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CHAPTER 6

Enhancing Hydrochar Yield from Rice Husk Using Rapid Thermochemical Conversion: Influence of Process Conditions on Properties and Performance

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Abstract: The hydrochar yield of microwave hydrothermal carbonization (MHTC) is greatly influenced by its critical parameters. This study investigates the impact of various process variables on the quantity of hydrochar obtained from rice husk via MHTC. Results indicate that larger particle sizes, lower biomass-to-water ratios, shorter reaction times, and reduced temperatures boost hydrochar output within the tested ranges. The maximum yield, reaching about 63.4%, was recorded at 955 W, 228°C, and 7 minutes. The higher heating value (HHV) exhibited a marked increase, rising from 5.89 MJ/kg in untreated rice husk to 15.25 MJ/kg in hydrochar. Chemical composition analysis revealed a carbon content increase from 27.3% to 47.6%, with oxygen content decreasing from 67.8% to 46.6%, improving the fuel's energy performance and combustion characteristics. SEM analyses verified structural changes in rice husk after MHTC, accompanied by enhanced porosity, as confirmed by BET

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surface area data, which rose from 21.2148 m²/g in rice husk to 91.9653 m²/g in hydrochar. Thermal durability also advanced, with hydrochar achieving 376°C compared to 344°C for rice husk.

Keywords: Biomass Conversion, Porosity, Carbon Content, Reaction Temperature, Microwave Processing

Introduction

Growing concerns over energy shortages, ecological consequences, and dwindling fossil fuel supplies have spurred researchers to explore viable substitutes that address these challenges sustainably.[1] Biomass stands out as a renewable, environmentally benign option due to its widespread availability.[1] It exists in plentiful, high-quality forms, especially from agricultural sources,[3],[4] and offers the potential to curb carbon dioxide emissions.[5] Rice husk, a plentiful byproduct of rice milling, exemplifies this resource. Improper disposal methods, such as open burning, pose significant environmental risks.[6] Composed of roughly 33% cellulose, 25% hemicellulose, 20% lignin, 13% silica, and 2% miscellaneous components, rice husk is a lignocellulosic material.[7] Its makeup varies depending on factors like farming practices, weather patterns, and soil conditions.[8] With a global yearly production of about 142 million tonnes, rice husk represents an economically attractive asset. Converting it into hydrochar via microwave hydrothermal carbonization (MHTC) offers a practical utilization strategy.

The concept of hydrothermal carbonization (HTC) originated in 1913 with Bergius and Specht, who heated cellulose and water at 255-305°C in a sealed system to produce a carbon-dense material.[9] This hydrochar exhibited a low O:C ratio (0.18-0.32), reflecting substantial carbon enhancement. In 1932, Berl and Schmidt refined this technique, applying it to diverse saccharides at 145-355°C.[10] Known for smokeless burning and elevated carbon levels, hydrochar retains approximately 58-93% of its initial mass and 80-96% of its energy content.[11,12] Hydrothermal carbonization (HTC) entails a thermochemical decomposition process where biomass is heated in water at temperatures ranging from 170 to 250°C, producing hydrochar as the primary output along with water-soluble organic compounds,[13] and it can be effectively carried out using either conventional or microwave as heating source.

Microwave-mediated hydrothermal carbonization (MHTC) has recently outpaced traditional HTC, delivering a cutting-edge, energy-efficient, and environmentally friendly option that significantly shortens processing duration.[8,15] Water, being abundant, non-toxic, non-combustible, and an environmentally friendly solvent, excels in MHTC by superheating in sealed vessels, enabling efficient chemical modification.[16] Its strong microwave absorption makes it ideal for biomass treatment. MHTC produces carbon-rich solids with oxygenated fractions in an aqueous suspension. Factors influencing reaction outcomes include temperature, duration, biomass type, particle size, microwave power, purge gas rate, catalyst (HCl) concentration, and solid-to-liquid ratio, all of which shape the properties of the resulting materials under microwave influence.[18,19,8,20]

A variety of studies have delved into microwave-assisted hydrothermal carbonization (MHTC) across different biomass substrates, such as pine residues and α-cellulose,[14] *Prosopis africana* husks,[12] glucose,[21] and blends of sewage with human waste.[11] Investigations have also encompassed rapeseed shells.[8] Guiotoku et al.[14] evaluated how processing duration impacts hydrochar generation from two distinct lignocellulosic sources using MHTC. Meanwhile, Elagwu and Greenway[8] assessed the combined effects of temperature and time on rapeseed shell MHTC, comparing traditional approaches with MHTC regarding output percentages for *P. africana* husks.[12] As yet, no work has addressed hydrochar synthesis from rice husk through MHTC, and a thorough exploration of how MHTC variables influence biomass broadly is lacking. This investigation aims to uncover how key MHTC factors—namely temperature, duration, particle scale, and biomass-to-water proportion (w/v)—affect hydrochar output. Evidence suggests that higher temperatures and extended durations notably modify hydrochar properties. Thus, this study characterizes hydrochar formed at 950 W, 225°C, and 35 minutes, evaluating traits like higher heating value (HHV), energy concentration, and chemical makeup via techniques including FTIR, SEM), BET surface analysis, and TGA.

Raw Materials and Methods

Local rice mill was our primary source of rice husk. It was collected and thoroughly washed to eliminate contaminants. It was subsequently dried in an oven at 102°C for 24 hours. The prepared rice husk was utilized in experimental procedures. The dried material was pulverized with an MF 10basic crusher to explore how particle size influences yields. The ground particles, varying between 0.3 and 3.5 mm, were then used for additional analysis.

Generation of Hydrochar from Rice Husk using Microwave

The MHTC process for rice husk was conducted with a microwave digestion system capable of 1000 W and temperatures up to 300°C. Rice husk was mixed with distilled water at a chosen biomass-to-water ratio in a sealed vessel. Specific experimental conditions were set via the control interface, and the process was initiated. After completion, the reactor cooled to room temperature with fan assistance. Unanalyzed exhaust gases were released to a fume hood. The resulting bio-oil and hydrochar mixture was separated by filtration, with the hydrochar rinsed multiple times with distilled water and dried at 102°C for 24 hours.

Yield (%) of Hydrochar

According to Eq (1), the percentage of hydrochar yield is calculated by dividing the initial dry rice husk mass in the reactor by the dry hydrochar mass.

$$\text{Yield (\%)} = \left(\frac{\text{Weight}_{\text{hc}}}{\text{Weight}_{\text{rh}}}\right) \times 100$$

- $\text{Weight}_{\text{hc}}$ = mass of dry hydrochar post-MHTC.
- $\text{Weight}_{\text{rh}}$ = mass of dry rice husk initially used.

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Characterization

Elemental composition of rice husk and hydrochar was determined using a PerkinElmer 2400 Series II CHNS/O analyzer, with oxygen content calculated by subtracting carbon, hydrogen, sulfur, and nitrogen masses from the total. HHV was derived using Boie's equation (Eq. 2),[22] and energy density was calculated from Eq. 3:

$$\text{HV (MJ/kg)} = 0.3516(\text{C}) + 1.16225(\text{H}) - 0.1109(\text{O}) + 0.0628(\text{N}) \ldots\ldots(2)$$

$$\text{Energy Densification} = \frac{(HHV)_{Hydrochar}}{(HHV)_{Rice\ husk}} \ldots\ldots(3)$$

The proximate composition of rice husk and hydrochar was determined using thermogravimetric analysis (TGA), based on the method described by Tripatha *et al.*[23] FTIR investigations were performed using a PerkinElmer TA 8000 spectrometer, acquiring 30 scans per specimen across a range of 4050 to 540 cm^{-1} with a resolution of 3 cm^{-1}. Using a Micromeritics ASAP 2440 analyzer, surface area (BET), pore diameter, and total pore capacity were determined. SEM imaging was performed with a Variant XL50 SEM under high vacuum at 16 kV, with a spot size of 4.6-5.1 and a 9 mm working distance. Structural analysis employed a Bruker D4 Endeavor X-ray diffractometer, scanning a 2θ range of 4-66° at 105 mA and 42 kV, with peak intensities recorded every 0.03° at a 1.1° 2θ/min rate. TGA and derivative thermogravimetry (DTG) were conducted using a PerkinElmer STA 6000 from 48 to 905°C in a nitrogen atmosphere, with 11 mg samples in an alumina crucible scanned at 11°C/min, measured every 28 seconds under a 22 ml/min nitrogen flow.

Results and Discussion

This research investigates how various processing conditions influence the quantity of hydrochar generated through the MHTC method. The analyzed parameters encompass temperatures ranging from 155 to 225°C, reaction times between 4 and 35 minutes, particle dimensions from 0.4 to 3.5 mm, and (biomass: water) proportions spanning 1:12 to 1:42 w/v. The specific effects of each variable are elaborated as follows.

Temperature is a vital parameter in MHTC, driving biomass breakdown by providing essential heat. Its effect on hydrochar yield was tested at 950 W, a 1:12 biomass-to-water ratio, 3.5 mm particles, and 35 minutes, varying temperature from 155 to 225°C. Results showed a yield decline from 59.2% at 155°C to 50.1% at 225°C (**Figure 1a**), consistent with Elagwa and Greenway's 18.9% drop from 145 to 205°C[8] and Afolaba *et al.*'s reduction from 155 to 205°C with biowaste.[11] Higher temperatures boost gasification, releasing volatiles and reducing yield via dehydration and decarboxylation, as noted by Keng *et al.*[24] and others.[25]

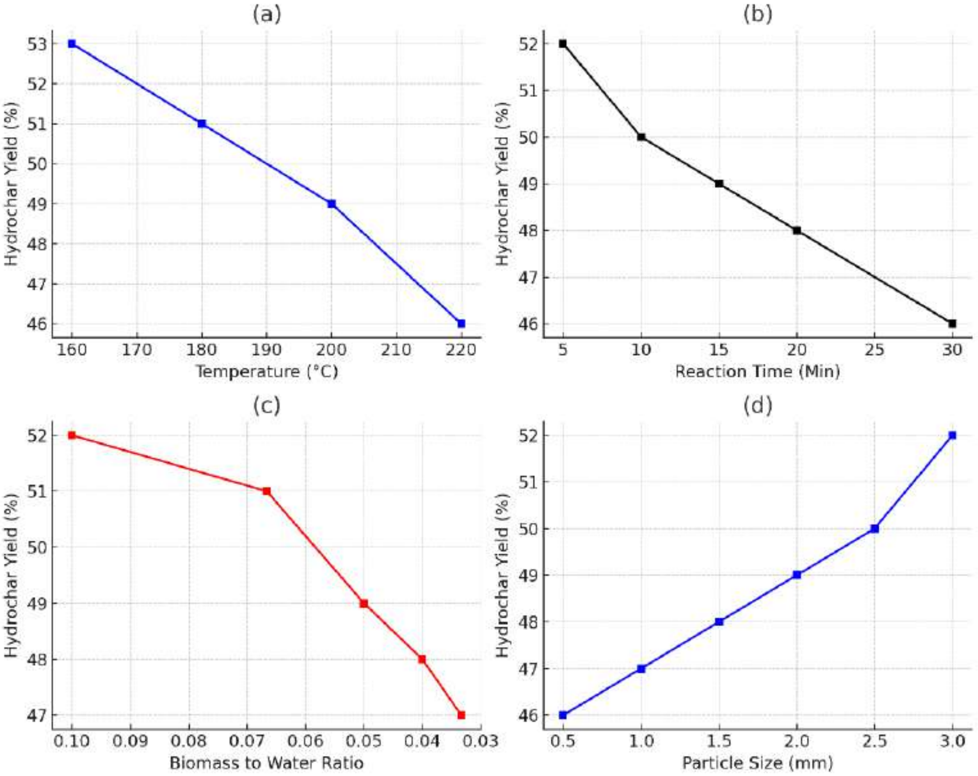

Fig. 1: Effect of process conditions on hydrochar yield

Processing duration critically affects hydrochar yield in MHTC, a process typically slower than HTC (ranging from minutes to days).[26] Its impact was assessed at 950 W, 225°C, and a 1:12 w/v ratio, adjusting time from 4 to 35 minutes. Figure 1b shows higher yields with shorter durations, dropping from 63.1% at 4 minutes to 50.1% at 35 minutes. This aligns with Elagwa and Greenway's 12.9% decline over 14 minutes[8,12] Chan *et al.,*[18] and Afolaba *et al.,*[11] though Guiotoka *et al.*[14] found longer times increased pine sawdust yields but decreased α-cellulose yields at 205°C over 55, 115, and 245 minutes.

Biomass-to-water ratio effects were tested at 950 W, 225°C, 3.5 mm particles, and 35 minutes, varying ratios from 1:12 to 1:42 w/v. **Figure 1c** shows improved yields at lower ratios, reaching a maximum of 52.0% (1:12) and decreasing to 46.8% (1:42), consistent with the gradual decline in HTC yield observed by Nizamudin *et al*. for oil palm shell across a similar ratio range from 1:12 to 1:62[26]. Diminished performance at elevated ratios is observed, although Rogalinska *et al*.[27] and Kannana *et al*.[28] report limited effects at 175°C and 70 minutes with ratios ranging from 0.4 to 1.6, attributed to differences in substrate type (fish waste versus rice husk) and the scope of ratio variations.

Particle size aims to improve hydrothermal exposure, aiding hydrolysis.[29] Tested at 950 W, 225°C, 32 minutes, and 1:12 w/v, sizes ranged from 0.4 to 3.5 mm. **Figure 1d** shows yields rising from 45.9% (0.4 mm) to 54.6% (3.2 mm). A related study found char yields increasing from 18.6 wt% (<1 mm) to 45.78 wt% (9-13 mm), a 146% rise,[17] due to slower volatile diffusion in larger particles, enhancing secondary char formation.[30,31,32]

The Higher Heating Value (HHV) measures the energy content of biomass and hydrochar. **Table 1** provides the HHV data for rice husk and hydrochar, processed at 950 W, 225°C for 35 minutes, with a 1:12 w/v ratio and a particle size of 3.5 mm. HHV of rice husk was 6.92 MJ/kg, rising to 16.23 MJ/kg in hydrochar, nearing brown coal and exceeding low-rank coals (charcoal: 22, lignite: 16.5, peat: 13.5-20.8, all values are in MJ/kg). HHV correlates with carbon content, rising with temperature,[33] reducing hydrogen and boosting combustion. Studies show HHV increases from 16.75 MJ/kg (14 min) to 21.45 MJ/kg (47 min) for glucose MHTC[21] and 18.to 21.25 MJ/kg from 58 to 122 minutes.[34]

Hydrochar production through the hydrothermal carbonization (HTC) process demonstrated significant carbonization and energy densification of biomass.[12] This study yielded a hydrochar energy densification ratio of 1.53, indicating effective conversion of low energy biomass into a higher energy fuel[35]. This result aligns with existing literature reporting similar energy densification ratios ranging from 1.21 to 1.57.[21] A ratio >1 indicates energy gain via MHTC[11,28] rising with temperature, e.g., from 1.0 (170°C) to 1.24 (290°C) for rice hulls.[36] Zhang *et al*.[37] noted biochar energy density rising from 1.03 (165°C) to 1.14 (245°C) for rice husk, while Nakason *et al*.[38] saw it increase from 1.05 to 1.22 (135-205°C) and 1.14 to 1.22 (0.9-4.2 hours). Ultimate analysis, vital for fuel characterization, assesses combustion gas composition. **Table 1** shows hydrochar at 950 W, 225°C, 32 min, 1:12 w/v, and 3.2 mm, with carbon rising from 26.2% to 47.5%, oxygen dropping from 68.2% to 46.7%, and hydrogen from 4.9% to 4.1%, enhancing energy akin to brown coal. Lower oxygen reduces HHV loss and corrosion risks.

Temperature and duration in MHTC drive carbon enrichment and oxygen reduction via deoxygenation.[24] Longer durations amplify this, e.g., glucose hydrochar carbon rose from 36.8% to 49.3% and oxygen fell from 50.82% to 39.15% (58-122 min).[21] Fish waste MHTC showed carbon from 26.8% to 50.3% and oxygen from 64.7% to 36.8%.[28] Nitrogen edged up from 0.5% to 0.8%, possibly from amination or protein retention, with a lower N/C ratio in hydrochar signaling nitrogen stability.

Table 1: Energy Content, Compositional Breakdown, and Surface Characteristics of Hydrochar Derived from Rice Husk at 950 W, 225°C, 35 Minutes, 1:12 w/v, and 3.5 mm

Properties	Rice Husk	Hydrochar
HHV (MJ/kg)	7.92	15.23
UL (Ultimate Analy.)		
Carbon-Content (%)	26.2	47.5
Hydrogen (%)	4.9	4.1
Oxygen (%)	68.2	46.7
Nitrogen (%)	0.5	0.8
Sulfur (%)	0.2	0.6

Properties	**Rice Husk**	**Hydrochar**
PA (Proximate Analy.)		
Fixed Carbon (%)	19.6	36.2
Moisture (%)	8.8	4.3
Volatile-Matter (VM) (%)	61.7	44.1
Ash-Content (%)	9.9	15.4
Analysis through BET		
Surface Area (m²/g)	26.1423	93.9214
Pore Capacity (cm³/g)	0.002513	0.01302
Avg. Width of Pore (Å)	62.892	98.587

Alterations following MHTC were correlated with fuel characteristics using the Van Krevelen diagram (**Fig. 2**), which charts H/C and O/C ratios.[39] Compared to rice husk and various coals (lignite, sub-bituminous, peat, brown coal), hydrochar exhibits reduced ratios, suggesting elevated aromatic content,[40] a consequence of decarboxylation, demethylation, and dehydration processes during MHTC,[34] consistent with standard HTC traits.[8] These diminished ratios stem from specific reaction settings, producing semi-carbonized materials.[14]

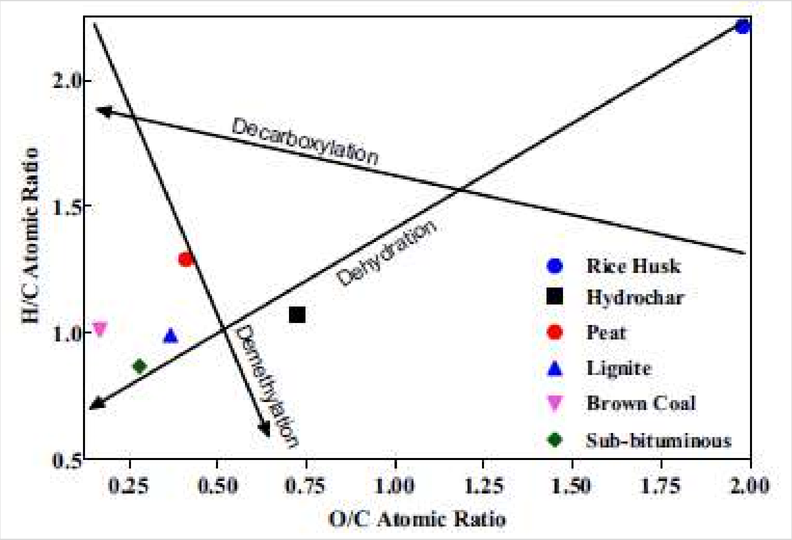

Fig. 2: O/C & H/C of rice husk, hydrochar (950 W, 225°C, 35 min, 1:12 w/v, 3.5 mm), and coals

Table 1 highlights compositional shifts, with fixed carbon rising from 19.6% to 36.2% and volatile matter falling from 61.7% to 44.1%. Lyu *et al.*[41] attribute this to volatilization at high temperatures, enhancing fuel quality, as seen in corn stalk MHTC.

FTIR analysis (4050-540 cm^{-1}) identified functional groups on rice husk and hydrochar (950 W, 225°C, 35 min, 1:12 w/v, 3.5 mm), shown in **Fig. 3**. Peaks at 3445 and 3648 cm^{-1} indicate NH and OH stretching,[42] reduced in hydrochar due to dehydration. Peaks at 2890 and 2810 cm^{-1} (C-H from -CH_2/-CH_3 or CH_n)[43,44] vanish in hydrochar. A 1745 cm^{-1} C=C band shifts to 1740 cm^{-1} in hydrochar, suggesting ester changes,[45] with lignin reduction confirmed by SEM. Peaks at 1650 and 1640 cm^{-1} (C=N) and 1095 and 748 cm^{-1} (amines/chlorides) persist, indicating thermal stability. These specific peaks are eliminated in the hydrochar profile. At around 1750 cm^{-1}, a band correlating to C=C was observed in rice husk; this altered in hydrochar to a stronger intensity at 1738 cm^{-1}, suggesting alterations in ester components during MHTC.[45] Additionally, a decrease in hydrochar peak near 1750 cm^{-1} implies modifications in lignin content, corroborated by SEM analyses.[45] Peaks at 1653 and 1637 cm^{-1} have been maintained across both samples, likely due to C=N stretching from oxime groups. Furthermore, peaks representing amines and chloride groups at 1100 and 752 cm^{-1} were consistent, indicating stability under thermal processing conditions.

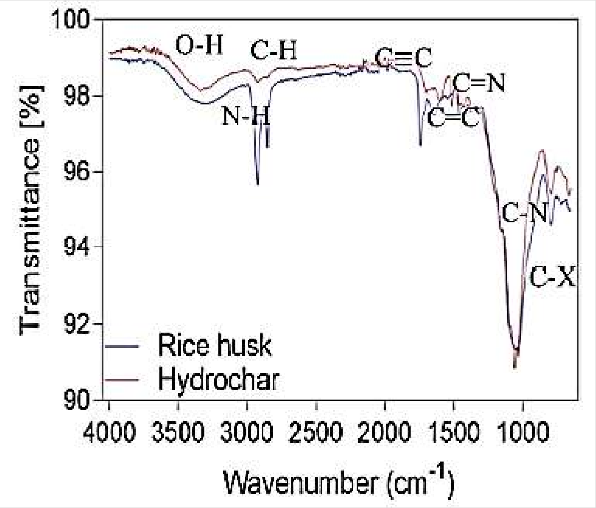

Fig. 3: FTIR Scan of RH and hydrochar (950 W, 225°C, 35 min, 1:12 w/v, 3.5 mm).

SEM, BET and XRD Analyses

SEM assessed MHTC's morphological impact on rice husk and hydrochar (using the condition 950 W, 225°C, 35 min, 1:12 w/v, 3.5 mm), shown in **Fig. 4**. Rice husk (**Fig. 4a**) appears rough and non-porous due to 20.2-33.9% lignin,[8] while hydrochar (**Fig. 4b**) shows pores, cracks, and fibers from lignocellulosic breakdown,[11] aided by volatile release.[11] High temperatures and times decompose cellulose and hemicellulose,[42] enhancing porosity, with Marz *et al.*[46] noting enlarged pores from wall breakdown, aiding dewatering and drying[11] and supporting sequestration/adsorption uses.[34]

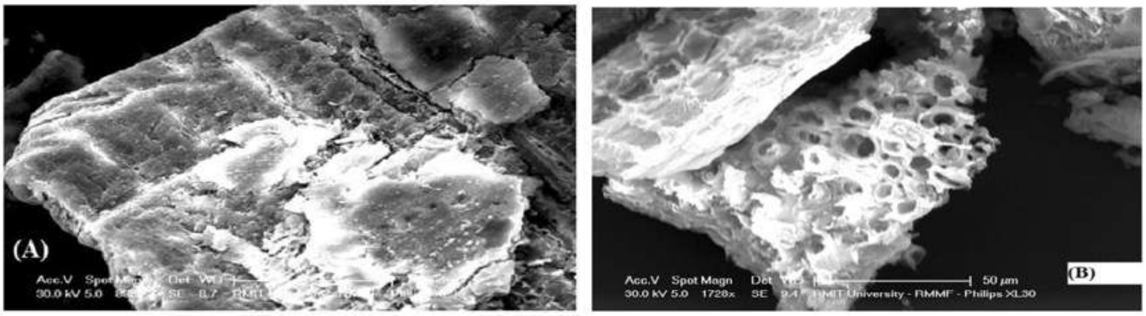

Fig. 4: (a) RH and (b) Hydrochar (using the condition 950 W, 225°C, 35 min, 1:12 w/v, 3.5 mm).

Table 1 shows surface area rising from 26.1423 m²/g to 93.9214 m²/g, pore volume from 0.002513 m³/g to 0.01302 m³/g, and pore width from 62.892 Å to 99.587 Å, due to fiber erosion in MHTC,[19] increasing porosity via hydrogen bond or phase shifts.

The physical characteristics of hydrochar, including surface area, overall pore capacity, and mean pore diameter, experience improvements driven by the operational parameters of temperature and time in the microwave hydrothermal carbonization (MHTC) process. These conditions promote the degradation of rice husk structures, leading to enhanced porosity traits.[35] Such changes and porosity gains are supported by scanning electron microscopy (SEM) studies. Additionally, research on hydrochars from pistachio nutshells demonstrates that increased temperatures boost the Brunauer-Emmett-Teller (BET) surface area due to intensified volatile releases that encourage pore development.[47] Higher temperatures also lead to the breakdown of barriers between neighboring pores, thereby expanding pore dimensions.[46] Moreover, the interplay of processing duration and temperature notably affects surface area, with longer times and lower temperatures promoting greater surface areas.[48] These shifts in surface properties can be attributed to mass transfer mechanisms and thermal interactions within the MHTC system.

The crystal framework of rice husk and its resulting hydrochar, generated under conditions of 950 W microwave power, 225°C temperature, 35-minute duration, a 1:12 w/v solid-to-liquid ratio, and 3.5 mm particle size, was analyzed via X-ray diffraction (XRD), with findings displayed in **Figure 5**. Examination of the diffraction pattern revealed three distinct peaks at 2θ angles of 14°, 22°, and 36°, typical of cellulose.[49] These peaks lie within the 9° to 36° (2θ) range, pointing to the presence of amorphous carbon,[42] which signals successful carbonization of the rice husk. A comparative study showed the crystallinity index rising from 75.8% in untreated rice husk to 78.7% in hydrochar. This rise in crystallinity after microwave hydrothermal carbonization (MHTC) likely stems from the breakdown of amorphous components, such as hemicellulose and lignin,[50] found in the biomass. Lyu *et al*.[51] suggested that increased crystallinity in hydrochar mainly arises from the hydrolysis of cellulose and hemicellulose during hydrothermal processing. The influence of processing conditions, especially temperature, on crystallinity was observed, with elevated temperatures associated with diminished crystalline structures.

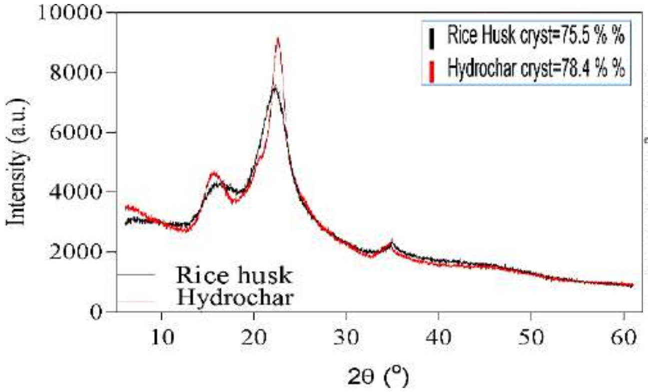

Fig. 5: XRD for both RH and hydrochar at 950 W, 225°C for 35 minutes, with a solid: liquid of 1:12 w/v, and a particle size of 3.5 mm.

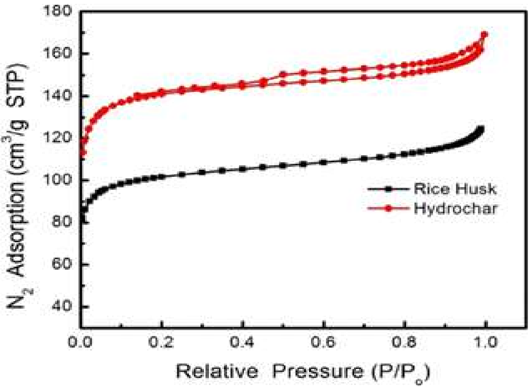

Fig. 6: N_2 absorption and release from RH and hydrochar conditions at 950 W, 225°C for 35 minutes, with a solid: liquid of 1:12 w/v, and a particle size of 3.5 mm.

Texture Based Properties

The nitrogen (N_2) adsorption and desorption isotherms for rice husk and hydrochar (**Fig. 6**), generated at 950 W and 225°C for 35 minutes, using a solid-to-liquid ratio of 1:12 w/v and a particle size of 3.5 mm. Notably, the hysteresis loop pattern indicates characteristics of both type I and type IV isotherms. Comparative evaluation shows that hydrochar demonstrates a markedly greater N_2 adsorption capacity compared to rice husk, attributed to elevated relative pressure driving N_2 molecules into larger pore networks, enhancing adsorption efficiency. This phenomenon highlights the increased prevalence of mesopores and micropores in the hydrochar. Initial N_2 uptake at lower relative pressures ($P/P_0 < 0.12$) points to significant micropore development, a consequence of the microwave hydrothermal carbonization (MHTC) process applied to rice husk, promoting pore creation. At higher relative pressures ($P/P_0 > 0.18$), the rise in adsorption aligns with the formation of mesopores and the expansion of micropores. Furthermore, a steady increase in N_2 adsorption at even higher relative pressures indicates an expanded micropore volume alongside the presence of smaller mesopores.

TGA/DTG Analysis

The thermal stability of rice husk and its hydrochar, created at 950 W, 225°C for 35 minutes with a 1:12 w/v ratio and a particle size of 3.5 mm, was evaluated using Thermogravimetric Analysis (TGA). This method measures the rate of mass reduction in a sample, either at a constant temperature over a period or as the temperature rises. Tests were carried out from 48 to 905°C at a heating rate of 11°C/min in a nitrogen environment (see **Figure 7**). Analyzing the thermal responses and weight loss patterns of hydrochar and rice husk highlights the impact of Microwave Hydrothermal Carbonization (MHTC) on their thermal resilience. Early slight weight loss below 145°C in both samples reflect moisture evaporation.[35] Significant breakdown occurs between 245-365°C for rice husk and 245-385°C for hydrochar, linked to the pyrolysis of cellulose and hemicellulose in these ranges. Hemicellulose specifically degrades at 185-310°C, while cellulose breaks down at 300-408°C.[52] As noted by Elagwu and Greenway,[12] the 215-415°C interval involves the cleavage of chemical bonds and the emission of low-molecular-weight volatiles, signifying cellulose and hemicellulose breakdown. After decomposition, a stable weight trend indicates considerable ash content in the samples.

Analysis of DTG Profiles for Thermal Decomposition Peaks

The DTG profile identifies peak points tied to the temperature of greatest mass reduction. For rice husk, a peak emerged at 328°C, possibly linked to cellulose degradation within the material.[43] In contrast, hydrochar displayed a peak near 373°C, suggesting enhanced thermal resilience after MHTC processing, aligning with prior studies.[53]

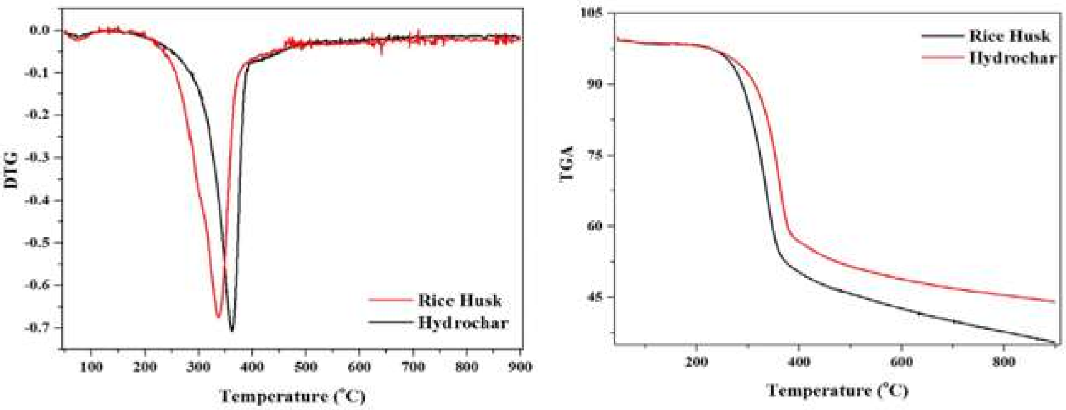

Fig. 7 TGA/DTG analysis was conducted on RH and hydrochar at 950 W, 225°C for 35 minutes, with a solid: liquid of 1:12 w/v, and a particle size of 3.5 mm.

Conclusion

This work initiates the exploration of Microwave-Assisted Hydrothermal Carbonization (MHTC) with rice husk, offering a thorough assessment of how essential variables—such as treatment time, temperature, water-to-biomass ratio, and grain size—impact hydrochar generation. Observations reveal that shorter processing periods, lower temperatures, decreased water-to-biomass ratios, and larger grains increase hydrochar yield. Notably, temperature and time significantly shape hydrochar characteristics. Through MHTC, rice husk, initially possessing a modest heating value (HHV), was transformed into hydrochar with superior energy density, porosity, and thermal endurance. Compared to raw rice husk, the HHV of hydrochar produced via MHTC showed a substantial increase. Post-MHTC, hydrochar exhibited elevated carbon content alongside diminished hydrogen and oxygen levels, boosting its energy efficiency and combustion attributes. The reduced Oxygen/Carbon and Hydrogen/Carbon ratios in hydrochar versus rice husk demonstrate MHTC's ability to improve the value of energy-poor biomass. Enhanced porosity, surface area, and heat resistance were also observed in hydrochar. Consequently, hydrochar derived from rice husk through MHTC holds considerable potential for applications in energy production, carbon sequestration, adsorption, and agriculture.

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