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Microwave Pyrolysis of Agricultural and Plastic Wastes for Production of Hybrid Biochar: Applications for Greener Environment

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ABSTRACT

The microwave-assisted pyrolysis (MAP) is a promising technology for converting waste feedstocks (AWB and PW) into valuable products, primarily biochar. The residual product generated from the AWB and PW MAP process is called hybrid biochar. The hybrid biochar made by MP is highly stable, has distinctive physical and chemical characteristics, and outperforms its conventional usage. Microwave heating is an efficient and fast energy heating method. It helps with yield production, eliminates the need for liquid convection, makes thermal control easier, restores waste products' chemical and energy value, and produces the highest quality and most cost-effective hybrid biochar. Different feedstocks and microwave pyrolysis settings affect how well hybrid biochar restores the environment. This article examines hybrid biochar's potential to boost agricultural productivity, nutrient availability, co-composting, water retention, and consumption efficiency. The report also reveals knowledge gaps and suggests further research to better understand hybrid biochar deployment. The study also detailed hybrid biochar's production, characterization and, most importantly, environmental use.

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1. INTRODUCTION

A significant obstacle in the 21st century is solid waste management, which has become increasingly difficult due to the growing population, urbanization, and technological developments (Emenike *et al*., 2022; Kumar *et al*., 2021; Mohammed *et al*., 2024). The term "municipal solid waste" (MSW) describes a wide variety of solid trash abandoned regularly by rural and urban residents, such as garbage, waste, and refuse (Iwuozor *et al*., 2022a). Examples of feedstocks include polymers, tire leftovers, agricultural Biomass, and municipal solid waste. Other examples include material from tires. Several researchers have identified Biomass and plastics as the most significant components of municipal solid waste (MSW) among the many elements that make up MSW (Du *et al*., 2021; Hibino *et al*., 2021). Massive amounts of waste are being produced all over the world as a result of the ever-increasing global population, as well as the consumption of various types of plastic and wood. Significant negative consequences have been brought about for the ecology and the ecosystem. Rather than placing excessive reliance on finite natural resources, it has been argued that there is a requirement for environmentally responsible production and utilization through trash recycling. Recycling trash and recovered energy is significant in any economy's growth. During the year 2017, agriculture significantly impacted the Gross Domestic Product (GDP) of several countries, which is evidence of the relevance of agriculture in these states (Shahbaz *et al*., 2022). which highlights the significance of agriculture in nations with fertile land and emphasizes the substantial economic impact of the agricultural sector on their national economies (Ge *et al*., 2021; Rex *et al*., 2023). Lignocellulosic agricultural by-products (ABW) are abundant, environmentally friendly, renewable, and cost-effective resources for producing bioenergy. Hence, it is imperative to promptly engage in the recycling or reutilization of AWB, whether as raw materials or as an energy source. Energy recycling is highly significant because 30 X 10 21J Bioenergy can be generated from waste biomass already present all over the planet. According to the findings, this quantity is comparable to one billion billion tons of coal (Potnuri *et al*., 2023).

However, plastics, which are extensively utilized globally, are primarily derived from petroleum. The global production of plastic products in 2020 amounted to 367 million tons, as reported by Rex *et al*. (2022). Simultaneously, there is a growing quantity of plastic garbage. Unrecycled waste plastics are either incinerated or disposed of in landfills. The biodegradation rate of plastic trash is extremely sluggish (Ge *et al*., 2021; Rex *et al*., 2022). Plastics are commonly found in the water, particularly in polar regions and trenches. As plastic particles continue to decrease in size, certain microplastics have acquired toxicity. The microplastics will ultimately enter the human body through biological enrichment, leading to potential health consequences (Yang *et al*., 2023). Hence, the issue of plastic pollution has led to a very critical scenario, emphasizing the importance of enhancing plastic recycling efforts and establishing a sustainable plastic recycling economy. The chemical recovery techniques utilized for agricultural and waste plastics encompass pyrolysis, gasification, and solvolysis, as described by Abbas-Abadi *et al*. (2023) and Yang *et al*. (2020). Pyrolysis is regarded as a cost-effective method of recovery. This technology can convert agricultural and plastic wastes from low-value to high-value chemical raw materials, which has garnered significant interest. Pyrolysis is a critical stage in the manufacturing of hybrid biochar as it impacts both the effectiveness of the biochar and the production expenses. Microwave-assisted pyrolysis has gained increasing attention recently due to its efficient and targeted heating approach.

Furthermore, this hybrid biochar possesses unique surface properties, such as a high porosity, surface area, and increased aromatic Carbon and mineral content (Potnuri *et al*., 2023). The research investigation investigated the use of hybrid biochar as a microwave susceptor and found that recirculating hybrid biochar substantially impacted the yields and quality of the end product (Shukla & Neelancherry, 2022). The feed's Chemical preparation can substantially impact the MWP process. Subjecting pre-treated feed to catalysts in a microwave environment can significantly enhance the amount of product obtained (Hamzah *et al*., 2023a; Ren *et al*., 2020). Microwave Co-pyrolysis is a technique that involves using two or more materials as feedstock to create high-quality pyrolysis products. It is a straightforward and efficient method, as stated by Ryu *et al*. (2020). A comprehensive understanding of co-pyrolysis is essential for minimizing production expenses and addressing diverse waste management challenges. This process enables the simultaneous treatment of two or more types of trash, resulting in enhanced waste utilization, reduced response time, and decreased energy usage. Potnuri *et al*. (2022) researched to investigate the impact of torrefaction temperatures ranging from 125 to 175 degrees Celsius and catalyst quantity ranging from 5 to 15 grams on the co-pyrolysis of torrefied sawdust (TSD) and polystyrene (PS) to generate products with increased value. An analysis was conducted to examine the impact of torrefaction on the co-pyrolysis of TSD: PS. The focus was on understanding the resulting product yields, synergy, and energy consumption. With an increase in torrefaction temperature, there is a corresponding increase in oil production (48.3–59.6 wt%) and char yield (24.3–29 wt%), but the gas output (27.4–11.4 wt%) falls. The catalytic co-pyrolysis exhibited a substantial degree of synergy compared to the non-catalytic co-pyrolysis. In the case of municipal solid waste (MSW) pyrolysis, previous research mainly concentrated on the generation and analysis of bio-oil and gas rather than biochar. Biochar is typically believed to be a by-product of municipal waste treatment (MWP) of biomass. Very few studies have focused on the formation of hybrid biochar using MWP, and even fewer studies have focused on the yield and quality of hybrid biochar when exposed to MW irradiation. The current research reviews the characteristics of microwave heating (MWH), MW co-pyrolysis of agricultural and plastics wastes to create hybrid biochar, hybrid biochar characteristics, including product distribution and hybrid biochar yield, and hybrid biochar manufacturing (Hamzah *et al*., 2023b).

Adsorbents with distinctive nanostructures made of char from biomass and plastic waste have been employed to remove contaminants. Electrostatic attraction, pore filling, hydrogen connection, and π-π connections are standard mechanisms in the adsorption of pollutants by waste char. **Figure 1** shows that these interactions significantly affect how pollutants are absorbed by waste char. Hence, much work has been done to improve these properties by changing the composition and porosity.

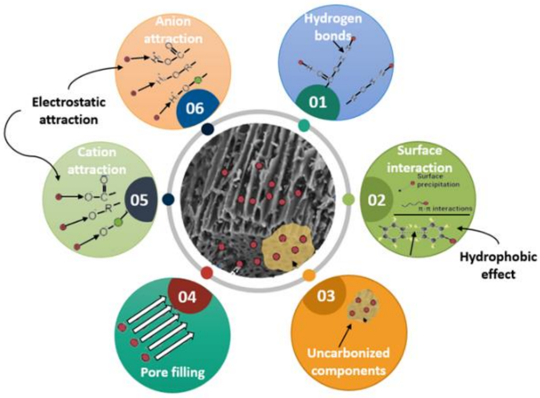

Figure 1. A schematic representation of char is affected by hydrogen bonding, π-π interactions, and pore packing.

This work aims to understand the parameters of the process that will ensure the production of high-quality hybrid biochar, which can be utilized for various purposes, including the amendment of soil, the treatment of water, the sequestration of carbon, and the reduction of emissions. The hybrid biochar economy, the techno-economic assessment, and the challenges faced for future growth are also discussed. Also, the novelty of this work lies in the comprehensive investigation and optimization of process parameters for the production of high-quality hybrid biochar. This study goes beyond conventional biochar production by focusing on the multiple applications of hybrid biochar. By addressing the economics of hybrid biochar, conducting a techno-economic evaluation, and identifying key challenges for future growth, this work provides a unique, multidisciplinary perspective that integrates ustainability with economic feasibility, paving the way for scalable industrial applications.

2. METHODS

It explored citation trends, co-authorship networks, and keyword frequencies to identify significant contributors and topics in the field of hybrid biochar, agricultural waste biomass (AWB), plastic waste (PW), and microwave-assisted pyrolysis (MAP). Our research was based on papers collected from academic databases like Scopus, Web of Science, and Google Scholar. It was used for "microwave-assisted pyrolysis," "hybrid biochar," "agricultural waste biomass," "plastic waste," and "environmental applications of biochar" among other detailed terms. After sourcing papers from databases and Google Scholar, it was conducted critical reviews focusing on hybrid biochar. Later, it was synthesized the findings into tables and charts to demonstrate hybrid biochar, including proximate and ultimate analyses of different agricultural samples, proximate and ultimate analyses of different plastic samples, Utilizing machine learning techniques to predict biochar production, Control settings for the microwave-assisted pyrolysis procedure, Thermochemical properties of agricultural and plastic by-products co-pyrolyzed with microwaves, Strategies for the evaluation of hybrid biochar, Hybrid biochar's potential uses include Views for the future and suggestions.

3. RESULTS AND DISCUSSION

3.1. Agricultural Wastes

Agriculture is a significant economic backbone in the countries of Pakistan, Nigeria, India, Indonesia, Malaysia, China, Denmark, and Thailand. As a result of its contribution to around 25 percent of Pakistan's gross domestic product, agriculture is one of the most important economic sectors in the country. Agriculture in Nigeria was responsible for 21.60 percent of the country's gross domestic product in 2017. Similar to the situation in the United States, agriculture contributed 15.40% of India's gross domestic product, which is a significant amount considering the size of the country's economy. Agriculture significantly contributed to Indonesia's gross domestic product in 2017, accounting for 13.90% of the country's total GDP (Rex *et al*., 2023), which makes agriculture an essential industry for Indonesia's economy. Similarly, agriculture was responsible for 8.40% of the gross domestic product in Malaysia. In China, agriculture was responsible for 8.30% of the national GDP in 2017. Denmark is considered a developed country but strongly depends on agriculture, contributing 8.30% to the national GDP. In conclusion, agriculture significantly contributed to Thailand's gross domestic product (GDP), accounting for 8.20 percent of the country's total economic output. A significant amount of agricultural waste biomass (ABW) is produced after crop products are harvested. Up until the year 2025, it is anticipated that Asian nations will generate between four and five kg of ABW per capita each month (Cheng *et al*., 2019; Hasan *et al*., 2019; Wang *et al*., 2019). In addition, the enormous quantity of ABW takes up land and poses a possible environmental risk. It is also possible to generate environmental difficulties by disposing of waste on the land. The release of greenhouse gasses like methane and carbon dioxide during the natural biodegradation of ABW contributes to the acceleration of global warming (Ganesan *et al*., 2022). As a result of the fact that ABW is frequently loaded with soluble organics, the undesirable leaching that occurs during wet seasons has the potential to pollute and clog the irrigation systems. It is recommended that direct dumping be avoided when disposing of ABW. Instead, it is recommended that more effective alternatives be developed. In the pyrolysis process, the feedstock's content significantly determines the products' composition and yield. Pyrolyzing feedstock with high moisture content requires a considerable amount of time. **Table 1** is a list of the defining properties of the agricultural feedstocks. There was not much of a difference between their elemental analysis and their proximate analysis. The feedstocks had ash contents ranging from 0.24-25.2 weight percent, fixed carbon contents between 5.32-28.0 weight percent, and volatile matter contents between 53.5-91.5 weight percent. Carbon, oxygen, and carbon/hydrogen were the primary components of the feedstocks, and their weight percentages ranged from approximately 32.7 to 76.8, 7.41 to 56.2, and 5.08 to 9.90, respective (Hamzah *et al*., 2023c; Potnuri *et al*., 2023).

Table 1. Proximate and ultimate analysis of various Agricultural samples.

Agricultural Samples	**Proximate analysis, %**				**Ultimate analysis, %**						**Ref.**
	Moisture	**Volatile matter**	**Ash**	**FC**	**C**	**H**	**C/H**	**N**	**S**	**O**	
Rice bran wax	1.45	91.50	1.74	5.32	76.80	15.10	5.08	0.02	0.68	7.41	(Akancha *et al.*, 2019)
Wood	9.31	75.00	0.24	15.50	45.70	7.57	6.03	1.89	1.01	56.20	(Ansah *et al.*, 2016)
Hazelnut	9.20	70.00	1.30	19.50	51.50	5.20	9.90	0.20	–	43.20	(Aydinli & Caglar, 2012)
Pine cone	9.60	77.80	0.90	–	42.60	5.56	7.66	0.76	0.05	51.00	(Brebu *et al.*, 2010)
Enteromorphaclathrate	12.90	53.50	25.20	8.40	32.70	5.38	6.07	4.85	2.01	51.90	(Cao *et al.*, 2019)
Corn stalks	3.41	80.80	5.87	12.00	43.30	6.12	7.07	2.12	–	48.40	(Fan *et al.*, 2020)
Wheat straw	7.53	70.60	6.06	15.80	43.70	6.11	7.15	0.52	0.10	49.60	(Jerzak *et al.*, 2021)
Pine bark	10.10	61.10	0.89	28.00	48.50	5.90	8.22	0.17	0.03	45.50	(Jerzak *et al.*, 2021)
Pinewood	–	77.00	5.00	18.00	47.90	5.50	7.44	0.60	0.10	40.90	(Lu *et al.*, 2018)

Table 1 (continue). Proximate and ultimate analysis of various Agricultural samples.

Agricultural Samples	Proximate analysis, %				Ultimate analysis, %						Ref.
	Moisture	Volatile matter	Ash	FC	C	H	C/H	N	S	O	
Alder wood	3.13	81.50	1.58	–	49.50	6.43	7.69	0.07	0.06	43.00	(Sajdak *et al.*, 2015)
Wheat straw	–	69.20	13.10	17.70	41.10	5.50	7.47	0.10	0.10	43.40	(Cao *et al.*, 2019)
Rice husk	7.04	61.70	16.00	15.30	46.80	6.66	7.02	0.66	–	45.90	(Wantaneeyakul *et al.*, 2021)
Oil palm shell	11.30	65.70	3.10	19.70	45.60	5.40	8.44	0.30	0	36.50	(Potnuri *et al.*, 2023)
Bagasse	0.00	74.50	6.00	19.50	36.30	5.80	6.25	0.30	0	51.50	(Potnuri *et al.*, 2023)

3.2. Plastic Wastes

For example, plastics, tyres, food, animal dung, woody biomass, and their combinations are all examples of solid wastes that are present in significant quantities over the globe. Plastic is one of these solid wastes that is receiving considerable attention because it is produced in large quantities and significantly impacts the environment (Chang, 2023). Plastics are frequently used for packing because they are less expensive, lighter, more accessible to process, and have superior performance. PVC, polystyrene (PS), polyvinyl chloride (PVC), polyethene (PET), high-density polyethene (HDPE), and polypropylene (PP) are the most common types of waste plastics. More than sixty percent of the solid plastic trash generated by municipalities is made up of polyolefins, primarily low-density polyethylene (LDPE), linear low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP). The average amount of moisture in waste plastic is 48 percent. The volatile content may be significant for thermochemical processing. That is because volatile matter has the potential to generate tar, which can be harmful to reactors. The complexity of polymer recycling is highlighted by the fact that plastic wastes come in various compositions, as seen in **Table 2**. Analyses and evaluations of various plastic samples, both proximate and ultimate. Although a low moisture content (≤0.6%) indicates a rapid drying process for plastic waste, a high ash content may negatively impact pyrolysis performance. On the other hand, a higher fixed carbon content of PET (11.4%) may typically result in a higher hybrid biochar yield during MWP processes. Furthermore, plastic's high mechanical strength and chemical resistance can make it challenging to upcycle waste. The feedstocks' volatile matter, fixed Carbon, and ash contents were approximately 78.6-100, 0-11.4, and 0-6.20 wt%, respectively. The feedstocks were primarily composed of Carbon, oxygen, and C/H, which were approximately 38.2-88.7, 0-30.5 and 5.83-13.80 wt%, respectively. Since the C/H molar ratio in feedstock significantly impacts the pyrolysis yields of products, the diverse elemental composition of various plastic wastes offers a problem for converting polymers into high-value-added products (Avinash *et al.*, 2016). For instance, raising the molar ratio of Carbon to hydrogen could increase the output of hybrid biochar while lowering the tar yield. Either by including biomass or preserving the waste plastic, this problem might be solved by bringing the elemental composition of the waste plastic into equilibrium. In the case of polyethylene (PE), for instance, secondary carbons are resistant to oxidation when subjected to heat or UV radiation (Fan *et al*., 2020). Plastic, on the other hand, may be manufactured to display radically varied qualities, and it can be used for a wide variety of applications, ranging from plastic sandwich bags, bottles, and garbage cans to hip implants; this is similar to the case with many other commodity polymers. It is essential to have a more in-depth understanding of the connections that exist between the chemical structure and content of a polymer and its degradability to build recycling procedures that are specifically personalized. In general, the carbon-to-hydrogen ratio of waste falls somewhere between 5.83 to 13.80, and a high C/H ratio (PET) could lead to a high hybrid biochar production during the pyrolysis process. In the process of manufacturing hydrocarbons with an easy removal of oxygen, it may be advantageous to have a low oxygen content (PE). The presence of sulfur serves as evidence that hydrogen sulfide (H_2S) may be produced during thermochemical reactions. The co-pyrolysis of plastics and biomass is extremely advantageous to the environment since it reduces the amount of waste consisting of plastic while simultaneously transforming it into energy that can be reused several times (Hamzah *et al*., 2024).

Table 2. Proximate and ultimate analysis of various plastic samples.

Plastics	**Proximate analysis, %**				**Ultimate analysis, %**						**Ref.**
	Moisture	**Volatile matter**	**Ash**	**FC**	**C**	**H**	**C/H**	**N**	**S**	**O**	
PP	0.67	98.60	0.24	0.45	83.70	14.30	5.85	0.01	0.84	1.14	(Akancha *et al*., 2019)
PET	–	88.60	–	11.40	64.20	4.65	13.80	0.05	0.55	30.50	(Ansah *et al*., 2016)
PVC	0.17	96.40	0	3.42	38.20	4.94	7.73	-	-	-	(Cao *et al*., 2019)
PP	–	99.60	–	0.05	85.70	14.30	5.99	0	0	–	(Chen *et al*., 2017)
PP	–	78.60	0.04	0.04	83.60	14.00	5.97	0.08	0.01	2.39	(Chen *et al*., 2020)
PE	0.05	99.90	0.01	0	85.40	13.49	6.33	0.06	–	1.02	(Fan *et al*., 2020)
LDPE	0	99.90	0.10	0	85.90	14.00	6.13	-	-	-	(Gunasee *et al*., 2017)
PE	–	100	0	0	85.70	14.30	5.99	0	0	0	(Lu *et al*., 2018)
PU	–	83.50	6.20	10.60	62.30	6.30	9.88	6.40	0.60	24.00	(Cao *et al*., 2019)
HDPE	0.22	97.10	2.64	0	88.70	15.20	5.83	0.21	–	0.88	(Wantaneeyakul *et al*., 2021)

On the other hand, it also makes it possible to renew and replace fossil fuels and chemicals. The primary focus of the co-pyrolysis process is the synergistic impact produced by the reaction between the materials that interact with one another in the mixed feedstock.

3.4. Machine learning technique for Predicting biochar production performance

Machine learning has proven to be an efficient method for simulating pyrolysis processes. It has the potential to predict the optimal pyrolysis settings for achieving certain product distribution goals (Thiruvengadam *et al.*, 2021). For example, according to Shahbeik *et al.* (2022), bio-oil production was found to be best when pyrolysis was carried out at temperatures between 500 and 600 ◦C, whereas syngas generation was shown to be more favorable at temperatures between 700 and 800 ◦C. When it comes to predicting the distribution of pyrolysis products, different ML learning algorithms may demonstrate different capabilities. Alabdrabalnabi *et al.* (2022) forecasted the distribution of pyrolysis products using neural networks and traditional machine learning algorithms. A dense neural network performed better at predicting bio-oil yield (RMSE2.6, R2=0.96), while XGBoost performed better at predicting biochar yield (RMSE1.77, R2= 0.96) (Alabdrabalnabi *et al.*, 2022). Yang *et al.* (2022) modeled the distribution and characteristics of products from microwave-assisted pyrolysis using a combination of support vector regression, random forest regression, and gradient boost regression. With an R2 greater than 0.822, the gradient boost regressor model fared better than the others. Various recommendations included picking suitable prediction models with caution and using various machine-learning techniques for training and testing. Various biomass properties and pyrolysis parameters substantially impacted the distribution of pyrolysis products. Altikat and Alma (2023) used support vector machine (SVM) and deep artificial neural network (DLNN) techniques to forecast the production of biochar, bio-oil, and syngas. Top performance was demonstrated by DLNN, with an R2 value exceeding 0.96. According to the sensitivity study, the biochar/bio-oil production was most affected by reaction time, but the syngas yield was substantially affected by carbonization temperature. To forecast the output of pyrolysis, (Dong *et al.*, 2023) employed regression (RF), gradient boosting decision tree (GBDT), extreme gradient boosting (XGBoost), and adaptive boosting (AdaBoost) methods. While high-carbon biomass increases bio-oil production, it reduces biochar yield. To enhance the syngas yield and decrease the charcoal yield, raise the pyrolysis temperature. The yield of biochar was predicted in several experiments using machine learning methods. The usual research is listed in **Table 3**. The primary factors influencing biochar yield were pyrolysis conditions, particularly pyrolysis temperature, and biomass feedstock characteristics, including ash concentration. Zhu *et al.* (2019) used the RF model to predict biochar yield and carbon content (C-biochar). Pyrolysis conditions, not feedstock qualities, were the most critical component, contributing 65% to biochar output and 53% to C-biochar, respectively. Leng *et al.* (2022) forecasted biochar yield, nitrogen content, and specific surface area using RF and gradient boosting regression (GBR). The prediction was most affected by pyrolysis conditions, which include reaction temperature and residence duration. The specific surface area and production yield of biochar were predicted by Hai *et al.* (2023) using a supervised machine learning technique that included K-nearest neighbours (KNN), RF, SVM, DT, and multiple linear regression (MLR). It was shown that pyrolysis temperature significantly impacted performance, and RF demonstrated the best performance. Potnuri *et al.* (2022a) A machine-learning model based on polynomial regression was used to forecast the yield of sawdust-derived biochar produced by microwave-assisted catalytic pyrolysis (R2 > 0.93). Increasing the pretreatment temperature and catalyst dosage enhanced the efficiency of microwave conversion. Narde and Remya (2022) used linear, interactive, and quadratic regression models to forecast the yield of biochar from microwave-assisted pyrolysis. It was found that reaction temperature, biomass ash content, and volatile matter were the most important variables, and quadratic regression models performed the best (R2 = 0.894). Li *et al.* (2022) an ANFIS and a multilayer perceptron neural network (MLP-NN) were used to forecast biochar and composition. The projected biochar yield was satisfied by the MLP-NN (R2 = 0.964), with the important factors being the biomass's pyrolysis temperature, ash concentration, and N content. One possible approach that shows promise for improving model prediction performance is a hybrid model. Ewees and Abd Elaziz (2020) suggested a hybrid model incorporating ANFIS and the grey wolf optimization method. The suggested hybrid model achieved better results than ANFIS and LS-SVM. Machine learning models linked with GA and PSO were used to forecast the yield of biochar (Ul Haq *et al.*, 2022). The ELT-PSO integrated model predicted biochar yield, with an R2 of 0.99 and an RMSE of 2.33. Less than 2% of the time, the actual values differed from the predictions.

Table 3. Machine learning application for modelling biochar yield.

Feedstocks	**Input parameters**	**ML models**	**Prediction performance**		**Ref.**
			R2 (train/test)	**RMSE (train/test)**	
Agricultural waste	carbon content (C), nitrogen content (N), volatile matter (VM), moisture content (M), cellulose content (Cel), hemicellulose content (Hem), pyrolysis temperature (T), pyrolysis time (t), heating rate (HR)	random forest (RF), multiple linear regression (MLR), decision tree (DT), K-nearest neighbours (KNN)	0.855/, 0.821/, 0.559/, 0.510/	3.119/, 4.758/, 7.245/, 7.543/	(Hai *et al.*, 2023)
Biomass	carbon content (C), hydrogen content (H), oxygen content (O), nitrogen content (N), volatile matter (VM), fixed carbon (FC), Ash, amount of feedstock (FD), microwave power (W), pyrolysis time (t), microwave absorber (Mab)	eXtreme gradient boosting (XGBoost), random forest (RF), support vector machine (SVM)	/0.89, /0.89, /0.69	/7.03, /7.03, /12.6	(Selvam & Balasubramanian, 2023)
agricultural waste, manure, food waste, algae, grass, sludge, and their mixtures, and others	carbon content (C), hydrogen content (H), nitrogen content (N), oxygen content (O), volatile matter (VM), fixed carbon (FC), Ash, pyrolysis temperature (T), pyrolysis time (t), heating rate (HR)	gradient boosting regression (GBR)	1.00/0.90	0.39/4.66	(leng *et al.*, 2022)
Agricultural products, forest plants, algae	carbon content (C), hydrogen content (H), nitrogen content (N), volatile matter (VM), fixed carbon (FC), Ash, moisture content (M), pyrolysis temperature (T), heating rate (HR), sweep flow rate (FR), particle size (PS)	random forest (RF)	/0.78	/4.09	(Dong *et al.*, 2023)
Lignocellulose biomass, waste plastics	carbon content (C), hydrogen content (H), nitrogen content (N), oxygen content (O), volatile matter (VM), carbon (FC), Ash, moisture content (M) (biomass); C, H, N, O, chlorine content (Cl) (plastic); T, t, HR, plastic percent in the sample (Wp)	eXtreme gradient boosting (XGBoost), dense neural network (DNN)	/0.86 /0.86,	/1.77 /3,26	Alabdrabalnabi *et al.* (2022)

3.5. Machine learning techniques for Predicting biochar properties

Biochar properties, including elemental composition (C, H, N, O), fixed carbon (FC), volatile matter (VM), and ash content (Ash), have been successfully predicted by machine learning techniques. Leng *et al*. (2022) utilized biomass characteristics and pyrolysis conditions to predict and optimize the yield, nitrogen content, and specific surface area of biochar based on random forest (RF) and gradient boosting regression (GBR) models. Results revealed that GBR performed better in most predictions with R2 over 0.97. (Li *et al*., 2022) used MLP-NN and ANFIS to forecast biochar properties, including elemental compositions (C, H, N, O), VM, and ash. Satisfied prediction performance could be achieved with R2 in the range of 0.785 to 0.940. Shahbeik *et al*. (2022) adopted RF to successfully predict the H/C, H/N, and O/C ratio of sludge-derived biochar with R2 over 0.9.

3.6. Microwave heating technology

Since the middle of the nineties, there has been a growth in the utilization of microwave technology to treat biomass thermally. Not only does this method cut down on the amount of energy consumed and the amount of time spent processing, but it also makes it possible to use novel chemistry, a rare internal heating phenomenon related to microwave energy. It is also capable of improving the quality of the production as a whole. One type of electromagnetic radiation is microwave irradiation, which has wavelengths ranging from 0.01 meters to 1 meter with a frequency range corresponding to 0.3 to 300 gigahertz respectively (Davis-Wheeler Chin *et al*., 2021). Because the electric field component interacts with charged particles in the material, most of the heating effects induced by an incident microwave electromagnetic field result from this interaction. Having said that, there is also the potential for interaction between the microwave magnetic field and the substance's magnetic dipoles (Kitchen *et al*., 2014). The mobility of charged particles in the substance is a factor that determines how the material interacts with the MW electric field. This interaction might result in either of two major heating processes. Dipolar polarization occurs when the bound dipoles of polar solvent molecules or reagents align themselves in the same direction as the incident microwave electric field. The molecule's rotational motion, which it generates as it attempts to realign itself to the variable MW electric field, causes the energy transfer that occurs due to this motion. The polarity of the molecules presents in the reaction mixture, in addition to their capability to align themselves with the field, determines the capacity of this mechanism to couple off with other molecules (Zhu & Chen, 2014). The value of Pd in a material exposed to an electric field with strength E is given by Equation [1].

$$P_d = \varepsilon_0(\varepsilon_r - 1)E \qquad (1)$$

Where ε_0 and ε_r represent the free space and relative material permittivity, respectively.

As shown in **Figure 2**, microwave heating involves the interaction of microwave radiation with the reaction mixture. This interaction causes the mixture to undergo instantaneous localized superheating, resulting in the combination's uniform heat distribution. The motion of charged particles in response to the electric field of microwaves is the primary cause of the heating effects generated by microwaves. This is the case for materials that have a higher charge carrier mobility. In this process, known as ionic conduction, charged particles oscillate back and forth under the influence of the microwave electric field that is incident on them, and they occasionally collide with molecules or atoms that are close to them. The agitation that occurs as a consequence of these collisions results in the production of heat, the amount of which is set by the temperature of the reaction. Energy transfer efficiency from ionic conduction increases as the temperature rises (Davis-Wheeler Chin *et al*., 2021).

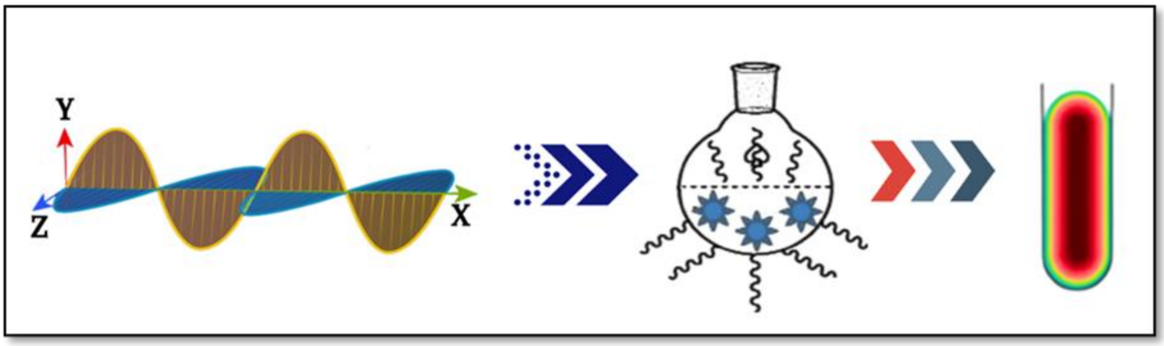

Figure 2. Microwave heating involves the interaction of microwave radiation with the reaction mixture.

Compared to the heat-generation pathways that originate from dipolar polarization (dipolar rotation), the capacity for heat generation represented by ionic conduction pathways is significantly higher. Because of this, synthesis tactics for MW heating are altered considerably. It is possible to express the capacity of a specific reaction species to convert MW energy into heat by calculating its loss tangent (tan δ), which is calculated by Equation [2]:

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2}$$

where the dielectric loss ε”, which is the complex permittivity, is used to quantify the efficiency with which the species transforms electromagnetic radiation into heat, and the dielectric constant ε′, which is the relative permittivity, is used to characterize the species' polarizability in an electric field. Respectively.

3.7. Effect of parameters on MWP

The microwave pyrolysis of AWB and PW sheds information on the impact of the parameters of the process on the distribution of the products. These parameters, essential for comprehending microwave pyrolysis, are explained concisely in this section (**Figure 3**).

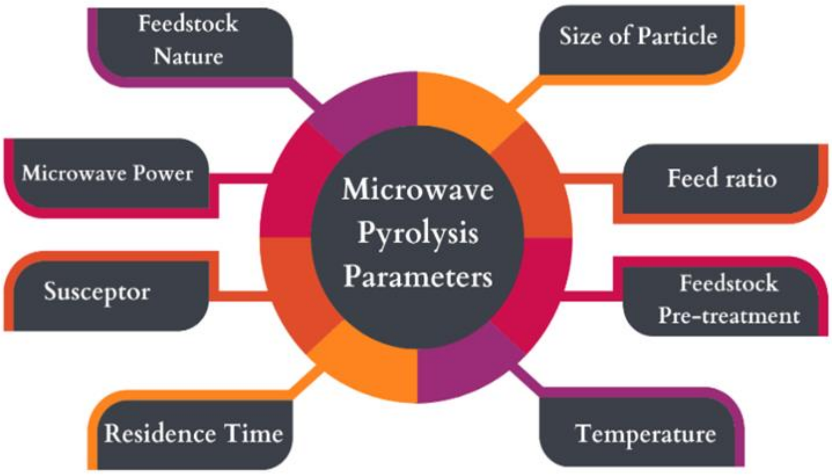

Figure 3. Operating parameters for the microwave-assisted pyrolysis process.

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3.7.1. Temperature

Regarding the MAP process, temperature is the most crucial component since it has the most significant influence on the kinetics rate, which in turn affects the yield and composition of the output product. A laboratory-scale MWP experiment was carried out with pine, spruce chips, mixed larch, and softwood pellets to produce hybrid biochar at three distinct temperatures ranging from 350 to 550 degrees Celsius. The temperatures were chosen to achieve the desired results. The stability of the hybrid biochar improves as the temperature of the pyrolysis process rises, even though the yield of stable hybrid biochar appears to decrease in a manner that is essentially linear with temperature (Potnuri *et al*., 2023).

3.7.2. Heating rate

"Heating rate" refers to the rate at which the temperature increases. According to previous research (Foong *et al*., 2020), a low heating rate has the potential to improve the structure and properties of hybrid biochar and significantly enhance its yield. However, when high heating rates are applied, a blockage of pore apertures may occur due to the accumulation of volatiles.

3.7.3. Microwave power

It is possible to enhance the heating rate by raising the microwave power, which will increase the MWP temperature and speed up the entire pyrolysis process. In general, the material's qualities define the highest heating rate required. As a result, the consequences of raising the power of microwaves are only relevant to a certain amount (Kong *et al*., 2019). The power consumption of a microwave oven directly correlates with the pyrolysis and food yield (Zhao *et al*., 2018). The amount of pyro-oil, char, and gas that is produced has a direct bearing on the amount of power that is delivered to the feedstock. Regarding power, biomass begins to pyrolyze at approximately 300 W, polymers require approximately 300 to 500 W, and coal pyrolyzes at approximately 500 to 700 W. It appears that there is a connection between the characteristics of the feedstock and the amount of electricity necessary for MWP. In addition, there is a connection between the power delivered by the microwave and the temperature at which the pyrolysis occurs.

3.7.4. Residence time

The duration of time that the solid biomass feedstock consumes is the primary factor that determines the residence time in MAP. This time frame typically falls between a few minutes and hours. Longer residence durations negatively impact the yield of liquid bio-oil products created through microwave processing. This is because more extended residence periods allow non-condensable gases to develop due to secondary cracking, which raises energy consumption. In most cases, a relatively short processing time is preferable for MAP because it is essential to avoid the secondary cracking of volatile agents (Siddique *et al*., 2022).

3.7.5. Feedstock composition and blending ratios

One of the most critical factors determining the composition and yield of pyrolytic products is the content of the feedstock. Using feedstocks with varying compositions to produce a product with increased yield and composition is the principal objective of co-pyrolysis processing. Because co-pyrolysis involves the utilization of two distinct types of feedstock components, namely plastic and biomass, the ratios of these two types of feedstock components also have an impact on the composition and yield of pyrolytic products (Siddique *et al*., 2022). The char generation from woody biomass depends on the biomass's source. It has been found that feedstock from coniferous trees produces a higher yield of hybrid biochar than feedstock from deciduous trees. In general, higher amounts of cellulose and hemicellulose benefit the formation of liquids and gasses. Still, higher proportions of lignin are more suitable for synthesizing hybrid biochar (Hamzah *et al*., 2023c). There was a direct correlation between the amount of lignin in feedstock and the amount of hybrid biochar produced. The char produced from woody biomass with a higher lignin content is better suited for soil application because it reduces wind-based loss and soil hydrophobicity. The latter factor can potentially cause increased retention of herbicides and other industrial products in soils, which in turn lowers the soil quality (Al-Rumaihi *et al*., 2022).

3.7.6. Particle size

Smaller particles have a greater heat flow during the pyrolysis process, which causes the heating rate to increase while the yield of hybrid biochar decreases; this is because smaller particles have a greater heat flux. Larger particle sizes, on the other hand, should be preferred to produce a greater quantity of hybrid biochar. As a result, the utilization of MH can potentially conserve some of the energy required for grinding.

3.7.7. Catalyst and absorber addition

Pyrolysis from feedstock with a high moisture content takes considerable time. Utilizing microwave absorbers accelerates the process of the microwave power plant (MWP). These materials boost the process's efficiency and minimize the time it takes for the reaction to occur (Dai *et al*., 2017). The pyro-char produced from the feedstock following MWP or other thermochemical reactions is typically connected with absorbers. There is an expectation that absorbers will have a high capacity for storing and converting microwaves. Some char produced from the feed during the succeeding batch can be recycled and reused. However, the char and the feedstock must be completely mixed to ensure that the radiation is distributed evenly and that the heating process is carried out consistently. Char can also be utilized economically. It was discovered that plastics have low dielectric constants; hence, the incorporation of a MW absorber ultimately proved to be highly helpful. The utilization of catalysts allows for the elimination of oxygenated compounds and the acceleration of the cracking of high molecular weight compounds into products with the necessary length of carbon chains (Talib Hamzah *et al*., 2022). In general, excellent catalysts should have a high selectivity to specific products, a high catalytic efficiency, a long service life, the ability to be recycled easily, and a reasonable price. The use of acid-base catalysts is thought to increase the generation of hybrid biochar. Zeolite catalysts based on ZSM-5, zeolite-like catalysts, metal oxides, and natural minerals are the types of catalysts utilized in MWP regularly (Potnuri *et al*., 2023).

3.7.8. Carrier gas flow rate

Because of its inert qualities and low cost, nitrogen gas (N_2) is the carrier gas utilized most in microwave power plants (MWP). It is the job of the carrier gas to help in the collection of gases and to get rid of any residual gases present before the pyrolysis process. On the other hand, results from earlier studies indicated that gas flow rates might impact MWP. The heat loss during pyrolysis can be exacerbated by a high flow rate, which slows the reaction speed and restricts the creation of pores in hybrid biochar.

3.7.9. Energy Consumption of MAP of AWB and PWP

Two of the most notable benefits of MAP are its low energy usage and its excellent energy efficiency. According to the findings of (Suriapparao *et al.*, 2018), who carried out the microwave pyrolysis process on rice husk and plastic, the microwave co-pyrolysis process can achieve a maximum efficiency of 68%.

3.7.10. Effect of pressure

Additionally, the pressure present within the reactor has a substantial impact on the amount of MWP products that are produced. It is possible for the organic matter that is present in the vapour to decompose and generate secondary carbon as a result of the higher pressure, which causes the vapour residence time to increase. The secondary carbon on the surface of the hybrid biochar also enhances the hybrid biochar's synthesis when the depolymerization process is carried out. As a result of carbon deposition on its surface at increasing pressure, hybrid biochar becomes a superior solid fuel. Because the increased pressure causes the energy density of the biochar to increase. Therefore, high pressure increases the amount of Carbon included in hybrid biochar and increases the production of hybrid biochar (Anand *et al*., 2022). Although the approach is appropriate, it still needs to be subjected to extensive research to establish appropriate control to achieve the highest possible yield and specified composition of goods. It is also possible that inappropriate control of process parameters could result in non-uniform heating, which could produce hotspots, reducing the overall treatment efficiency and decreasing the effective energy utilization offered by microwave systems. Even though the initial capital cost of a microwave system is considerable, this can be compensated for by the economic benefits that can be obtained in operation. These benefits include reducing process time, producing by-products that can be sold, and environmental compatibility.

3.8. Effects of feedstock quantities on Microwave-assisted catalytic co-pyrolysis of AWB & PW

Most of the time, polymers with a higher hydrogen-to-carbon (H/C) ratio will be introduced into the co-pyrolysis system of biomass with a lower H/C ratio of this particular activity, the process of converting AWB into hydrocarbons is rendered more efficient. For instance, research conducted on the co-pyrolysis of lignin (with a hydrogen-to-carbon ratio ranging from 0 to 0.3) and plastics highlights the fact that interactions between the two substances can lower the apparent energy needed for activation and influence the production of products (Zou *et al*., 2022), **Table 4** lists the general features of the MW-assisted catalytic co-pyrolysis of wastes derived from agriculture and plastics. The feedstocks were primarily composed of carbon and oxygen elements, approximately 35–45.6 and 22.3 –53.2 wt%, respectively. The maximum hybrid char yield (29%) was obtained from the microwave catalytic co-pyrolysis of rice husk and PET with CaO catalyst at temperature 600^{0}C, blending ratio of 3:1, 450 W power. The observed higher concentration of carbon in the hybrid char includes the inclusion of PET in the biomass feedstock, which acts as an additional carbon source for the synthesis of biochar. Treating the feedstocks separately resulted in a lower yield of hybrid biochar than processing them together.

Table 4. Characteristics of the microwave-assisted catalytic co-pyrolysis of agricultural and plastic wastes.

Biomass waste	**Elemental analysis (%)**					**Plastic waste**	**Elemental analysis (%)**					**Catalyst**	**Temp**	**Time**	**Blend**	**Char yield**	**H.R**	**Power**	**Ref.**
Feed	**C**	**H**	**N**	**S**	**O**	**Co feed**	**C**	**H**	**N**	**S**	**O**	**Type**	**°C**	**min**	**Ratio**	**%**	**°C/ min**	**W**	
Empty fruit bunch	42.7	6.2	0.6	0.1	50.4	WT	80.3	7.7	0.4	0.9	10.8	Activated carbon	505	60	03:01	28	41.8	1000	(Idris *et al.*, 2021)
Corn stover	44.9	6	1.5	0.1	44	PP	65.7	11.5	1	0	17.7	CaO and HZSM-5	550	15	04:01	25.9	40	750	(Liu *et al.*, 2016)
Empty fruit bunch	42.7	6.2	0.6	0.1	50.4	WT	80.3	7.7	0.4	0.9	10.8	Activated carbon	600	30	01:01	26.8	40.7	800	(Idris *et al.*, 2021)
Palm kernel shell	47.9	6.6	0.1	1.1	44	HPW	86.2	13.3	0	0	0.4	Clay	700	20	01:01	20.5	43	700	(Wan Mahari *et al.*, 2018)
Rice straw	37.1	5.2	0.5	0.1	43.5	PP	90.8	7.1	0.1	0	2	HZSM-5	500	30	01:01	18	24.5	3200	(Suriapparao *et al.*, 2022)
Rice straw	37.1	5.2	0.5	0.1	43.5	PS	89.5	8.5	0	0	2	HZSM-5	500	30	01:01	19	31.2	3200	(Suriapparao *et al.*, 2022)
Chilli straw	42.4	5.1	0.9	0.1	46.6	PP	85.8	14.1	0	0	0	HZSM-5	600	10	01:01	20	40	567	(Zhang *et al.*, 2021)
Wheat straw	42.5	5.5	1.1	0.1	50.8	EPS	91.4	8.6	0	0	0	Graphite	450	30	01:01	24.9	65.6	600	(Suriapparao, Attada, *et al.*, 2020a)
Wheat straw	42.5	5.5	1.1	0.1	50.8	PP	92.5	7.5	0	0	0	Graphite	450	30	01:01	25.6	63.4	600	(Suriapparao, Attada, *et al.*, 2020a)
Rice husk	41.1	5	0.4	0.3	53.2	EPS	91.4	8.6	0	0	0	Graphite	450	30	01:01	21.7	66.7	600	(Suriapparao, Vinu, *et al.*, 2020b)

Table 4 (continue). Characteristics of the microwave-assisted catalytic co-pyrolysis of agricultural and plastic wastes.

Biomass waste	**Elemental analysis (%)**					**Plastic waste**	**Elemental analysis (%)**					**Catalyst**	**Temp**	**Time**	**Blend**	**Char yield**	**H.R**	**Power**	**Ref.**
Feed	**C**	**H**	**N**	**S**	**O**	**Co feed**	**C**	**H**	**N**	**S**	**O**	**Type**	**°C**	**min**	**Ratio**	**%**	**°C/ min**	**W**	
Rice husk	41.1	5	0.4	0.3	53.2	PP	92.5	7.5	0	0	0	Graphite	450	30	01:01	21.5	64.5	600	(Suriapparao, Vinu, *et al.*, 2020b)
Rice husk	41.1	5.2	0.4	0.3	53.2	PET	62.4	4.3	0	0	3.4	CaO	600	20	03:01	29	163	450	(Suriapparao *et al.*, 2022)
Cocoa pod husk	40.0	5.5	1.4	0.2	53.0	WT	71.8	6.7	0.3	1.8	10.6	Activated carbon	500–600	30	1:1	24	10	440	(Vaštyl *et al.*, 2022)
Straw stalk	40.0	5.3	1.0	11.2	42.2	HDPE	74.7	8.1	0.0	0.0	3.2	HZSM-5	550	20	1:1	21.4	52	600	(Zhou *et al.*, 2017)
Groundnut shell	41.0	6.3	1.0	0.2	41.2	PS	89.5	8.5	0.0	0.0	2.0	Ash	600	10	1:1	21.6	57.1	450	(Suriapparao *et al.*, 2018)
Bagasse	36.3	5.8	0.3	0.0	51.5	PS	89.5	8.5	0.0	0.0	2.0	Ash	600	10	1:1	26.3	51.3	450	(Suriapparao *et al.*, 2018)
Rice husk	35.0	4.8	1.2	0.2	22.3	PS	89.5	8.5	0.0	0.0	2.0	Ash	600	11	1:1	24.3	57.8	450	(Suriapparao *et al.*, 2018)
Groundnut shell	41.0	6.3	1.0	0.2	41.2	PP	90.8	7.1	0.0	0.0	2.0	Ash	600	11	1:1	31.5	46.3	450	(Suriapparao *et al.*, 2018)
Bagasse	36.3	5.8	0.3	0.0	51.5	PP	90.8	7.1	0.0	0.0	2.0	Ash	600	11	1:1	26.7	49.9	450	(Suriapparao *et al.*, 2018)
Rice husk	35.0	4.8	1.2	0.2	22.3	PP	90.8	7.1	0.0	0.0	2.0	Ash	600	12	1:1	21.1	51.7	450	(Suriapparao *et al.*, 2018)

3.9. Hybrid biochar characterization and its methods

Different biochar characterization methods exist, as shown in **Figure 4**. Biochar is an excellent marker of its nature. The following characterization methods are used to assess the characteristics of biochar.

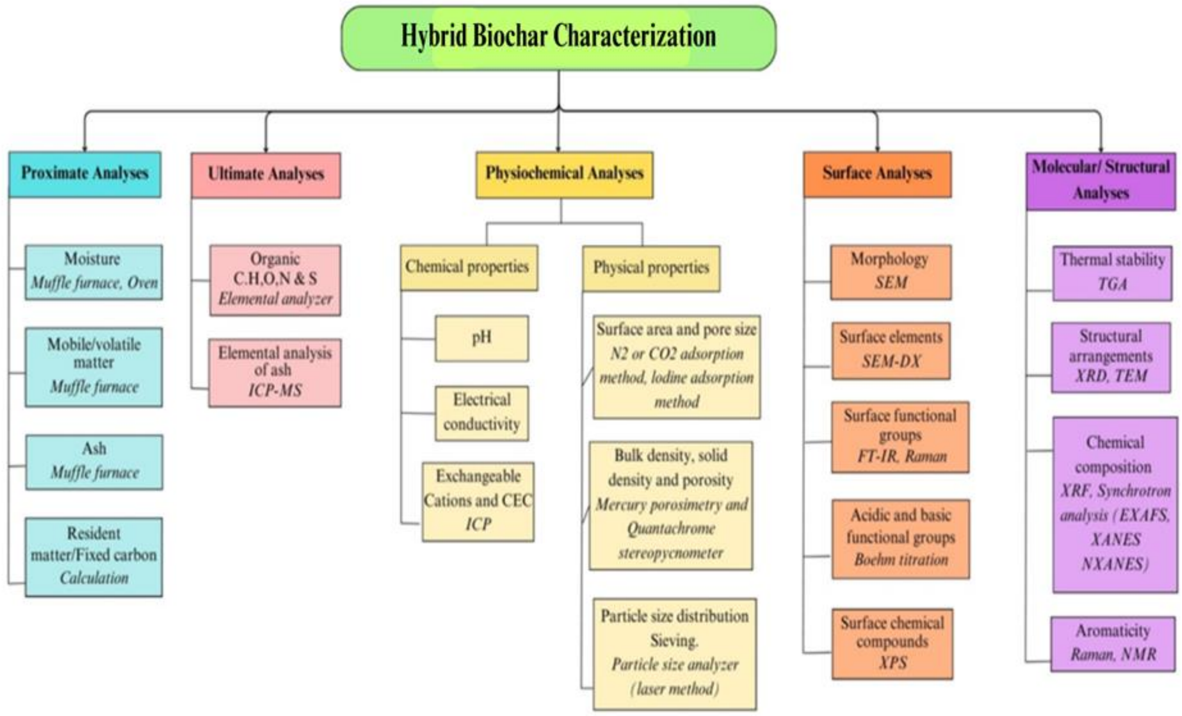

Figure 4. Hybrid biochar characterization methods.

3.9.1. Proximate Analysis and Ultimate Analysis

Proximate analysis is a method of determining the entire biomass components of solid Fuel in terms of moisture content (ASTM D 1762-84), ash content, volatile solids, and fixed Carbon (ASTM D1762-84) (Phadtare & Kalbande, 2022). It includes the analysis of the organic Carbon, oxygen, nitrogen, and sulfur. The ultimate analysis of the instrument, an elemental analyzer, also consists of the analysis of the ash contents of the sample (Zou *et al*., 2022).

3.9.2. Physiochemical Analysis

The physicochemical analysis is divided into two subcategories for the determination of physical properties and chemical properties; chemical properties include the determination of pH, Electrical conductivity, and cations exchange capacity; this physical property can be determined on calibrated electric instruments instantly (ASTM D 4972–01). Regarding physical properties, surface area and porosity are determined by CO_2 and N_2 or Iodine absorption methods. Physical properties also include the determination of bulk density (ASTM D 7263-09) and particle size distribution (ASTM D 422-63), which is done by an instrument called a particle size analyzer (Liu *et al*., 2017; Tomczyk *et al*., 2020). Researched on applying hybrid biochar in agriculture has demonstrated that the size of the hybrid biochar particles affects the amount of water stored in the soil. This is accomplished by altering the pore space between the particles (interpore) and adding pores that are a part of the hybrid biochar (intrapore). A method for applying hybrid biochar as an addition to improve soil quality can be derived from determining its physicochemical parameters.

3.9.3. Surface Analysis

The surface analysis of hybrid biochar includes the determination of the following properties:

3.9.3.1. Morphology by SEM

Surface morphology is analyzed using scanning electron microscopy; this technique is used to visualize and characterize surfaces of various materials, including hybrid biochar.

3.9.3.2. Surface elements by SEM-EDX

SEM-EDX does the surface elements analysis. It is the analytical instrument called energy-dispersive X-ray spectroscopy (EDX). It is used analytically or chemically to characterize materials; these systems are typically used with an electron microscope, such as a transmission electron microscope (TEM) or a scanning electron microscope (SEM). The EDX method is based on the emission of a specimen's unique X-rays. The peaks connected to the elemental makeup of the studied sample are shown in an EDX spectrum.

3.9.3.3. Surface functional groups by FT-IR and Raman

The chemical composition of hybrid biochar can be determined using Fourier Transform Infrared Spectroscopy (FT-IR), which involves recording the infrared spectra of hybrid biochar samples (Ben salem *et al*., 2021). For surface binding of polar pollutants, surface functional groups such as hydroxyl, aldehyde, and ketone groups are exceptionally significant. Fourier transform infrared spectroscopy makes it possible to determine the appearance of specific functional groups (Janu *et al*., 2021). Raman spectroscopy is a type of inelastic scattering phenomenon that investigates molecules' vibrations to determine a substance's molecular fingerprint.

3.9.3.4. Acidic and basic functional groups

According to Schnherr *et al*. (2018), Boehm Titration is a method for determining acidic and basic functional groups. This approach is being investigated for its ability to measure surface groups that include oxygen in order to acquire trustworthy results in a shorter amount of time.

3.9.3.5. Surface chemical compounds (XPS)

The elemental composition, chemical states, and electronic states of the elements inside the material are measured using X-ray photoelectron spectroscopy (XPS), a surface-sensitive quantitative spectroscopic approach.

3.9.3.6. Molecular/Structural Analysis

According to Phadtare and Kalbande (2022), the study of biomass thermal analysis is included in the molecular or structural analysis. The thermogravimetric analysis (TGA) is an efficient method for measuring the thermal stability of materials. While carrying out this method, the temperature of a specimen is raised, and the changes in its weight are measured. The moisture and volatile content of a sample can be determined using TGA. X-ray diffraction (XRD), which provides substantial information on the crystallographic structure of materials, chemical composition, and physical qualities, is one of the methods utilized in structural analysis (Tomczyk *et al.*, 2020). In the previous section, it was said that the selection of a particular kind of feedstock is mainly dictated by the location of the feedstock concerning the location where the hybrid biochar is likely to be generated. The reason for this is that the location of the feedstock reduces the amount of money spent on transportation while simultaneously lowering the carbon footprint that the hybrid biochar technology leaves behind. The pyrolysis temperature affects the quality of hybrid biochar. Creating hybrid biochars with more extensive carbon contents at higher temperatures is possible. However, the volatiles and molar ratios of oxygen to Carbon, hydrogen to Carbon, and nitrogen to carbon decrease as the pyrolysis temperature increases. Most applications are best served by hybrid biochars that include a higher percentage of Carbon. Hybrid biochars formed at moderate pyrolysis temperatures are acceptable to limit the release of fertilizer nutrients. On the other hand, high temperatures would result in the production of material that is comparable to activated Carbon. The pH of hybrid biochars is another critical element that plays a role in determining the applications for which it is used. Hybrid biochars, which are more basic and have a higher pH, are typically favoured for correcting soil acidity. Regarding adsorption procedures, neutral pH hybrid biochars are the most preferred option for removing pollutants and toxins from industrial effluents. As a result of their vast surface areas, hybrid biochar formed at higher pyrolysis temperatures has a solid attraction for organic contaminants. Regarding energy sources, neutral pH hybrid biochars are utilized since acidic hybrid biochars are responsible for corrosion, while basic hybrid biochars are responsible for fouling issues. In light of this, the temperature at which the hybrid biochars are pyrolyzed should be chosen per their ultimate application.

3.10. Applications of hybrid biochar

3.10.1. Agricultural sustainability

Biochar is a black charcoal-like substance (Jamaludin *et al.*, 2019). It has been the subject of much discussion recently due to its remarkable benefits on soil and compost, which benefit more than just your garden. Biochar is one of the most essential elements for the earth's long-term sustainability. It may be incorporated into new organic systems for farming, construction, textiles, electronics and electrical, and various products (Ayaz *et al.*, 2021). Although the primary focus of these early applications has been on the exploitation of hybrid biochar as a soil supplement in agricultural contexts, it is feasible that alternative applications in environmental remediation engineering could make an equally significant contribution. A few uses of hybrid biochar are discussed in this article (**Figure 5**), which includes the following examples.

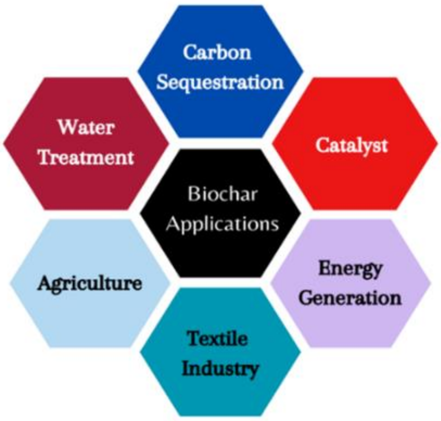

Figure 5. Applications of hybrid biochar.

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3.10.2. Water Treatment

Hybrid biochar has also been shown to be capable of removing a wide range of chemical and microbiological pollutants from aqueous systems (Liang *et al*., 2021). Hybrid biochar's integration into the water sanitation-nutrient-food nexus has numerous unique features. It provides water security and health advantages, providing a low-cost adsorbent for water treatment and can be used for drinking water purification and wastewater treatment (Gwenzi *et al*., 2017).

3.10.3. Soil Health

Hybrid biochar’s use in soils offers a lot of promise for enhancing soil fertility and encouraging plant development. Biochar can be used to manage a variety of soils because a variety of biomass sources can be employed as biochar feedstocks, and the feedstocks can be pyrolyzed at different temperatures. Biochar also has a large surface area, a well-developed pore structure, a high concentration of exchangeable cations and nutritional elements, and a high liming content (Seow *et al*., 2022).

3.10.4. Textile Industry Uses

Many countries with low and middle incomes, notably those in Asia, rely heavily on the textile industry as one of their most important businesses. It is common practice for dye factories in the textile industry to dump unused dye solutions into drains or the environment because there are no other viable alternatives that are economically viable. These colors have the potential to hurt both the health of humans and the health of the environment. It was demonstrated that the harmful dyes could be removed by the use of efficient filtration conditions, which was then followed by high dye adsorption onto pine-derived biochar (conducted in batch and column experiments), and recommendations were provided about the reuse of water (Mamane *et al*., 2020).

3.10.5. Renewable Fuel

The hybrid biochar produced by pyrolyzing corn cob and coconut shell biomass samples at 800 degrees Celsius demonstrated a wide range of physical and chemical features. A more extensive volatile matter, fixed Carbon, Carbon, and hydrogen content, as well as a higher heating value or gross calorific value, are all characteristics of hybrid biochar produced from these wastes. This conversion from pyrolysis to hybrid biochar can substitute fossil-derived fuels (such as coal, oil, and so on) with green renewable energy sources (Suman, 2020).

3.10.6. Catalyst

Fine-tuning hybrid biochar can be accomplished using a variety of physical and chemical processes. Regarding this particular matter, hybrid biochar has the potential to replace conventional catalysts, which are both expensive and non-renewable. The manufacture of biodiesel, the removal of tar from bio-oil and syngas, the reduction of nitrogen oxides, the production of syngas, and the hydrolysis of biomass are all examples of processes that can benefit from the utilization of hybrid biochar-derived catalysts (Lee *et al*., 2017). On the other hand, the surface functionality, surface area, porosity, and acidity of hybrid biochar catalysts are highly dependent on the origin of the biomass, the conditions under which hybrid biochar is formed, and the pre-and post-treatments that are applied.

3.10.7. Carbon sequestration

Reducing carbon dioxide emissions into the atmosphere is becoming an increasingly important topic in light of climate change. In the carbon cycle, which directly impacts climate change, soil plays an essential role. Carbon sequestration is a potentially helpful strategy for lowering carbon dioxide emissions from soil. Including aromatic structure in hybrid biochar makes it only slightly resistant to destruction by microbes; hence, hybrid biochar demonstrates a beneficial effect on the amount of Carbon sequestered in soil.

3.10.8. Electrochemical devices

Various electrochemical systems, such as lithium-ion and Li-S batteries, supercapacitors, and microbial fuel cells, use hybrid biochar and employ it as an electrode. On account of its large surface area and porosity, efficient electrical and thermal conductivity, high stability, low economical cost, and availability, hybrid biochar, specifically activated biochar, has been discovered to be more environmentally friendly than its equivalents that are based on Fuel (Goldfarb *et al*., 2017).

3.10.9. Energy production

The creation of tar during biomass gasification is an unpleasant occurrence since the condensation of tar leads to the contamination and clogging of processes that occur farther downstream, as well as a reduction in the efficiency with which energy is processed. Tar can be converted into hydrogen and carbon monoxide by a process known as catalytic transformation, which can convert tar. These two gases, hydrogen and carbon monoxide, are regarded as the significant constituents of syngas. The tar removal is affected by the char created from various types of biomasses, such as char made from rice straw and char made from corn straw. The effectiveness with which tar is removed is, therefore, influenced by the char types. With an increase in char particle size, tar removal's efficiency diminishes, as studied. Reasons for this include the surface area and the active site impacts. When it came to enhancing the hybrid biochar's overall qualities, it was discovered that feedstock that contained a high percentage of cellulose was beneficial.

3.11. Future perspectives and recommendations

3.11.1. Technical improvement

Additionally, the techno-economic life cycle assessment of the co-conversion operation ought to be promoted to reduce the time spent on the process and the overall cost indicated earlier. Furthermore, because the plastic is sticky, which diminishes the longevity of the co-generation reactors, there is a requirement to study methods that can lengthen the lifespans of the reactors. The reason for this is that the stickiness reduces the period that the reactors can function. Although the process's gaseous emissions are limited to building a circular economy (**Figure 6**), evaluating the process's effects on the environment is also vital because the process is causing the emissions to be contained (Adeniyi *et al*., 2023).

3.11.2. Economic viability

In addition to alleviating the waste management problem, the solid product produced as a result of the process is helpful in various applications. By achieving the goal of commercializing hybrid biochar, it will be possible to ensure the acquisition of monetary value as well as the application of the material in its ultimate form. The mantra "waste to wealth" has the potential to be accelerated by this possibility. The hybrid biochar created by this procedure can compete with natural fertilizers. This is principally the case if the biomass material contains a high concentration of the primary nutrient required for the soil's growth. Hybrid biochar, on the other hand, can improve a wide range of soil properties (including water retention and nutrients) when applied to the soil. Additionally, hybrid biochar can serve as a substitute for commercial activated Carbon in the purification of materials and in the treatment of water and wastewater (Owsianiak *et al*., 2021).

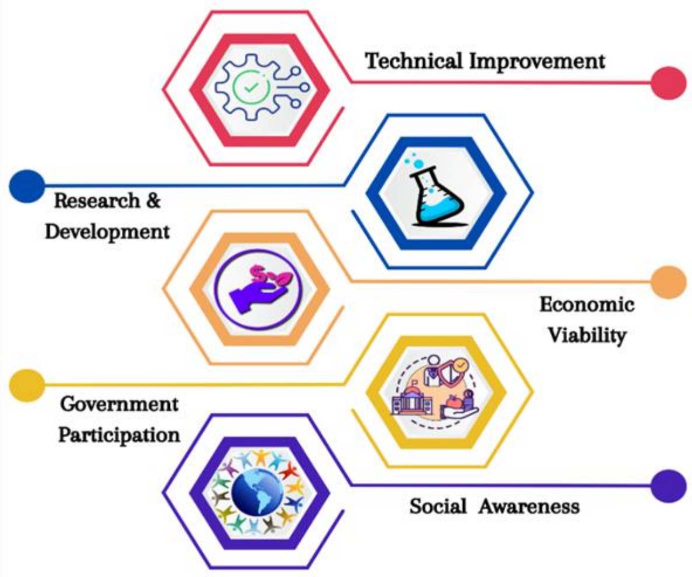

Figure 6. Future perspectives and recommendations.

3.11.3. Improved government participation

Any program must obtain significant backing from the government for it to be broadly accepted by the general population. Governmental authorities have to be aware of their responsibilities and formulate policies that will assist in accomplishing this task. They can expand the market for hybrid biochar by offering financial assistance to cover the initial expenses connected with establishing facilities that simultaneously convert biomass and plastic. In addition, they can develop strategic strategies to assist in activities that aid in creating a circular economy (Pourhashem *et al*., 2018).

3.11.4. Social awareness

The dissemination of information to the general public regarding the significance of proper disposal of solid waste, notably plastics and biomass, as well as the recycling of these substances via thermochemical co-conversion and the multiple applications of hybrid biochar, is of the utmost importance. The appropriate disposal of rubbish can be encouraged due to this understanding, which will reduce the expenses of waste gathering and separating for recycling companies and, consequently, the cost of recycling a product. In addition, this would promote the widespread acceptance of hybrid biochar, which would ultimately increase its commercial utility. The International Biochar Initiative (IBI), the European Biochar Certificate (EBC), the Biochar Quality Institute (BQI), the Australian Biochar Certification Scheme (ABCS), and the Japan Biochar Association (JBA) are some of the hybrid biochar certifying organizations that exist around the world. In addition to the organizations above, additional hybrid biochar certification options are also available. The production and utilization of biochar in a manner that is both responsible and environmentally friendly is dependent mainly on the efforts of these organizations. Organizations seek to develop guidelines governing biochar, provide certification services to guarantee these requirements are met, and attempt to carry out these standards. Besides educating stakeholders on the benefits and relevance of sustainable biochar production and application, they also seek to set standards for the standards themselves (Shi & Yin, 2021).

3.11.5. Research and development

Activities aiming to improve the production and consumption of hybrid biochar are being planned to promote its wider acceptability and assist in addressing environmental challenges such as soil deterioration and climate change. As a result of the significant contributions made by these groups, they mainly specify the variety of feedstock that can be employed for the production of hybrid biochar. It would be beneficial for these groups to accept trash made of plastic and biomass as feedstock for the creation of biochar. With this, public awareness and acceptance would be increased (Igliński *et al*., 2023).

4. CONCLUSION

One promising alternative is using MAP to transform various kinds of AWB and PW into valuable resources. Several different industries can make use of hybrid biochar that is produced from the MAP of AWB and PW. The operating parameters play a significant role, including the type of feedstock, the temperature of the pyrolysis process, the pressure, the heating rate, the residence time, the susceptor, the particle size, and the microwave power. The AWB could produce an impressive quantity of hybrid biochar if it contained sufficient fixed carbon and ash. When the pyrolysis temperature and the heating rate are both high, it is easy to generate high yields of hybrid biochar. Hybrid biochar could also be used as a susceptibility in MAP, improving heat and mass transfer transmission. Physicochemical, surface, and structural investigations are used to characterize the hybrid biochar that is created through the MAP application. In the tertiary wastewater treatment process, hybrid biochar is a valuable product that can be used for various purposes, including soil remediation, applications as an adsorbent, and applications as an ion exchange resin.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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