

# BIOCHAR PRODUCTION OF KITCHEN WASTE AND WATER HYACINTH BY LOW TEMPERATURE STEAM TORREFACTION

## Abstract

The rapid industrialization, urbanization, and population growth in India have resulted in a drastic increase in waste generation, particularly food waste, leading to widespread pollution and environmental degradation. This pollution affects all water bodies, including groundwater, soil, air, and even crops such as vegetables and fruits. As a consequence, certain regions of the country are facing a severe proliferation of water hyacinth in their water bodies causing eutrophication

This study proposes the adoption of a new waste management method: biochar production with water hyacinth and food waste. Biochar, with its high carbon content, has garnered attention from researchers worldwide due to its ability to convert waste into valuable products in a remarkably short time. The study explores various methods of biochar production, with a particular focus on torrefaction, which has gained popularity among researchers for its ability to produce biochar at low temperatures (200-300°C) and in a short timeframe (10-120 minutes).

The study conducts various tests on biochar samples, including grain size distribution analysis of raw feedstocks, proximate analysis, pH measurement, water retention capacity assessment, and Brunauer-Emmett-Teller (BET) surface area analysis. This research underscores the potential of biochar production as a viable and sustainable solution for managing waste. By understanding the properties and applications of biochar, researchers and policymakers can promote its adoption to

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address pollution, reduce landfill usage, and foster a healthier environment.

**Keywords:** Food waste, Water Hyacinth, Biochar, Torrefaction.

## I. INTRODUCTION

The global population outbreak has triggered a significant increase in waste generation, posing a grave threat to the environment. Improper waste management, particularly the lack of source segregation in India, has resulted in vast quantities of waste being dumped into landfills, burdening existing sites and necessitating the creation of new ones. As a result, there is an urgent need for effective waste management practices, with a primary focus on waste reduction at the source itself.

According to CPCB 2016, India produced 62 metric tons of municipal solid waste (MSW) in 2015, projected to rise to a staggering 436 metric tons by 2050. Among the states, Maharashtra generated the largest quantity of 14,900 metric tons per day in 2015 [1].

In addition to waste management, eutrophication, exacerbated by the increasing use of chemical fertilizers globally, is a pressing concern. Raising awareness about the detrimental effects of chemical fertilizers and promoting the adoption of natural alternatives, such as biochar, is vital. Eutrophication has led to the proliferation of water hyacinth in rivers, forming a harmful layer that hinders sunlight and air penetration, endangering aquatic life [2].

To address these challenges, various waste management methods are being employed, including composting, incineration, anaerobic digestion, refuse-derived fuel, and biochar production [3]. Biochar production, in particular, is gaining traction among researchers due to its thermochemical process that converts waste into valuable biochar. Efforts are underway to popularize this method globally and create market demand [4].

Among the thermal treatments involved in biochar production, the torrefaction method has garnered significant attention. Researchers are drawn to its ability to produce biochar at low temperatures (200-300°C) and within a short timeframe (10-120 minutes) [5].

In the current scenario, managing waste and adopting sustainable practices, like biochar production, are critical steps towards mitigating environmental issues and promoting a cleaner, greener future.

## II. METHODOLOGY

**1. Biochar Production Methods:** Biochar, a carbon-rich charcoal, is synthesized through diverse thermal decomposition methods employing organic biomass and agricultural residues as feedstocks. Constituting elements like carbon, hydrogen, nitrogen, ash, oxygen, and sulphur, biochar production yields by-products such as bio-oil and biofuels like hydrogen gas. Thermal treatments, including pyrolysis, gasification, carbonization, hydrothermal carbonization, and torrefaction, are integral to its creation. Biochar's porous nature augments soil surface area, enhancing water retention capacity, thereby serving to enrich soil nutrient content and sequester carbon.

Though the biochar concept is ancient, the term itself was coined recently. Evidence of its historical use exists in the Amazon Basin, where regions known as terra preta boasted soil enriched with organic matter and char, contributing to fertility. Amidst escalating global carbon dioxide emissions largely attributed to energy use, biochar

production presents a significant avenue for mitigating greenhouse gases (GHGs). Predicted reductions of up to 12% in human-caused GHG emissions through biochar's carbon sequestration potential are substantial.

Biochar production techniques encompass a range of methods, all converging on the conversion of feedstocks into carbon-rich material under oxygen-deficient conditions. As the world confronts multifaceted sources of CO<sub>2</sub> emissions—ranging from natural carbon cycles to vehicular discharges, deforestation, and wildfires—biochar emerges as a promising solution, embodying potential for carbon reduction, waste management, soil enhancement, and sustainable agriculture.

- **Pyrolysis:** Pyrolysis is a thermochemical decomposition process that converts feedstock into a value-added product, biochar, at elevated temperatures. The temperature range for pyrolysis falls between 250°C and 1000°C, yielding solid, liquid (bio-oil), and gaseous (syngas) products. This process involves reactions such as depolymerization, fragmentation, and cross-linking of lignocellulosic components (lignin, cellulose, and hemicellulose) at specific temperatures. Biochar yield is influenced by the feedstock type and nature, with higher pyrolysis temperatures favouring syngas production over biochar [5], [6].

Classified based on parameters like temperature, residence time, pressure, and heating rate, pyrolysis comprises two types:

- **Slow Pyrolysis:** Operating between 300°C and 700°C, this process features longer residence times exceeding 1 hour and gradual heating at 5-7°C/min. The extended residence time contributes to higher biochar yields, retaining up to 50% of feedstock carbon. It is utilized for producing activated carbon, methanol, and converting ethylene dichloride to polyvinylchloride (PVC) [4], [5].
  - **Fast Pyrolysis:** Employing temperatures between 500°C and 1000°C, with a residence time of 0.5-2 seconds, this method is suited for bio-oil production when biochar yield is less emphasized [5].
- **Carbonization:** Carbonization involves pyrolytic processes akin to traditional charcoal production, converting carbon-rich materials. Conversion temperatures range from 280°C to 500°C, spontaneously yielding charcoal alongside combustible and non-combustible gases [4], [7].
  - **Gasification:** Gasification is a thermochemical decomposition process converting carbonaceous materials into syngas, primarily composed of CH<sub>4</sub>, CO, H<sub>2</sub>, CO<sub>2</sub>, and trace hydrocarbons, under temperatures exceeding 700°C. Gasification agents like air, oxygen, and steam facilitate the conversion. Syngas can be combusted efficiently at high temperatures or in fuel cells, making it more effective than direct fuel combustion. Biomedical waste can serve as a suitable input for gasification, where corrosive elements like chloride and potassium are effectively removed due to the high temperature [4], [5].

- **Hydrothermal Carbonization (HTC):** Hydrothermal carbonization, conducted under pressure, transforms wet biomass into a carbon-rich product, hydrochar. The process operates within a pressure range of 2 to 10 MPa [6], [8]. Hydrothermal treatment encompasses three categories: hydrothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification.
  - **Hydrothermal Carbonization:** Operating at temperatures below 250°C, this process yields hydrochar (solid product) as the primary output, with a residence time of 1-16 hours [9][10].
  - **Hydrothermal Liquefaction:** Ranging from 250°C to 400°C, this method prioritizes bio-oil (liquid product) yield over solid and gaseous products [5].
  - **Hydrothermal Gasification:** Requiring temperatures above 400°C, these variant yields syngas, including CO<sub>2</sub>, H<sub>2</sub>, CO, and CH<sub>4</sub>, with a higher emphasis on gaseous products over solid and liquid counterparts [5], [11].

HTC stands out as a cost-effective process, eschewing pre-drying procedures, and directly accommodating wet feedstock in the reactor [12]. Often referred to as wet pyrolysis or wet torrefaction, HTC capitalizes on water's dual role as both a catalyst and reactant, particularly in hydrolysis reactions [3], [11]. The resulting hydrochar exhibits an elevated heating value attributed to diminished lignin and cellulose components from the feedstock during the HTC process [11].

- **Torrefaction:** Torrefaction is an emerging methodology within the realm of biochar production. Often referred to as mild pyrolysis, it distinguishes itself by its low heating rate requirement. Operating at temperatures ranging from 200°C to 300°C, and with a residence time spanning 10 to 60 minutes, torrefaction yields higher biochar quantities compared to bio-oil and syngas. This process induces alterations in feedstock properties, encompassing surface area, particle size, energy density, moisture content, and heating rate [5]. Key factors influencing torrefied output's mass and energy yield include torrefaction temperature, residence time, particle size, and biomass type [13].

The Torrefaction process is categorized into four distinct types [5]:

- **Steam Torrefaction:** Under steam action, biochar production occurs at temperatures not exceeding 260°C, with a brief residence time of 10 minutes.
- **Wet Torrefaction:** Also known as hydrothermal carbonization, this process mirrors HTC in terms of required temperature (180-260°C) and residence time (1-16 hours). Wet biomass serves as the feedstock.
- **Oxidative Torrefaction:** Operating at 200-300°C for less than 30 minutes, with a heating rate under 50°C/minute, this partial pyrolysis process utilizes oxidizing agents like combustion gases (CO<sub>2</sub>, O<sub>2</sub>) for temperature generation.
- **Dry Torrefaction:** This process entails distinct phases - heating, drying (pre-drying and post-drying), torrefaction, and cooling. Feedstock is heated or pre-dried until complete moisture evaporation occurs at 100°C. The torrefaction phase stabilizes the temperature at 200-300°C, followed by post-drying at 200°C to eliminate residual moisture. Mass loss occurs due to temperature increase post-

torrefaction. The final product is cooled at room temperature prior to exposure to air.

Efficient pre-drying hinges on managing feedstock moisture and torrefaction degree. Integrating torrefaction with a combustion/gasification chamber can utilize waste heat for drying, enhancing overall system efficiency. The key advantage of torrefaction is the improved quality of biomass fuel, closely resembling coal combustion behavior [13].

The torrefaction process engages several reactions: hydrolysis, dehydration, decarboxylation, aromatization, and recondensation [8],[14]. Initially containing carbon, hydrogen, oxygen, and nitrogen, hydrolysis adds water, cleaving bonds to form alcohol groups. Dehydration involves water loss, resulting in alkene formation and carbon enrichment. Decarboxylation releases CO<sub>2</sub> gas by removing carboxyl (-COOH) groups. Aromatization removes hydrogen or other atoms, enhancing aromaticity or forming stable products. Recondensation combines molecules by eliminating small entities like -H<sub>2</sub>O, -NH<sub>3</sub>, and -HCl, facilitating hydrogen, oxygen, and nitrogen reduction while augmenting carbon content. The reaction sequence is variable, with no specific order or timing [6], [7], [11], [15].

- 2. Sample Collection and Preparation:** Household kitchen waste was gathered on a daily basis and subjected to sun drying to eliminate its excess moisture content. Approximately 5kg of the desiccated waste was utilized in the production of biochar, following a fine grinding process.

Water hyacinth is harvested from the Mula Mutha River, which flows behind MIT ADT University in Pune. A substantial quantity of 8-15 large bin bags filled with water hyacinth is collected for the purpose of biochar production. The water hyacinth undergoes sun drying on the rooftop of the house to eliminate excessive moisture. Subsequently, the stems of the plant are separated from the leaves and roots. The dried stems are then finely ground.



**Figure 1:** Shredded Feedstocks - Kitchen Waste and Water Hyacinth

In research both kitchen waste and water hyacinth have been independently employed for biochar production. In this particular study, a novel approach is undertaken by combining both feedstocks in varying proportions to create biochar.

The biochar samples were prepared using the following ratios:

- Sample 1: Pure water hyacinth (WH) biochar.
- Sample 2: Pure kitchen waste (KW) biochar.
- Sample 3: Equal parts of water hyacinth and kitchen waste biochar (50%:50% or 1:1 ratio).
- Sample 4: A mixture of 40% water hyacinth and 60% kitchen waste biochar (1:1.5 ratio).
- Sample 5: A blend of 30% water hyacinth and 70% kitchen waste biochar (1:2.33 ratio).
- Sample 6: A combination of 60% water hyacinth and 40% kitchen waste biochar (1.5:1 ratio).
- Sample 7: A mix of 70% water hyacinth and 30% kitchen waste biochar (2.33:1 ratio).

These different feedstock proportions were placed in a steel container and processed individually for 14-16 hours during working hours using a laboratory vertical autoclave reactor. The experiments were conducted in the Environmental Engineering Laboratory of the Civil Department at MIT School of Engineering & Science.

The laboratory vertical autoclave reactor is designed to operate at a temperature and pressure of 150°C and 30 kg/cm<sup>2</sup>, respectively. Its maximum achievable temperature and pressure are 124°C and 18-22 kg/cm<sup>2</sup> (1.76-2.16 MPa), respectively. The autoclave functions using steam. Consequently, the resulting biochar samples underwent additional drying in a hot air oven within the Environmental Engineering Laboratory to eliminate any remaining excess moisture.

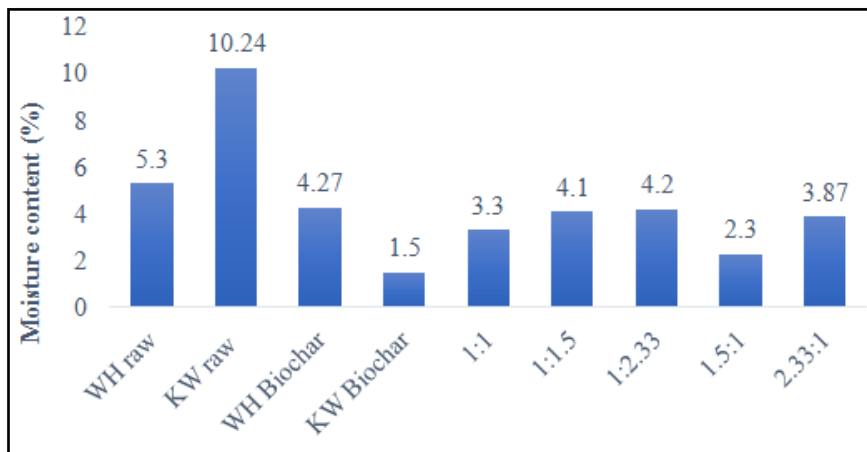
### III. RESULT AND DISCUSSION

**1. Proximate Analysis:** Proximate analysis is conducted to assess the moisture percentage, volatile matter, ash content, and, most importantly, the fixed carbon content within the biochar samples. Research indicates that a higher fixed carbon content corresponds to greater product stability. The ensuing findings are elaborated upon in the subsequent discussion.

- **Moisture Content Analysis:** Moisture content analysis is done based on ASTM standard E871[16]

**Table 1: Moisture Content Analysis of Biochar Samples**

Sample	Moist Weight $W_1$ (g)	Dry Weight $W_2$ (g)	Moisture Content (%) $\frac{W_1 - W_2}{W_1} \times 100$
WH raw	1.001	0.948	5.3
KW raw	1.006	0.903	10.24
WH Biochar	1.008	0.965	4.27
KW Biochar	1.007	0.992	1.5
1:1 Biochar	1.005	0.972	3.3
1:1.5 Biochar	1.002	0.961	4.1
1:2.33 Biochar	1.006	0.964	4.2
1.5:1 Biochar	1.006	0.983	2.3
2.33:1 Biochar	1.007	0.968	3.87



**Figure 2: Moisture % of Biochar Samples & Raw Waste Samples**

The raw samples exhibit a higher peak value of moisture percentage, reflecting the elevated moisture content in kitchen waste and water hyacinth. Upon comparing biochar samples to their raw counterparts, it becomes evident that water hyacinth biochar retains 4.27% moisture, while kitchen waste biochar contains the least moisture at 1.5%. Studies suggest a reduction in moisture percentage for torrefied biochar. The biochar in these samples demonstrates enhanced soil longevity without compromising the environment, owing to its lower moisture content. This characteristic minimizes nutrient runoff from agricultural fields, reducing the risk of eutrophication.

Consequently, kitchen waste biochar boasts an extended soil residence compared to other samples due to its minimal moisture content. It's noteworthy that the moisture content of biochar, ranging from 1% to 5%, aligns with that of coal (10-15%) and torrefied biochar. Thus, all seven biochar samples illustrated in Figure 15 maintain a moisture percentage within the range of 1-5%.



- **Volatile Matter (%)**

Volatile matter is calculated based on ASTM standard E872[17]

Calculation of weight loss percent is as follows:

$$(A) \text{ weight loss \%} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight} - \text{Weight of crucible}} \times 100$$

Calculation of volatile matter percent in the analysis of samples is as follows:

$$\text{Volatile matter in analysis sample} = (A) - (B)$$

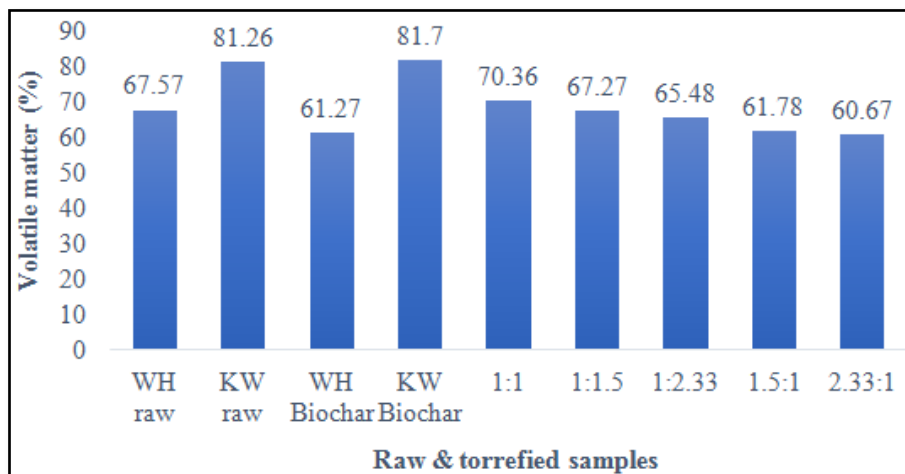
Where,

A = weight loss % and

B = moisture content % determine using ASTM E871

**Table 2: Volatile Matter Analysis of All the Seven Biochar Samples**

Sample	Weight of crucible $w_c$ (g)	Initial weight $w_i$ (g)	Final weight $w_f$ (g)	Volatile matter (%)
WH raw	18.752	19.257	18.889	67.57
KW raw	19.495	20.001	19.538	81.26
WH Biochar	18.891	19.393	19.064	61.27
KW Biochar	19.439	19.945	19.524	81.7
1:1 Biochar	18.940	19.445	19.073	70.36
1:1.5 Biochar	18.716	19.219	18.860	67.27
1:2.33 Biochar	18.893	19.401	19.047	65.48
1.5:1 Biochar	19.446	19.95	19.627	61.78
2.33:1 Biochar	18.943	19.445	19.121	60.67



**Figure 3: Volatile % of Biochar Samples and Raw Waste Samples**

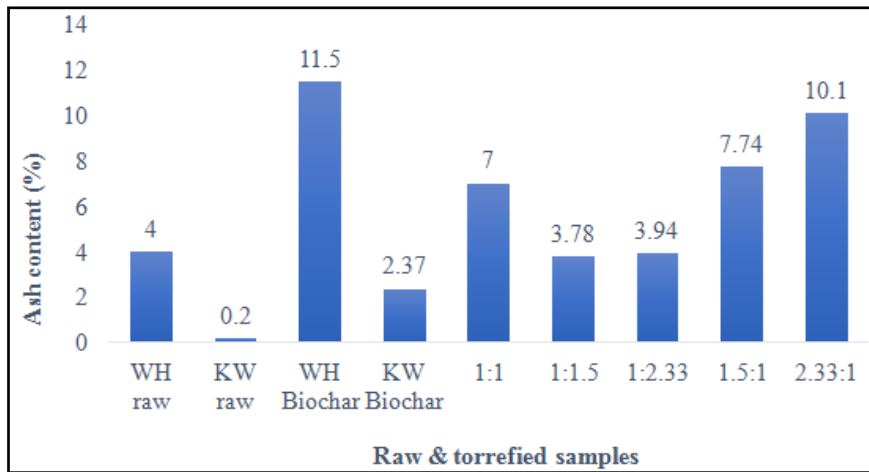
The biochar samples with high volatile percent are considered highly reactive and thus highly reactive torrefied biomass are compared to coal. Torrefied biochar

samples with high volatile matter are best substitute for fuel production and not for soil amendment. Thus, from figure 16. it is observed that 2.33:1 biochar sample which contains 70% by weight water hyacinth and 30% by weight kitchen waste can be best suited for soil amendment as it has the least volatile matter percent in comparison to other biochar samples [13].

- **Ash Content (%):** Ash content is calculated based on ASTM standard E1755 [18]

**Table 3: Ash Content Analysis of the Biochar Samples**

Sample	Weight of crucible $W_c$ (g)	Weight of sample $W_1$ (g)	Weight of ash + crucible $W_2$ (g)	Ash content (%)
WH raw	18.752	0.505	18.792	4
KW raw	19.495	0.506	19.496	0.2
WH Biochar	18.891	0.502	18.949	11.5
KW Biochar	19.439	0.506	19.451	2.37
1:1 Biochar	18.940	0.505	18.975	7
1:1.5 Biochar	18.716	0.503	18.735	3.78
1:2.33 Biochar	18.893	0.508	18.913	3.94
1.5:1 Biochar	19.446	0.504	19.485	7.74
2.33:1 Biochar	18.943	0.502	18.994	10.1



**Figure 4: Ash % of Biochar Samples and Raw Waste Samples**

According to the studies, low ash content of biochar sample is preferred for soil amendment as properties of biochar play a vital role in deciding the application of biochar in various fields. For example, biochar with high surface area along with presence of binding sites are useful as adsorbents for various contaminants, then biochar having porosity and high structural bound nitrogen groups are best suited for the development of supercapacitors etc.

Thus, from figure 17. We can determine that kitchen waste (KW) biochar is best suitable for soil amendment as it has least ash content [12].

- **Fixed Carbon Content (%)**

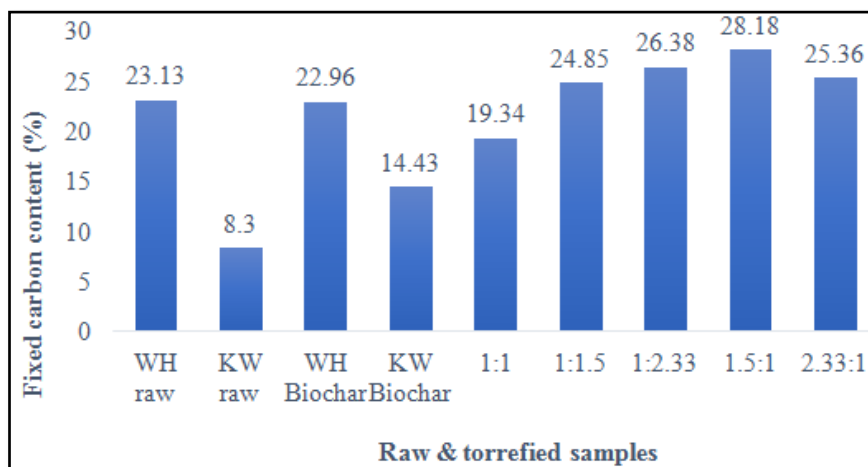
Fixed carbon is calculated as shown below [19]

$$\text{Fixed carbon} = 100 - [\% \text{ moisture content} + \% \text{ volatile matter} + \% \text{ ash content}]$$

**Table 4: Fixed Carbon Content of Biochar Samples**

Sample	% Moisture content	% Volatile matter	% Ash content	Fixed carbon (%)
WH raw	5.3	67.57	4	23.13
KW raw	10.24	81.26	0.2	8.3
WH Biochar	4.27	61.27	11.5	22.96
KW Biochar	1.5	81.7	2.37	14.43
1:1 Biochar	3.3	70.36	7	19.34
1:1.5 Biochar	4.1	67.27	3.78	24.85
1:2.33 Biochar	4.2	65.48	3.94	26.38
1.5:1 Biochar	2.3	61.78	7.74	28.18
2.33:1 Biochar	3.87	60.67	10.1	25.36

Studies say that fixed carbon content increases due to decomposition of lignin to small substances. Higher fixed carbon also signifies the stability of biochar sample. The more the fixed carbon value, more stable is the product. Also, torrefied biochar sample's behavior are compared to coal because coal has a fixed carbon content of 50-55% whereas torrefied biochar sample's fixed carbon content range between 28-35%. Therefore, from figure 18. we can determine that 1.5:1 biochar sample which contains 60% by weight water hyacinth and 40% by weight kitchen waste is the most stable biochar as it is lying within the range of 28-35% of fixed carbon content.

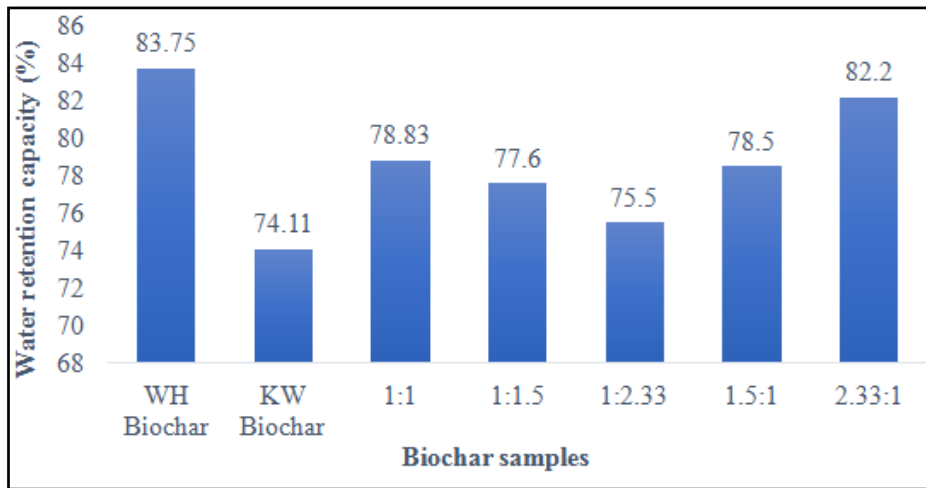


**Figure 5: Fixed carbon % of Biochar Samples and Raw Waste Samples**

**2. Water Retention Capacity:** Water retention capacity signifies that how much gram of water is being retained per gram of biochar.

**Table 5: Water Retention Capacity of Biochar Samples (cont.)**

Sample (1)	Wet weight (g) (2)	Dry weight (g) (3)	Weight of torrefied sample (g) (4)	Water retention capacity ( $\frac{g}{g}$ ) (5) = $\frac{(2)-(3)}{(4)}$	Water retention capacity (%) (6) = $\frac{(2)-(3)}{(2)} \times 100$
WH Biochar	45.181	7.343	10.008	3.78	83.75
KW Biochar	26.692	6.91	10.004	1.98	74.11
1:1 Biochar	33.222	7.033	10.002	2.62	78.83
1:1.5 Biochar	29.827	6.69	10.006	2.31	77.6
1:2.33 Biochar	26.982	6.619	10.003	2.04	75.5
1.5:1 Biochar	32.755	7.041	10.008	2.57	78.5
2.33:1 Biochar	39.88	7.107	10.004	3.27	82.2



**Figure 6: Water Retention Capacity of Biochar**

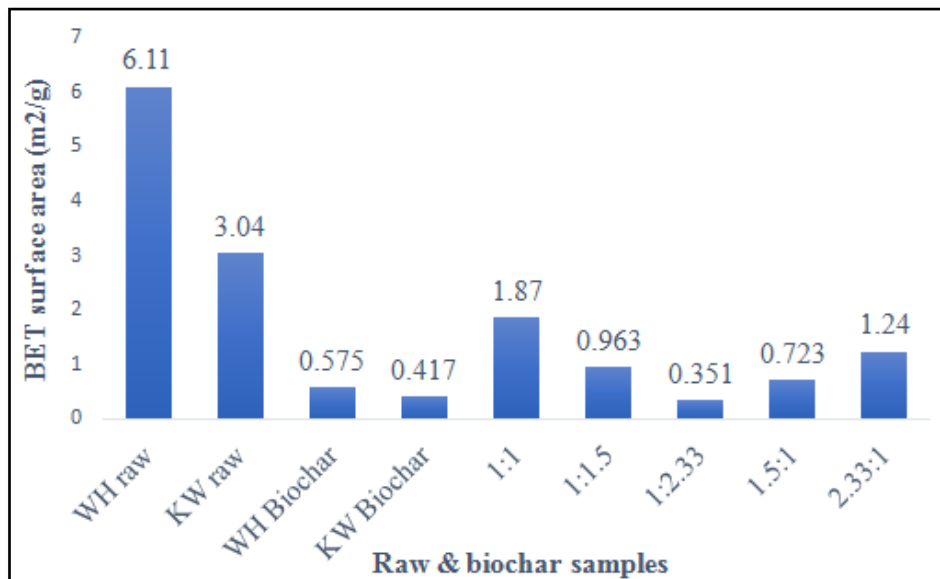
The results in table 5, Column 5 determine that certain gram of water is retained per gram of biochar. Highest water retention capacity is of water hyacinth biochar which means 3.78 g of water is retained per gram of biochar. Also, by calculating percent water retention capacity which is shown in figure 6. We can make out which biochar sample has the maximum capacity to retain water because according to the studies water retention

capacity of biochar ranges between 75-274%. So, after calculating percentage water retained also we can see that water hyacinth biochar has the highest water retention capacity [12][20].

- Brunauer-Emmett-Teller (BET) Surface Area Analysis:** This analysis explains the physical adsorption of gas molecules on a solid surface. Thus, it becomes the important analysis technique for measuring the specific surface area of any material.

**Table 6: Surface area of Raw Feedstock & Biochar Samples**

Sample	BET surface area (m <sup>2</sup> /g)
WH raw	6.11
KW raw	3.04
WH Biochar	0.575
KW Biochar	0.417
1:1	1.87
1:1.5	0.963
1:2.33	0.351
1.5:1	0.723
2.33:1	1.24



**Figure 7: Surface Areas Raw and Biochar Samples**

From figure 7. we can see that surface area of raw feedstock is more in comparison to the biochar samples. This may be due to less temperature difference between pre-drying of raw feedstock and the autoclaving to produce biochar. But studies say that even when the surface area is less the biochar can have a good effect in water retention and nutrient retention as it depends on the feedstock properties as well. Thus, this can best be explained when we do the soil application of biochar experiment and then conclude whether the biochar samples work well on soil or not [3].

## IV. CONCLUSIONS

The kitchen waste biochar exhibits the highest volatile matter content, attributed to its organic matter composition. Conversely, the biochar sample with a feedstock ratio of 2.33:1, comprising more water hyacinth and less kitchen waste, contains reduced volatile matter due to the lower organic matter content in water hyacinth.

Ash content displays an inverse relationship with volatile matter. Therefore, the biochar from kitchen waste reveals the least ash content at 2.37%, owing to its elevated volatile matter content. On the other hand, the water hyacinth biochar demonstrates the highest ash content at 11.5%, influenced by its lower percentage of volatile matter.

The fixed carbon content is influenced by the proportion of volatile matter. Raw kitchen waste biochar displays the lowest fixed carbon content at 14.43%, primarily due to its elevated volatile matter. In contrast, the biochar with a ratio of 1.5:1 (water hyacinth to kitchen waste) exhibits the highest fixed carbon content at 28.18%, attributed to the lower volatile matter content in water hyacinth.

The determination of water retention capacity serves to gauge the moisture-holding capability of a given biochar sample when applied to soils. Among the samples, raw water hyacinth biochar displays the highest water retention capacity at 83.75%, while raw kitchen waste biochar exhibits the lowest at 74.11%. This discrepancy arises from the dependence of water retention capacity on the specific feedstock used. The fibrous structure of water hyacinth's stem contributes to its exceptional moisture retention ability, reaching up to 95%.

The Brunauer-Emmett-Teller (BET) surface area test is employed to quantify the surface area of the samples. The surface areas for water hyacinth, kitchen waste, and biochars with ratios of 1:1, 1:1.5, 1:2.33, 1.5:1, and 2.33:1 are measured at 0.575 m<sup>2</sup>/g, 0.417 m<sup>2</sup>/g, 1.24 m<sup>2</sup>/g, 0.963 m<sup>2</sup>/g, 0.351 m<sup>2</sup>/g, 0.723 m<sup>2</sup>/g, and 1.87 m<sup>2</sup>/g, respectively. These biochar samples exhibit relatively smaller surface areas due to their production at a lower temperature of 124°C in the autoclave reactor. Elevated temperatures exceeding 124°C, particularly above 200°C, lead to the expansion of biochar pores and an increase in surface area.

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