolysis technique available because it uses volumetric heating to convert ABW into biochar. MAP is also known for its rapid heating, where the heating mechanism is applied from the core to the outer part of the material. However, there are limited scenarios pertaining to the production of biochar in continuous operations and

its scalability. Hence, this review has detailed and reinforced the machine learning process for large-scale production of biochar. Furthermore, a thorough discussion of the uses of biochar in soil amendments is provided. Finally, the biochar bioeconomy, technoeconomic assessment, technological readiness level, and challenges faced in terms of operational difficulties and significant implications for future growth are reviewed.

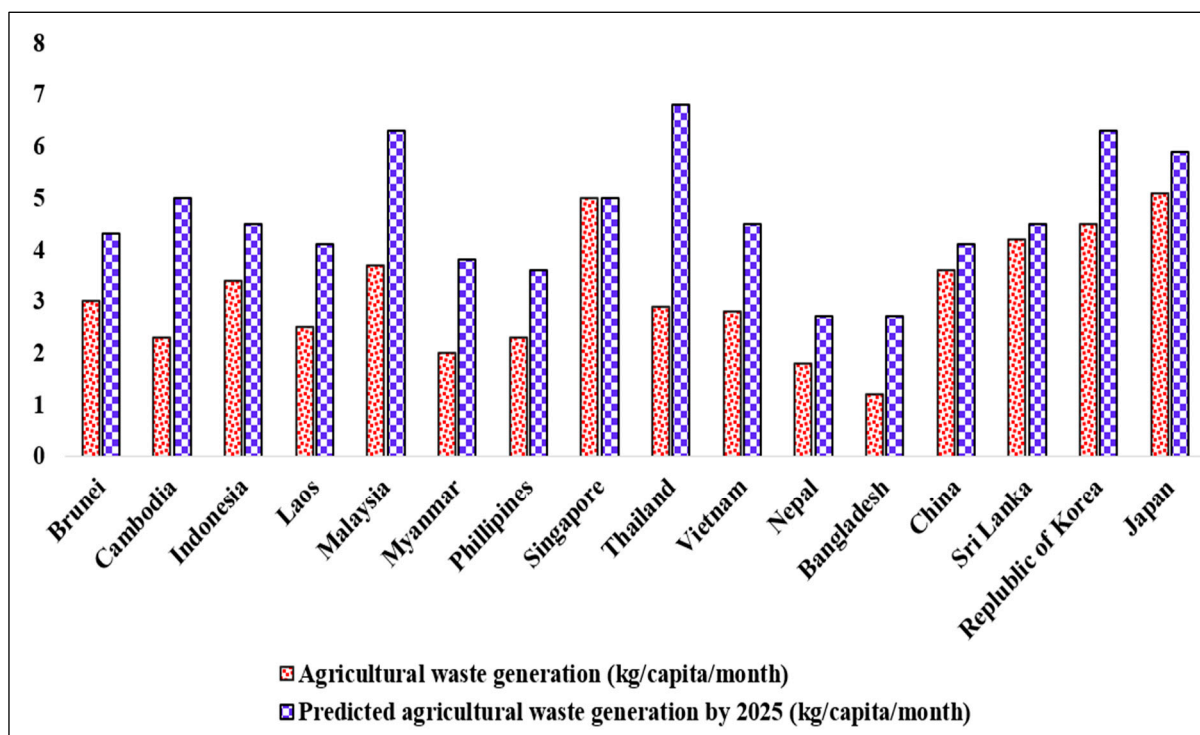


Figure 1. Agricultural waste generation in Asian countries.

## 2. Production of Biochar

Biomass was initially burned in an open flame to produce charcoal and ashes. Then, the charcoal was used for domestic purposes. Open burning of biomass releases air pollutants and limits charcoal yields; hence, the process of open-air burning of biomass was interrupted. Researchers and industrialists have found advanced technologies to obtain maximum potential energy outputs from biomass [14]. Biochar can be produced using different methods, such as torrefaction, combustion, gasification, and slow and fast pyrolysis. Among these processes, pyrolysis is a better option and an effective process for producing biochar. Gasification and combustion are exothermic processes. They convert the biomass material into gas in the presence of oxygen [15,16]. These technologies generate energy; however, they are very ineffective, costly, and emit a large number of hydrocarbons. In view of this, pyrolysis finds its place in the process of biomass pyrolysis and produces three kinds of yield: solid, char, and gas. Figure 2 represents the three different kinds of pyrolysis processes and the average biochar yield. Biochar is used in different applications, such as additives in bitumen, precursors for catalysts, carbon sources, and soil enhancers [17–19]. From the literature studied, the different components identified in biochar are shown in Table 2, in which corn cob and sugarcane bagasse have more than 70 wt.% carbon content. Industrial processes have incorporated the use of biomass as their source of energy production and this has reduced their operational costs [20,21].

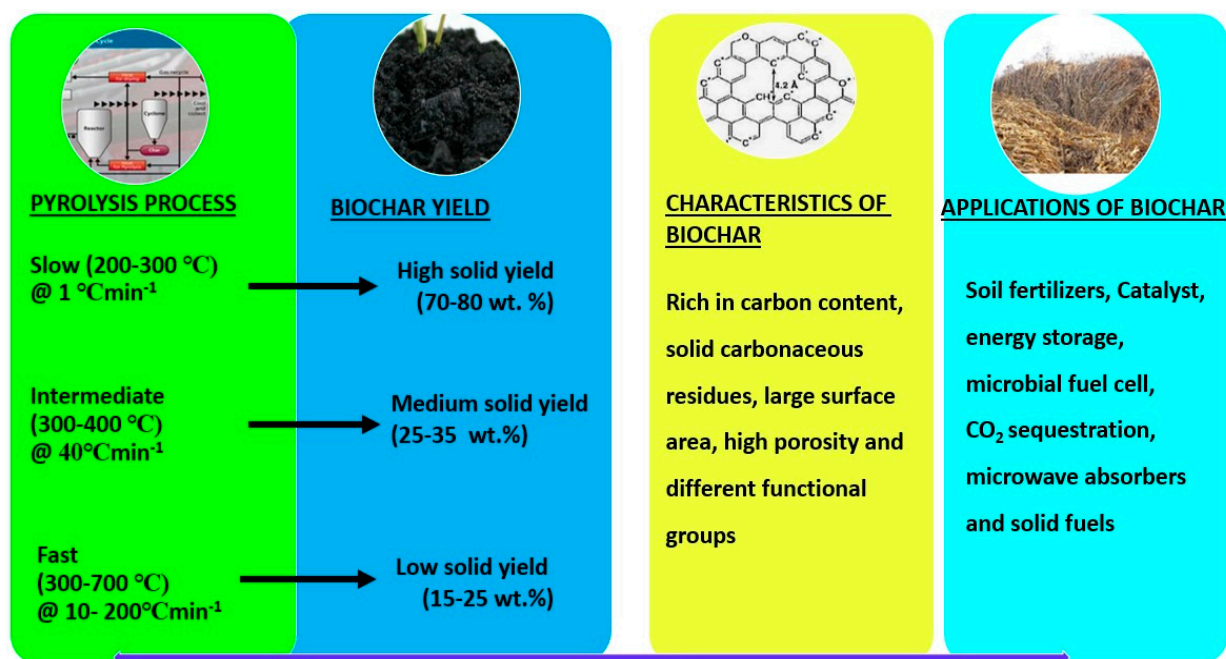


Figure 2. Production of biochar and its potential applications [17–19].

Table 2. Elemental composition of biochar.

Biochar Feedstock	Temperature °C	Components (wt.%)							Reference
		C	N	O	H	K	S	P	
Rice straw	800	36.2		39.8	-	-	-	-	[22]
Corn cob	600	79.1	4.25	-	-	10.1	-	-	
Corn stover	600	69.8	1.01	-	-	9.95	0.181	2.461	
Peanut hull	600	65.5	2.0	-	-	10.0	0.0016	0.0015	[23]
Corn stover	400	59.5	1.16	-	-	7.33	0.137	1.705	
Corn stover and cob	300	57.51	1.62	35.12	-	0.28	-	-	
Rice husk and high-density polyethylene	500	46.8	0.67	-	0.036	-	-	-	[24]
Sugarcane bagasse and PP	600	76.5	3.03	19.8	2.93	-	-	-	[10]
Wheat straw and PS	600	62.9	-	-	-	-	-	-	[24]
Walnut shell	900	55.3	0.47	1.6	0.89	-	-	-	[25]

### 3. Agricultural Uses of Biochar

Addition of biochar can greatly influence the soil characteristics. It also provides better aeration for the soil and has a large surface area to increase moisture penetration. Figure 3 depicts the various uses of biochar in agriculture and shows that around 20% of biochar can be utilized in horticulture and specialty crops to induce soil nutrients. Biochar can be effectively used for odor control in water treatment methods [26]. Biochar-based fertilizers are currently widely used as plant nutrients. They can improve and modify the soil characteristics. Researchers have identified that use of biochar-based fertilizers can help in the unfavorable agricultural soils, such as sandy soils and heavily worn soils prevalent in the tropics and has an effect on the microbial concentration of the biomass.

Biochar is often used in soil improvement and researchers are interested in this area of soil enhancers using biochar. Figure 4 is a pictorial representation of biochar application as a soil enhancer. It was identified from the studies that the penetration of biochar into the soil must be slower to be more advantageous. These are: (1) decrease in nutrient leaching; (2) reduced irrigation frequency; and (3) reduced greenhouse gas emissions [27–29]. However, a detailed analysis is recommended by the researchers before the application of biochar-based solid enhancers. The detailed analysis must include:



- Climatic conditions
- Characteristics of soil
- Environmental parameters
- Topography
- Frequency of application

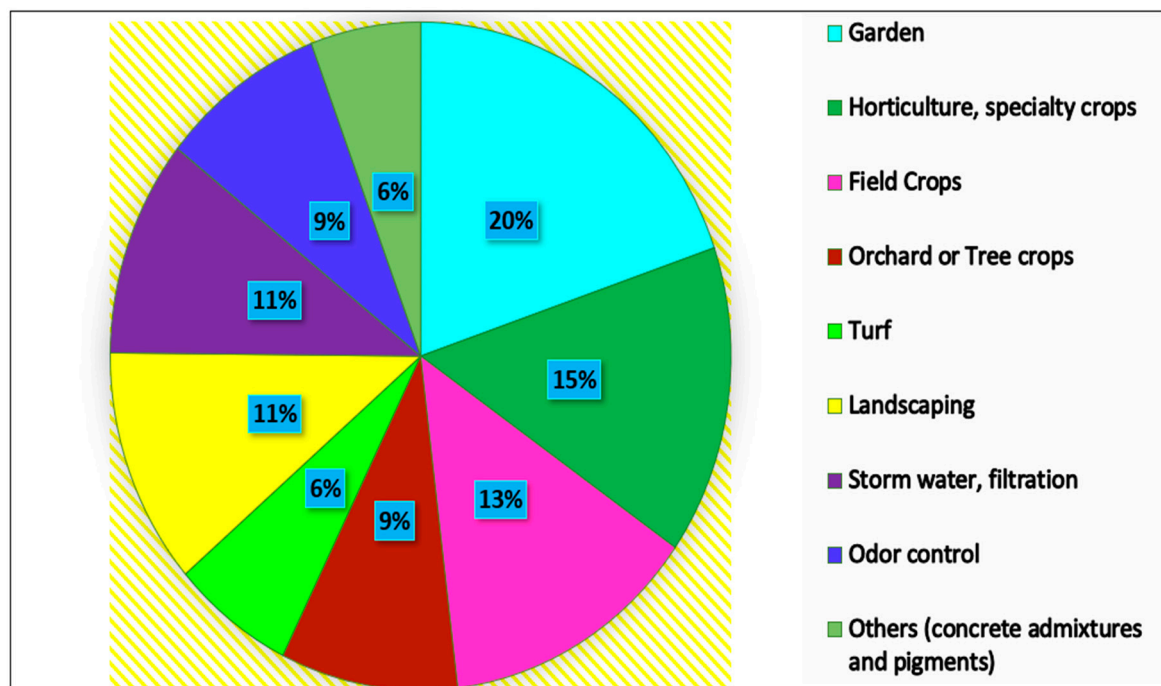


Figure 3. Agricultural uses of biochar.

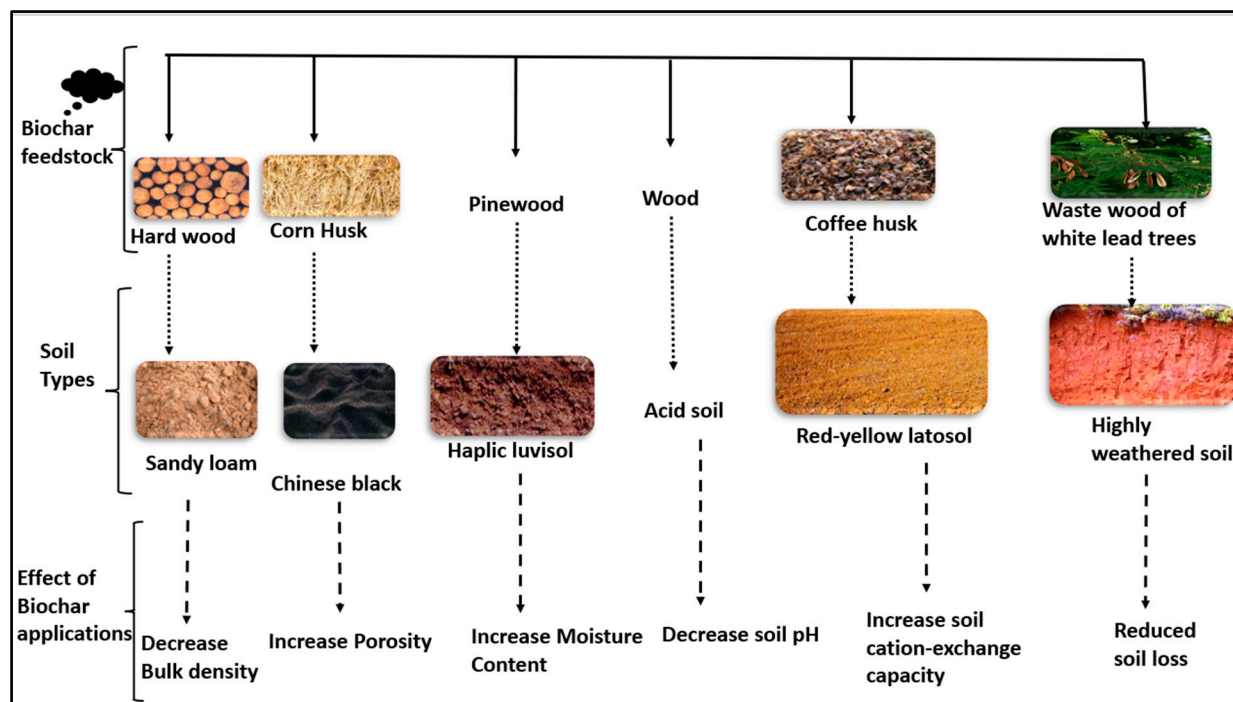


Figure 4. Applications of biochar in soil improvement [29,30].

This detailed analysis should be completed, and the use of biochar will be determined after the report is evaluated. Regular monitoring of crop performance and its effects on soil should be undertaken in field settings with different rates of application [30].

Recently, biochar has been used for the mitigation of NO<sub>x</sub> emissions. NO<sub>x</sub> emissions can be reduced in a sewage treatment plant by the addition of ammonium nitrate with biochar [31]. This proves the biochar's versatility.

#### 4. Microwave Reactors

Microwaves are the second radiation after radio waves in the electromagnetic spectrum, with a wavelength of  $10^{-2}$  m. Their frequency ranges from  $10^8$  to  $10^{12}$ . FCC has allotted 2.45 GHz for domestic microwaves [32]. Transfer of heat energy takes place through conduction. Microwaves directly penetrate into the core and complete transformation of materials occurs from internal to external heating. Microwaves are transparent and it depends on the dielectric properties of the materials. Microwave pyrolysis is extremely beneficial to convert biomass, plastic waste, food waste, and sewage sludge waste into useful products. Even though microwaves are advantageous, they have some disadvantages which are given in Table 3. In the food industry, microwave heating has been utilized extensively for numerous operations such as defrosting, heating, sterilizing, and baking. Recently, there has been increased interest in microwave heating in chemical and environmental engineering for drying [1,33], torrefaction [34], pyrolysis [35–37], and gasification [38]. Materials are classified based on their interaction with microwave radiation. They are classified as either conductors that reflect microwaves, absorbers that use microwaves to generate heat, or insulators that transmit microwaves. Rapid heating and reduced reaction time is achieved in MAP compared to conventional heating. Visual observation of plasma generation and hotspots are also noted during microwave pyrolysis as they drastically increase the heating rate of the materials. Biochar has a dielectric constant value between 0.11–0.29 and a pool of carbon content. It can be a good absorber of microwaves for different pyrolysis processes [39,40].

**Table 3.** Pros and cons of microwave-assisted pyrolysis.

Pros	Cons
Very selective and volumetric heating of microwave absorbers	Consumption of energy is greater in poor microwave absorbers
Cost effective with reduced reaction temperature and time	Generation of plasma and hotspots
Control of reaction temperature by ON/OFF system	Thermal disturbances and disproportionate heating
Indigenous temperature measurement by thermocouple and infrared thermometer	Microwave arcing

Selection of reactors is an important process. The yield of pyrolysis products depends on the reactor type, its residence time, reaction temperature, and the feedstock [41–43]. Fluidized beds, conical sprout beds, batches, and microwaves are some of the reactors used in pyrolysis studies. Reactor types are classified on the basis of feedstock movement and heat transfer mechanisms. During the process design of microwave pyrolysis reactors, factors to be considered are:

- Mode of operation
- Type of reactor
- Magnetron location (side, bottom, top)
- Frequency of microwaves
- Quartz or ceramic materials
- Microwave cavity
- Size of the reactor

The above are the crucial factors that are considered during microwave reactor design [44–47]. Fixed and fluidized beds use a fixed ratio of biomass feedstocks. In order to experiment with a lab-scale MAP, a single-mode domestic microwave is sufficient to perform the experiments [48]. Extensive research is available to support MAP in batch and semi-batch process, but more intensive studies are required to facilitate the process continuous mode. Feeding of agricultural biomass waste in continuous operations requires external supports such as an auger, belt conveyor, and free fall or free fall system. The preferred mode of operation for MAP is multimode with low-power magnetrons (<1000 W) [49–52]. It is more cost effective than using a single mode with high-power magnetrons. Using high power will also create too many hotspots and electrical arcing which might be a hinderance in continuous mode [53–56].

### 5. Use of Catalysts in MAP

Catalysts in microwave-assisted pyrolysis have good potential to enhance biochar yields. The addition of a catalyst can be undertaken at two stages [57], either in the primary or in the secondary stage or both. In the primary stage, a catalyst is usually incorporated by mixing it into the feedstock. In the secondary stage, a catalyst can be incorporated during the downstream process. There are numerous catalysts that have been explored with biomass feedstock such as ZSM-5, HZSM-5, oxides of copper, nickel, magnesium, and alumina [58]. Ao Fu [59] examined the effects of several catalysts in plastic pyrolysis. The results indicate that the addition of a catalyst increases the biochar yield and reduces the production of gas and oil. Chen [60] catalyzed biomass with ZSM-5 and obtained higher biochar yields than biomass catalyzed with sodium carbonate and alumina oxide. It was noted that biochar yields increase with different ratios of acid or basic content of biomass. The acid or basic content correlates with the available silica content in the catalyst. In general, it was identified that biomass and catalysts are in synergy to produce high yields of biochar. There are three stages for the degradation of agricultural biomass wastes (ABW) in MAP: (1) moisture removal, (2) primary degradation of simple molecules, and (3) secondary degradation of complex substances. These each encourage further cracking of complex molecules into oil and gas [61–63]. According to reports, microwave pyrolysis of ABW is superior to conventional pyrolysis because it offers a faster heating rate and industrial value-added products (syngas and furfural bio-oil) [64,65]. In Table 4, the use of agricultural waste in a MAP system produced more than 40 wt.% of phenols in the liquid yield [66].

**Table 4.** Microwave-assisted pyrolysis process with absorbers used for processing different agricultural biomass wastes.

Process	Microwave Absorber	Feed	Time (min)	Bio-Oil	Gas	Biochar	Reference
Domestic modified 1 kW microwave reactor	Char	Palm kernel shell	25	20	30	50	[67]
		Oil palm fiber	25	7	23	70	
Microwave pyrolysis reactor	Silicon carbide	Wheat straw	10	32	22	46	[49]
Lab scale multimode microwave reactor with 4 magnetrons	Char	Rice husk	20	23	34	43	[68]
Single mode microwave pyrolysis reactor with 1 magnetron	N/A	Bamboo leaves	30	44	34	22	[69]
		Corn stover	30	40	30	20	
Domestic lab scale single mode microwave reactor	Activated carbon	Coconut sheath	15	46	32	22	[8]

Table 4. Cont.

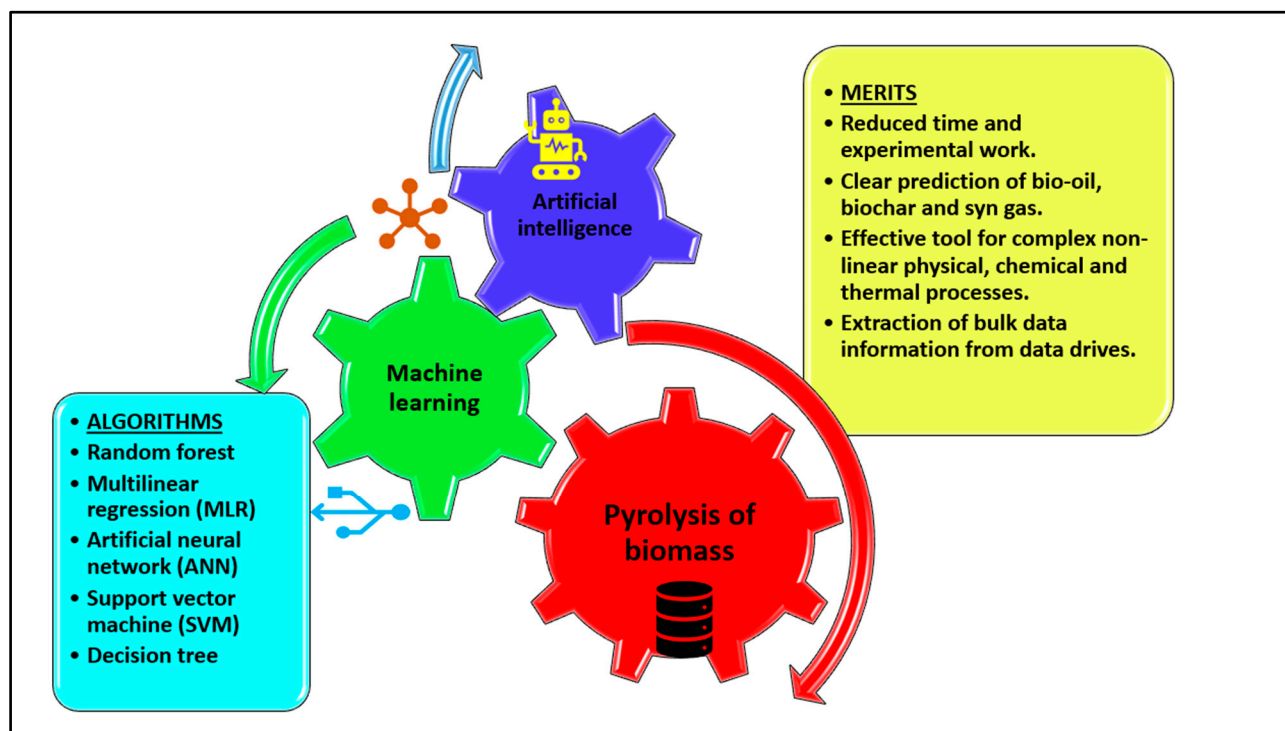
Process	Microwave Absorber	Feed	Time (min)	Bio-Oil	Gas	Biochar	Reference
Single mode microwave reactor with 1 magnetron	N/A	Waste coffee grounds	30	43	35	21	[69]
Single mode microwave reactor with 1 magnetron	N/A	Sugarcane peel	30	43	37	20	[69]
Pilot scale 2 magnetron multimode microwave reactor	Silicon carbide	Large wood block	15	18	61	21	[48]

## 6. Machine Learning in Prediction of Biochar

In recent decades, theoretical models were widely used to predict the yields of the pyrolysis process [70]. These models are time consuming, complex, and semi-empirical (relies on experimental results). Theoretical models cannot be used for the prediction of biochar, which requires advanced and sophisticated programs to predict the multidimensional biochar yield. Several attempts were made to predict the biochar yield with a combination of theoretical and experimental models, but they can be applied with limited experimental results and ratios of feedstock. These models will not suit for continuous modes of operation and enormous data. Increased interest is being shown towards the prediction of biochar yields using machine learning. This is an analytical model which has been widely used by researchers in different specializations.

There is an enormous amount of pyrolysis experimental data that could be used to predict biochar production using artificial intelligence and can be implemented using a data-driven modeling pattern. Models are highly productive, accurate, and require less time and repeatability of datasets. These models identify the inputs and predesigned datasets, through which output components are predicted with nil assumptions. However, the implementation of ML to predict biochar means a large amount of data should be processed. Zhu [71] used 245 datapoints of biomass feeds and operating parameters to predict biochar yield and carbon (wt.%) using an RF model, in which regression values were 0.85 for biochar yield and 0.84 for carbon (wt.%). Pathy [72] studied 91 datasets of biomass feedstocks and XGB ML was used to predict the algal biochar yield, in which  $R^2 = 0.84$ . Khan [73] used ANN to predict biochar yield, and a comparative study was conducted with metaheuristic algorithms. Good regression values ( $R^2 = 0.95$ ) were obtained. There are limited studies and efforts to develop a comprehensive data-driven model with the ability to determine biochar yield and its elements. From the literature, it is understood that biochar and its elements are relatively significant in pyrolysis process conditions. Large scientific interest is shown by researchers to evolve a complete machine learning process for the envision of biochar yields. Figure 5 shows a pictorial representation of algorithms and merits of machine learning that are used to predict biochar yield. Machine learning-based biochar production is an effective approach, and many researchers are involved in studies of this nature. ML helps in the optimization, design, and prediction of the biochar process [74]. Abdul [75] extracted 46 biomass datapoints from the literature and modeled biochar production with five different machine learning algorithms: multiple linear regression, decision tree, random forest, support vector machine, and K-nearest neighbor. Their studies revealed that pyrolysis temperature has an important role in predicting the output variable (biochar yield). Among the five algorithms, random forest performed best to predict the specific surface area and the biochar yield. Table 5 shows the level of neurons that was selected to predict different components such as, kinetics ( $A$  and  $E_a$ ), gas species, and biochar.





**Figure 5.** An overview of machine learning in the pyrolysis of biomass.

Validation of experimental models can be achieved using RSM, a statistical tool which uses mathematical equations to verify the validity of the model [76]. RSM is used to optimize the output variables using various designs of experiments (DOE's). Output responses vary significantly with the input variables, and optimization of responses can be achieved by statistical techniques. In this way, RSM finds an appropriate mathematical model for a given set of data and checks those values within the numerical ranges or categories [77]. Moreover, execution of this requires a large volume of data. RSM typically gives first, second order, and quadratic polynomial results. Polynomial regression is a good option to be used with RSM for multisource feedback. There may be discrepancies between the two predictor variables; in this case, polynomial regression allows us to examine the extent of correlation between input and output variables. Many research problems can be solved and benefited using this approach.

ANFIS (prediction model) and MLP-NN (data-driven model) are important models used for the recognition of patterns, signal controls, functional approximation, and simulations. They are used to model complex input and output variables. They also capture the statistical relationship for an unknown joint probability distribution of observed variables. Machine learning models can predict a rapid change in temperature and can understand and adapt the operational conditions [78]. Aziz [79] used particle swarm optimization and ANFIS to predict the biochar yield. ANFIS, on the other hand, is a hybrid adaptive control technique that can overcome the changing characteristics of biomass feedstock. ANFIS uses fuzzy logic and neural networks and has been used in broad areas such as renewable energy and wind and solar energy. It is a deep learning algorithm, and its fuzzy logic considers the human prediction of biochar yield. It can also be used for decision making in large-scale processes.

**Table 5.** Literature review for level of neurons to predict different components.

Type of Yield Prediction	Model	Input Variables	Output Variables	Neurons	MSE	R <sup>2</sup>	Reference
Gaseous products	ANN	<ul style="list-style-type: none"> <li>Size of biomass</li> <li>Air flow velocity</li> <li>Reaction temperature</li> </ul>	<ul style="list-style-type: none"> <li>H<sub>2</sub></li> <li>CO</li> <li>CH<sub>4</sub></li> <li>CO<sub>2</sub></li> </ul>	7	0.01	-	[80]
Refuse derived fuels (RDF)	ANN	<ul style="list-style-type: none"> <li>Heating rate</li> <li>Pyrolysis temperature</li> </ul>	<ul style="list-style-type: none"> <li>Biomass weight loss</li> </ul>	7	0.16	0.99	[81]
Gas species	ANN	<ul style="list-style-type: none"> <li>Moisture content</li> <li>Ash</li> <li>Carbon</li> <li>Hydrogen</li> <li>Oxygen</li> <li>Reduction temperature</li> </ul>	<ul style="list-style-type: none"> <li>H<sub>2</sub></li> <li>CO</li> <li>CH<sub>4</sub></li> <li>CO<sub>2</sub></li> </ul>	5	0.0873	0.99	[82]
Biomass gasification in FBR	ANN	<ul style="list-style-type: none"> <li>Ash</li> <li>Moisture</li> <li>Carbon</li> <li>Hydrogen</li> <li>Oxygen</li> <li>Reduction temperature</li> </ul>	<ul style="list-style-type: none"> <li>CO</li> </ul>	2	0.79	0.99	[83]
			<ul style="list-style-type: none"> <li>CO<sub>2</sub></li> </ul>		0.41	0.98	
			<ul style="list-style-type: none"> <li>H<sub>2</sub></li> </ul>		0.62	0.99	
			<ul style="list-style-type: none"> <li>CH<sub>4</sub></li> </ul>		0.15	0.99	
			<ul style="list-style-type: none"> <li>Producer gas</li> </ul>		0.07	0.99	
Kinetic parameters	ANN	<ul style="list-style-type: none"> <li>Percentage of carbon</li> <li>Ratio of air/biomass</li> <li>Volatile substance</li> <li>Ash</li> </ul>	<ul style="list-style-type: none"> <li>Pre-exponential factor (A)</li> </ul>	9	0.1	0.93	[84]
			<ul style="list-style-type: none"> <li>Activation Energy (E<sub>a</sub>)</li> </ul>	10	0.01	0.94	
			<ul style="list-style-type: none"> <li>Reaction order (n)</li> </ul>	23	0.004	0.90	
Kinetic parameters of biomass, pure and mixed components	ANN	<ul style="list-style-type: none"> <li>Biomass mass percentage composition of cellulose, hemicellulose, and lignin.</li> </ul>	<ul style="list-style-type: none"> <li>Pre-exponential factor (k<sub>0</sub>)</li> </ul>	20	<0.001	>0.90	[85]
			<ul style="list-style-type: none"> <li>Activation Energy (E<sub>a</sub>)</li> </ul>	17			
			<ul style="list-style-type: none"> <li>Reaction order (n)</li> </ul>	30			
Optimization of Cerbera Manghas biodiesel production	ANN integrate with ACO	<ul style="list-style-type: none"> <li>H<sub>2</sub>SO<sub>4</sub> catalyst concentration</li> <li>Methanol to oil molar ratio</li> <li>Reaction temperature</li> <li>Reaction time</li> </ul>	<ul style="list-style-type: none"> <li>Acid value</li> </ul>	10	0.03	0.99	[86]
Highest heating value of biomass	SVM integrate with PSO	<ul style="list-style-type: none"> <li>Fixed carbon</li> <li>Volatile matter</li> <li>Reaction temperature</li> <li>Residence time</li> <li>Atomic oxygen/carbon ratio</li> <li>Atomic hydrogen/carbon ratio</li> </ul>	<ul style="list-style-type: none"> <li>Higher heating value (cubic-SVM)</li> </ul>	0.39			[87]

## 7. Circular Bioeconomy on Biochar Production

Circular bioeconomy is a novel approach to sustainable development and biobased product research. Production of biochar by pyrolysis using ABW can be an alternative to open burning and add some value to the circular bioeconomy. The take-make-waste disposal cycle is traditionally followed for the production and consumption of materials. This should be redesigned for biobased resource production [88]. It will become an alterna-

tive to meet the increased demand for fuel. The European Commission has high regard for biobased products and the efficacy of biochar. The European Union's concurrence is connected to agricultural waste, food waste, and biological products. European policies are framed around the Sustainable Development Goals (SDGs) [89]. Even though biochar fits into the circular bioeconomy, market readiness and financially healthy enterprises are needed to uplift the process. A complete study on the operation and production costs can help to understand the adoption of biochar production. Proper planning and overcoming failure are essential in this venture. TRL and technoeconomic analysis will address any concerns. Policies can facilitate biochar production until a stable market is achieved. Some of the policies that are framed exclusively for biochar production are given in Table 6.

**Table 6.** Policies supporting biochar production.

Policy	Support	Reference
Biorefinery, renewable chemical and biobased product manufacturing assistance	80% project cost	[90]
Biomass crop assistance program (BCAP)	Sustainable development of crops	[91]
Natural resources conservation services (NRCS)	Biochar—soil amendment	[92]
India Biochar and Bioresources Network	Biochar—soil amendment	[93]

## 8. Technology Readiness Level

The TRL (technological readiness level) is a pictorial representation of the readiness level of the process or system and assessment tool for commercialization. It is a measure of the process maturity level. It has nine levels of implementation and three stages, which are:

- Lab
- Pilot
- Commercial

From TRL, policymakers, investors, and researchers get an overall view of the process and can proceed with extensive action [94]. The TRL of agricultural biomass and its products is presented in this section, and the pictorial view is given in Figure 6. Bio-oil from the pyrolysis process is at a developed stage. Globally, pilot operations and commercialization of bio-oil have commenced. The feed rate of biomass ranges from 200–800 kg/h. Industrial companies and universities have both pilot scale and commercial units, including France, Canada, CPERI, China, the USA, and Finland. All units are operative for research and industrial purposes [95] and rely on the fast pyrolysis process. When it comes to the gaseous products, there is no pilot or commercial level of utilization. Despite the fact that non-condensable gases have numerous industrial applications and hydrocarbons, they are still at the laboratory scale. Researchers conduct experiments and observe the results to commercialize the by-products and the valuable products from biomass pyrolysis. Production of biochar is between 15,000 and 20,000 tons per year, and a recent survey revealed that it is often between 35,000 and 75,000 tons per year, consuming 125,000 to 250,000 tons of feedstock per year with more than five plants producing 5000 tons per year of biochar [96]. Additionally, a few facilities generate more than 50 metric tons of biochar annually from biomass feedstocks in Germany and Canada [97].

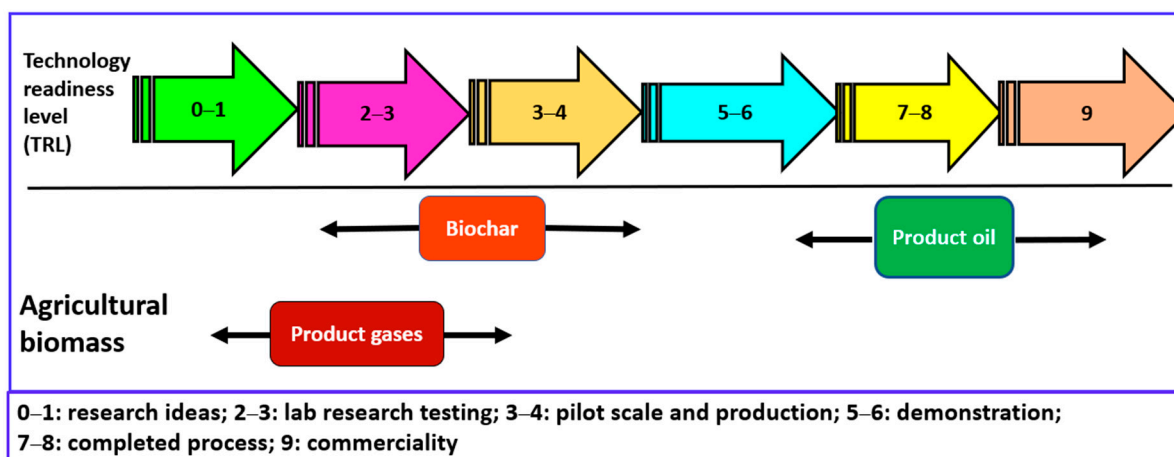


Figure 6. Technology readiness level of agricultural biomass waste.

### 9. Economic Viability of Biochar

Production of biochar is consistent with the SDGs since it mitigates CO<sub>2</sub> and GHG emissions [98]. Biochar has numerous applications [99], including:

- Adsorbents
- Soil enhancements
- Fertilizers
- Energy production
- Fixation of CO<sub>2</sub>
- Energy production
- Industrial value-added products

Matovic [100] illustrated that biochar helps in carbon sequestration, showing that globally 10% of biomass is converted into 50% biochar yield, amounting to 4.8 GtC/year. In addition, the pyrolysis method of producing biochar is very environmentally friendly in its management of the huge amount of solid waste [101]. It is uncertain whether production of biochar by enterprises or farmers will be profited. However, the invention of new technologies and the demand for energy and value-added products might elevate the market and become a profitable venture. Moreover, society's commitment towards the achievement of clean air and climatic regulations can help farmers or small-scale industries to kickstart a biochar production unit.

The commercial value of biochar can be increased by additional pyrolysis products, such as bio-oil and non-condensable gases. These gases (CH<sub>4</sub>, H<sub>2</sub> and CO, N<sub>2</sub>) can be used in industrial applications [100]. Positive economic effects of biochar can be observed when the cost of carbon is included in CO<sub>2</sub> sequestration. The application of biochar in soil amendments will become alluring when water conservational cost is included. The financial benefits of adding biochar to soil, if estimated, will help biochar to equally compete with chemical fertilizers [101]. Switchover from charcoal to biochar in steel and power sectors will increase the economic and social benefit of biochar. The public may, nevertheless, indicate positive approval of pyrolysis-produced biochar. More research and communication are required in this area to characterize the effects of biochar on the environment, soil, and public health [102].

### 10. Technoeconomic Analysis

Pyrolysis has gained interest among researchers for biochar production, but it is difficult to assess the technical and economic aspects of experiments before the conduction of experiments. There are also less reported studies in this area. Haelderman [103] was the first to report on the most profitable pyrolysis process for biochar production in a continuous process. In order to perform technoeconomic analysis, the most crucial variables should be

identified in biochar production. It is important that economic assessment is undertaken on a large scale as it is more efficient. The TEA analysis proceeds as follows:

- Data collection
- Mass and Energy balance
- Cost estimation
- Economic assessment
- Risk analysis
- Sensitivity analysis

For each investment, NPV and DPP should be estimated. NPV is an effective variable to determine the profitability scenarios. MSP of biochar is the price at which it is sold, as NPV equals zero. The price of biochar varies from €50 to €20,000 per ton. Drastic variation in biochar MSP is observed since biochar production is accompanied by different agricultural biomasses, elemental compositions, and types of process. Moreover, biochar production units are very limited for large-scale application. It is very difficult to create simulation models for the simultaneous pyrolysis of biomass and plastic before experimentation. Hence, assessment and analysis techniques, such as life cycle evaluation and technoeconomic assessments, can be helpful for process optimization. Moreover, it will reduce the cost and time. Net present value, DPP, and minimum selling price are some important factors in TEA. Additionally, data from experiments, models, and end-user surveys can give an elaborate view for socio-economic studies, which may help commercial units to open a biochar production unit. Effective advertising and awareness can educate the public about the correct disposal of plastic waste as well as the usage of biochar and other goods made from biomass and plastic, even at a somewhat higher cost, in order to protect the environment. Governments should also implement programs and give subsidies to biochar production units and carbon sequestration [94].

## 11. Conclusions

This review paper provides a comprehensive discussion on the scalability and feasibility of producing biochar through microwave-assisted pyrolysis of agricultural biomass feedstock. The authors explore various pyrolysis methods, reactor types, and pyrolysis parameters to determine the optimal process variables that can enhance biochar formation. Careful selection of feedstock with high carbon content and low moisture content, co-pyrolysis of different biomasses, and an extended residence period can improve the basic mechanism that transforms agricultural biomass waste into biochar. The review also highlights the importance of optimization and customization of process variables to produce biochar with an appropriate yield and enhanced qualities for a specific application. It suggests that by delivering the right composition of feedstock and setting process parameters efficiently, it is possible to address the yield of biochar and provide the desired qualities.

However, there are still significant challenges with co-pyrolysis and lab-scale biochar synthesis that need to be resolved to scale-up the pyrolysis process. Further research is essential to identify the key variables and maximize the biochar production process. Developing a good model by machine learning will help predict the biochar yield with better accuracy, and it is of great scientific interest. It enables the researchers to understand how to process and facilitate the circular bioeconomy. It can help conserve the environment, reduce carbon emissions, and promote sustainable economic growth. By leveraging waste biomass as a resource, the circular bio-economy offers a viable solution to the challenges of climate change and resource depletion. Overall, the review paper provides valuable insights into the production of biochar and highlights the importance of process optimization and customization to produce biochar with the desired qualities for a specific application.

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## Nomenclature

ANN	Artificial Neural Network
ML	Machine Learning
SVM	Support Vector Machine
RF	Random Forest
XGB	Extreme Gradient Boosting
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
ABW	Agricultural Biomass Wastes
MAP	Microwave-assisted Pyrolysis
RSM	Response Surface Methodology
MLR	Multi Linear Regression
ANFIS	Adaptive Neuro Fuzzy Inference Systems
FCC	Federal Communication Commission
MSE	Mean Square Error
R <sup>2</sup>	Regression Coefficient
DOE	Design of Experiments
A	Pre-exponential Factor
E <sub>a</sub>	Activation Energy
n	Reaction order
TRL	Technology Readiness Level
CPERI	Chemical Process Energy Research Institute
ECN	Energy research Center of Netherlands
CNG	Compressed Natural Gas
MMT	Million Metric Tons
MLP	Multi-Layer Perception
TEA	Technoeconomic Analysis
NPV	Net Present Value
DPP	Discounted Payback Period
MSP	Minimum Selling Price
GDP	Gross Domestic Product

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