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Energy Exploration and Recovery via Microwave Processing of Waste Spent Tea into Micro-Fuel Production

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ABSTRACT

Thermochemical biomass conversion is an effective method for contaminant removal, energy recovery, and the production of environmentally friendly fuels. This study investigates the conversion of waste-spent tea (WST) into solid carbon micro-fuel using microwave-assisted processing under inert (N_2) conditions. Experiments were conducted using 3 g of WST, with varying microwave powers (300, 500, and 700 W) and irradiation times (10, 15, and 20 minutes). Optimal conditions were identified as 700 W power and 20 minutes of irradiation, resulting in enhanced fuel properties. Under these conditions, the high heating value (HHV) increased significantly from 4.31 kJ/kg (raw WST) to 6.58 kJ/kg, an improvement of 81.50%. Additionally, micro-fuel yield increased by 8.9%, and the fuel ratio improved from 0.79 to 0.86. Proximate and ultimate analyses, along with the Van Krevelen diagram, confirmed the improved fuel quality. The enhanced HHV and fuel ratio indicate that the produced micro-fuel is a promising candidate for solid carbon-based energy generation.

1. INTRODUCTION

Thermochemical conversion is a promising approach for achieving an environmentally sustainable atmosphere and generating biofuel to protect the planet [1, 2]. Extracting valuable resources from various waste feedstocks requires efficient and sustainable solid waste management. One innovative technique for recovering assets from organic solid waste as functional liquid fuels and chemicals is microwave processing [3]. The effective use of agricultural waste as an energy source for decentralized power generation and heating applications can help meet the growing energy demand in rural regions. Numerous sources, including forests, agricultural outputs, domestic refuse, fauna, food processing, and industrial operations, contribute to biowaste generation [3]. Tea, the second most consumed beverage worldwide after water, is enjoyed by nearly two-thirds of the global population [4]. It also contributes significantly to recyclable waste [5]. The overreliance on fossil fuels has exacerbated global warming and the impending energy crisis, highlighting the need for alternative energy sources to achieve green energy or energy neutrality. Recently, scientific researchers have developed innovative units to improve manufacturing efficiency through empirical investigation [6]. More than 90% of tea is discarded after consumption [7]. Tea leaf brewing waste, a lignocellulosic biomass byproduct, is produced during the tea brewing process in both domestic and industrial settings [8]. This waste includes clipped branches, seed shells, and tea dregs, all of which contain substantial amounts of lignin, cellulose, hemicellulose, and other organic components that promote the development of a porous structure and large surface area during thermal conversion [9]. Tea waste can be converted into biofuel or activated carbon using methods such as pyrolysis, hydrothermal carbonization, and gasification [10]. Chemical agents are often used to enhance the surface characteristics, functional groups, and structures of biochar or activated carbon. The MW process generates a significant volume of treated water containing dissolved organic compounds, minerals, and nutrients. The conversion of waste biomass into electricity plays a critical role in solid waste management. Thermochemical conversion techniques are known for their speed, simplicity, and cost-effectiveness, requiring minimal equipment while yielding solid carbon fuel. Since SWT is biomass, it can be transformed using various thermochemical processes, including microwave processing, pyrolysis liquefaction, gasification, and HTC processes. The amount of final product from the thermal conversion process is influenced by the temperature and residence time in the high-temperature reactor. Micro-fuel, a solid carbonaceous material, is obtained through the thermochemical conversion of biomass in an oxygen-free environment [11-17]. In the MW process, irradiation power plays a crucial role as it penetrates

the material in a closed system with a nitrogen flow rate, facilitating dehydration and decarboxylation processes [18]. The gap in this work lies in the thermochemical conversion technique, particularly the microwave process of WST, which depends on the microwave power and irradiation time [19]. Among recent advancements, microwave processing (MW) is emerging as a promising technique for bioenergy generation, waste treatment, and energy recovery [20]. This study tackles a significant research gap, as limited work has been conducted on the thermochemical conversion of WST using microwave irradiation. An innovative aspect of this work lies in applying a controlled range of microwave power levels (300, 500, and 700 W), selected based on the decomposition behavior of WST under thermal stress. The research introduces a novel approach to simultaneously address environmental pollution and energy recovery by transforming WST into eco-friendly micro-fuel. Unlike conventional thermal methods, this study systematically explores the effect of both microwave power and irradiation time, offering new insights into optimizing microwave-assisted fuel production from biomass waste.

2. MATERIALS AND METHODS

2.1 Waste spent tea preparation

The WST sample used in this research was collected from household waste generated by the daily consumption of tea. The sample was dried at 105℃ for 24 hours [21]. After drying, the material was manually crushed to obtain a powder with a particle size of 2 mm, resulting in a homogeneous and fine consistency.

2.2 Micro-fuel preparation

Figure 1 illustrates the framework of the microwave power process of WST to micro-fuel production. In the first experimental run, three WST samples were each weighed to 3 g and placed into small crucibles in preparation for microwave treatment. The samples were then irradiated for 15 minutes under varying microwave power levels of 300, 500, and 700 W. The resulting micro-fuel products were designated as micro-300, micro-500, and micro-700, corresponding to the applied power levels. In the second experimental run, three WST samples were each weighed to 3 g and placed into small crucibles in preparation for microwave treatment. This time, the microwave power was kept constant while varying the irradiation durations to 10, 15, and 20 minutes, respectively. The resulting micro-fuel products were designated as micro-10, micro-15, and micro-20, based on the irradiation times.

The microwave-assisted processes were conducted in an oven with a nitrogen (N_2) flow rate of 4 L/min to maintain an anaerobic environment. The microwave oven operated with an electric self-heating source rated at 1.5 kW and 220 V. The heating rate was set to 10℃ per minute. The oven was sealed and adjusted to the predetermined power level before each irradiation period. Nitrogen gas injection began 15 minutes prior to each experiment and continued until the process commenced.

After processing, the resulting micro-fuel was hand-milled, sieved, and stored for subsequent analysis.

2.3 Investigations

The micro-fuel yields were calculated according to Eq. (1). The loss in weight (carbonization loss) determined as in Eq. (2). High heating value (HHV) was determined using Bomb calorimetry in accordance to ASTM E711-87. HHV improvement was determined according to Eq. (3). The volatile matter (VM) was investigated by heating 1 g of WST and micro-fuel to 950℃, for 7 minutes [22]. The ash content was determined in accordance with the standard method ASTM D1102–84 (Reapproved 2013) utilizing an electric muffle furnace [23]. The fixed carbon (FC) and residue were measured to ascertain the weight differential, as illustrated in Eq. (4). Assuming the total weight is 100%, the fixed carbon content was calculated by subtracting the volatile matter and ash contents [24]. The fuel ratio is determined by dividing VM by FC % as in Eq. (5). The ultimate results of CHN components were calculated according to ASTM D-5672 and O was calculated based on ASTM D-1552. The atomic ratio was calculated by utilizing Eq. (6).

$$\text{Micro-fuel yield} = \text{solid produced / feed amount of WST} \quad (1)$$

$$\text{Mass loss \%} = 100 - \text{micro-fuel yield \%} \quad (2)$$

$$\text{HHV improvement \%} = \frac{\text{HHV of micro-fuel} - \text{HHV of WST}}{\text{HHV of WST}} \times 100 \quad (3)$$

$$\text{Ash \%} = 100 - \text{FC \%} - \text{VM \%} \quad (4)$$

$$\text{Fuel ratio} = \text{FC\%/VM\%} \quad (5)$$

$$\text{Atomic ratio} = \text{O\% / C \%, H\% / C\%} \quad (6)$$

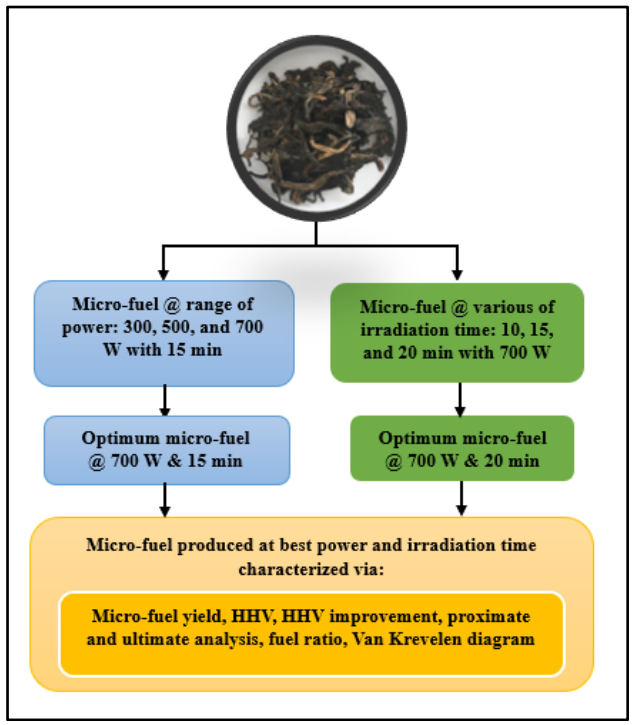

Figure 1. Methodology of microwave power process of WST into micro-fuel preparation

3. RESULTS AND DISCUSSIONS

3.1 Micro-fuel preparations

Micro-fuel production was successfully achieved under varying microwave power levels and different irradiation durations. Table 1 and Figure 2 the yield percentage of micro-fuel produced from WST under varying microwave power levels and irradiation times, respectively. In Figure 2(a), the yield increases progressively with higher microwave power: 83.22% at 300 W, 85.15% at 500 W, and 87.21% at 700 W, indicating that elevated power enhances the thermal decomposition and conversion efficiency of the biomass. In Figure 2(b), however, the yield decreases slightly with prolonged irradiation time: 89.54% at 10 minutes, 87.21% at 15 minutes, and 80.55% at 20 minutes. This decline may be attributed to increased volatilization and degradation of organic matter at extended exposure durations.

Correspondingly, the weight loss percentages were 16.87%, 14.84%, and 12.79% for micro-300, micro-500, and micro-700, respectively. These findings are consistent with those reported in previous studies [25-31]. According to Liu et al. [26] three main phases of mass loss occur during microwave treatment of WST: moisture removal at low power (300 W), transition at moderate power (300-500 W), and significant thermal decomposition at high power (500-700 W). Micro-300 and Micro-500 were classified as low-power samples in this study.

As the microwave power increased from 500 W to 700 W, the weight loss ratio increased further, reaching 19.45% at 700 W with a 20-minute irradiation time. Regarding the influence of irradiation time, the micro-fuel yields of WST showed a reduction in mass and volume with increasing irradiation durations (micro-10, micro-15, and micro-20). At a constant 15-minute irradiation, the weight loss was recorded as 12.79% at 700 W, 14.85% at 500 W, and 16.78% at 300 W.

Additionally, when holding the power constant at 700 W, the weight loss rates increased with time: 10.46% at 10 minutes, 12.79% at 15 minutes, and 19.45% at 20 minutes. These observations highlight the efficiency of thermochemical reactions, particularly decarboxylation and dehydration processes, under microwave irradiation.

3.2 High heating values

The HHVs of both raw WST and the resulting micro-fuel were examined under varying microwave power levels and irradiation durations. Table 1 and Figure 3 present the HHV outcomes corresponding to these conditions. Specifically, Figure 3(a) illustrates the variation in HHV with different microwave power levels, while Figure 3(b) shows the effect of irradiation time on HHV.

To assess the effectiveness of the microwave-assisted technique, the energy content of the produced micro-fuel was evaluated. The results revealed that the HHV of micro-fuel derived from WST was significantly higher than that of raw WST, confirming the efficacy of the microwave process [32]. Given that microwave power intensity is a crucial parameter in thermochemical conversion, samples treated with higher power exhibited improved thermal characteristics.

The HHV of micro-fuel increased with microwave power, reaching 6.11 kJ/kg at 300 W, 6.21 kJ/kg at 500 W, and 6.35 kJ/kg at 700 W, which aligns with SWT fuel enhancement criteria. Furthermore, extended irradiation times promoted greater oxygen elimination from WST, leading to an increase in HHV. As WST is predominantly composed of hydrocarbon-rich compounds, microwave treatment effectively enhanced its calorific value.

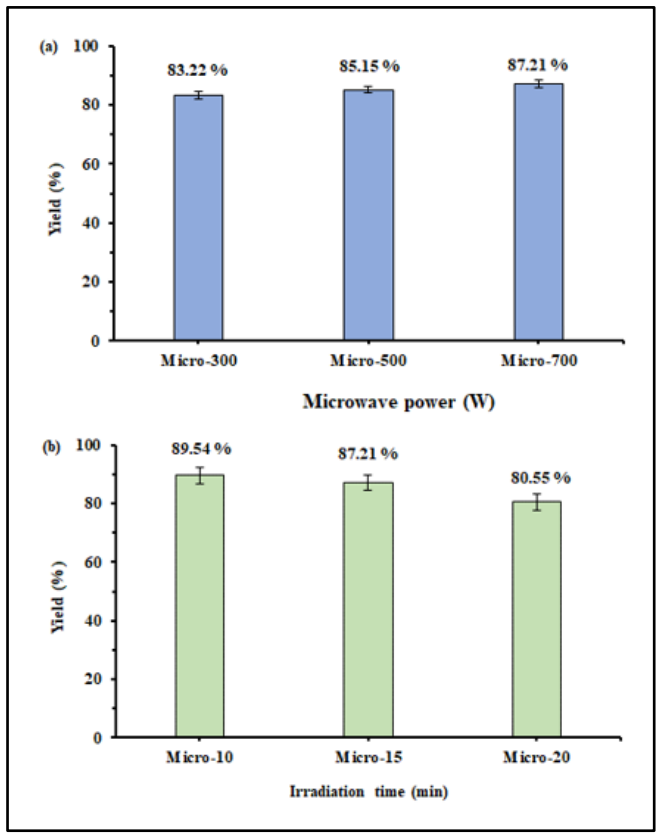

Figure 2. Micro-fuel yield of the WST via MW processes, (a) micro-fuel prepared at different power, (b) micro-fuel prepared at different irradiation times

Table 1. Micro-fuel yield, HHV, HHV improvement, of micro-fuel yield at different temperatures, and residence times

	SWT	Micro-fuel@ 15 min, & Different Microwave Power, W			Micro-fuel@ 700 W, & Various Irradiation Times, min		
		300	500	700	10	15	20
Micro-fuel yield, g	-	2.49	2.55	2.61	2.68	2.61	2.41
Micro-fuel yield, %	-	83.22	85.15	87.21	89.54	87.21	80.55
Mass loss %	-	16.78	14.85	12.79	10.46	12.79	19.45
HHV, kJ/kg	4.31	6.11	6.21	6.35	6.22	6.35	7.12
HHV improvement	-	41.76	44.08	47.33	44.31	47.33	65.19

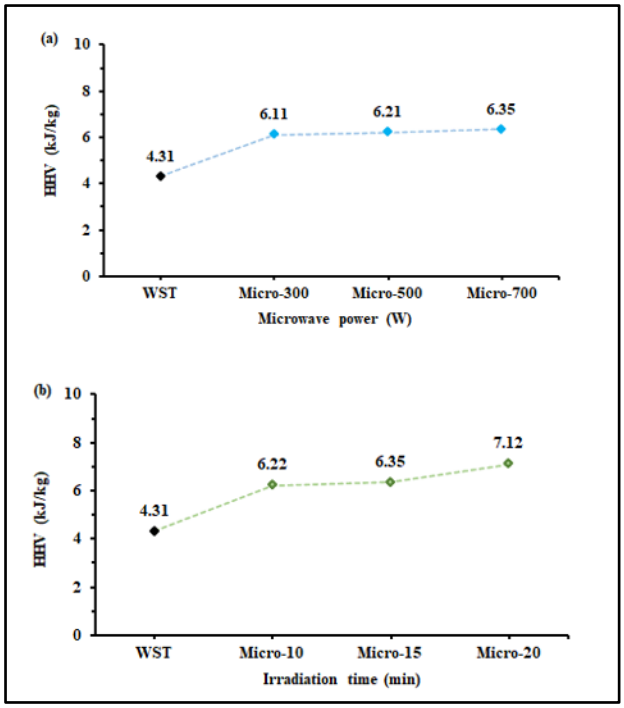

Figure 3. HHV of SWT and pyro-char, (a) pyro-char produced at different temperatures, (b) pyro-char produced at various residence times

At a constant microwave power of 700 W, the HHV improved significantly with increased irradiation time: from 4.31 kJ/kg for raw WST to 6.22 kJ/kg after 10 minutes, 6.35 kJ/kg after 15 minutes, and peaking at 7.12 kJ/kg after 20 minutes. These findings demonstrate the positive impact of microwave-assisted processing on fuel quality. The optimum condition for maximizing HHV was identified at 700 W and 20 minutes of irradiation time, consistent with observations reported in previous studies [30-36].

3.3 High heating value improvement

The improvement in the high heating value (HHV) of the prepared micro-fuel was evaluated under varying microwave power levels and irradiation times. Table 1 and Figure 4 present the HHV enhancement results under these different experimental conditions. Specifically, Figure 4(a) illustrates the HHV improvement with respect to different microwave power levels, while Figure 4(b) shows the HHV enhancement across various irradiation durations.

Initial results indicate that the percentage increase in HHV corresponds well with the improvement in fuel properties. The highest recorded HHV improvement was observed at 700 W for 20 minutes, achieving a 65.19% increase (MW@700 W–20 min). Moreover, the enhancement in HHV was found to be more significant with increased residence time than with changes in microwave power alone.

These findings confirm that longer irradiation durations contribute more effectively to improving fuel quality. Overall, the fuel properties of the micro-fuel were substantially enhanced in parallel with the observed HHV improvements [35-41].

3.4 Proximate and ultimate analysis

Table 2 presents the proximate and ultimate analyses of raw WST, micro-fuel produced at MW@700 W-15 min, and MW@700 W–20 min. The proximate analysis provides estimates of volatile matter (VM), ash (A), and fixed carbon (FC) content. A high percentage of VM typically results in prolonged, smoky flames and a reduction in HHV, whereas increased carbon content contributes to a higher heating value, characteristic of higher-quality fuels.

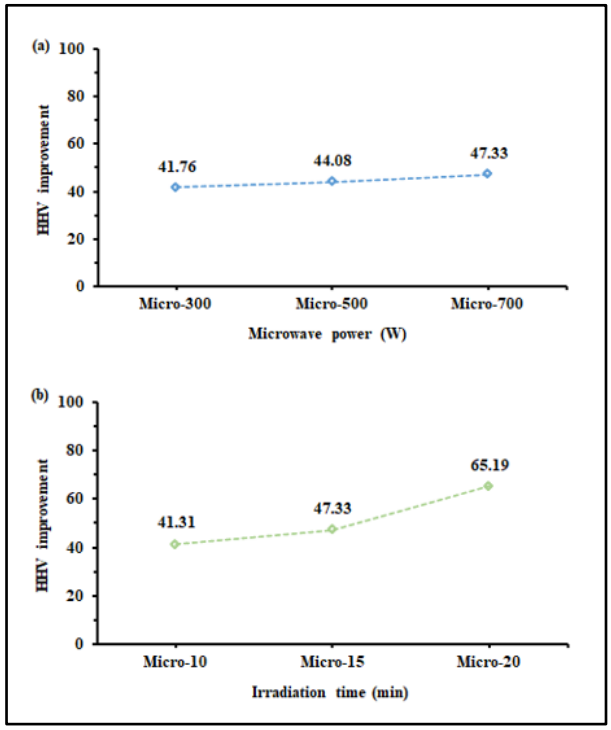

Figure 4. HHV improvement of micro-fuel, (a) micro-fuel prepared via microwave power, (b) micro-fuel prepared via residence times

The micro-fuel structure showed significant compositional changes in response to microwave treatment. Specifically, the VM content of WST decreased with increasing microwave power, while the carbon concentration in the micro-fuel increased. This indicates the successful transformation of the WST structure during the conversion process, leading to improved fuel characteristics. The ultimate analysis primarily examined the elemental composition of the micro-fuel, highlighting the enhancement in carbon content and reduction in VM.

The fixed carbon content of the micro-fuel was significantly higher than that of raw WST, particularly at elevated microwave power levels, confirming the positive effect of power intensity on carbon retention. A comparison with studies on other tea waste types reveals notable differences in elemental composition, which may be attributed to variations in soil characteristics and climatic conditions across different agricultural regions. This highlights the importance of selecting appropriate residual biomass sources to produce high-quality biofuels.

For instance, the study by Salman et al. [42] reported VM, carbon, and ash contents of 78.40%, 11.71%, and 3.55%, respectively, for tea waste. In contrast, our study found VM, fixed carbon, and ash contents of 40.96%, 32.73%, and 26.31%, respectively. Despite the general notion that high VM leads to poor fuel performance due to prolonged flames and reduced HHV, Salman et al. [42] reported an HHV of 20 MJ/kg for tea waste with 78.40% VM. This is inconsistent with typical expectations, suggesting possible overestimation.

Table 2. The proximate, ultimate analysis, and atomic ratio of WST and optimum micro-fuel

Characterizations		WST	MW@15 min-700W	MW@700 W-20 min
Proximate analysis	VM%	40.96	39.22	38.88
	Ash%	26.31	27.24	27.46
	FC%	32.73	33.54	33.66
Fuel ratio	FC%/VM%	0.79	0.85	0.86
Ultimate analysis	C %	38.55	41.54	42.12
	H %	7.22	6.12	6.08
	N%	3.59	3.21	3.16
	O%	50.64	49.13	48.64
Atomic ratio	O% / C%	1.31	1.18	1.15
	H% / C%	0.18	0.14	0.14

In our study, a maximum HHV of 7.12 kJ/kg (equivalent to 65.19% improvement) was achieved through optimized microwave treatment. Notably, Salman et al. [42] did not specify the ASTM standards used for HHV measurement, which may affect the reliability and comparability of their results.

3.5 Fuel ratio

The fuel ratio is a key indicator in determining the combustion performance of a fuel. Table 2 and Figure 5 present the fuel ratio values for raw WST, micro-fuel produced at MW@700 W-15 min, and MW@700 W-20 min. The highest fuel ratio value of 0.86 was achieved under optimal conditions at 700 W microwave power and 20 minutes of irradiation time. This marks a notable improvement from the initial fuel ratio of 0.79 observed at 15 minutes, indicating an 8.9% enhancement in micro-fuel properties.

The increase in fuel ratio, from 0.79 to 0.85 at 700 W for 15 minutes, and further to 0.86 at 700 W for 20 minutes, highlights the positive impact of prolonged irradiation and higher microwave power on fuel quality. A higher fuel ratio suggests a more efficient combustion process, with reduced CO_2 emissions compared to untreated WST.

This improvement demonstrates that the microwave-assisted process is effective in enhancing the combustion characteristics of the produced micro-fuel. The increase in fuel ratio through microwave treatment reflects a significant enhancement in the thermal and environmental performance of the alternative fuel.

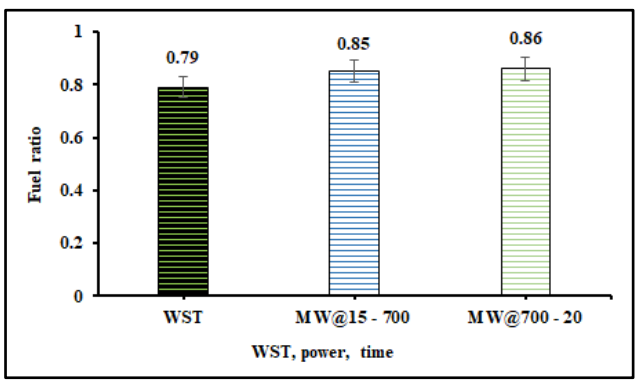

Figure 5. Fuel ratio of SWT, MW@15 min- 700 W, and MW@700 W- 20 min

3.6 Atomic ratio

The Van Krevelen diagram was analyzed based on the oxygen and hydrogen percentages divided by the carbon percentage to study the evolution of the micro-fuel. Table 2 and Figure 6 present the Van Krevelen diagram for raw WST, micro-fuel produced at MW@700 W-15 min, and MW@700 W-20 min. The diagram illustrates the effects of dehydration and decarboxylation, with arrows indicating the changes that occurred during the microwave processes (see Figure 5) are consistent with the findings of the studies [43-47].

The results show a decrease in hydrogen content, leading to a shift of hydrogen atoms along the carbon line, a consequence of the dehydration effects. Elemental analysis provides crucial insights into the chemical properties of the sample, while the ash content offers information on the reaction pathways involved. Table 2 details the carbon, hydrogen, and oxygen content, as well as the O/C and H/C atomic ratios.

The Van Krevelen diagram effectively illustrates the decarboxylation and dehydration reactions occurring during the microwave treatment, reflecting the chemical transformations that take place [48]. Several reactions, such as the release of CO, CO_2, and CH_4 gases, were observed as a result of the microwave process [49-52].

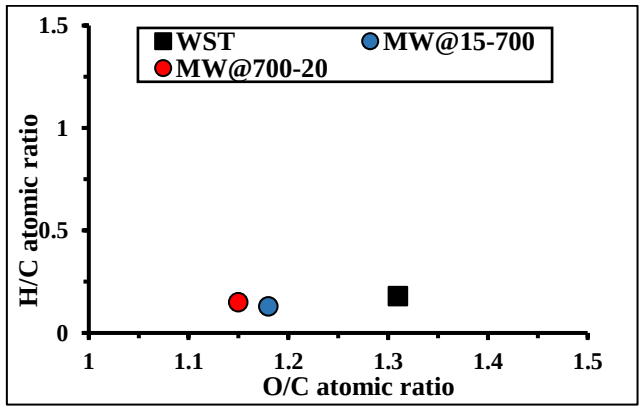

Figure 6. Atomic ratio of STW, MW@15 min-700 W, and MW@700 W-20 min

3.7 Assessment and life cycle analysis (LCA)

A theoretical LCA is applied to assess the microwave-assisted conversion of WST into micro-fuel. The assessment aims to quantify potential benefits and drawbacks, including energy efficiency, carbon emissions, and resource utilization. As shown in the Figure 7, the HHV exhibits a consistent upward trend with increasing microwave power and irradiation time, rising from 4.31 kJ/kg in the raw WST to a maximum of 7.12 kJ/kg at 700 W and 20 minutes. This reflects the enhanced energy content achieved through effective decarboxylation and dehydration processes. Similarly, the fuel ratio increases from 0.79 to 0.86, indicating improved

combustion properties due to greater carbon retention and volatile matter reduction. Conversely, mass loss also increases with treatment severity, reaching up to 19.45%, highlighting the thermal decomposition and release of light compounds. The overall pattern confirms that higher microwave power and longer exposure times significantly improve the fuel quality of WST, though with increased material loss an important trade-off for optimizing conversion efficiency.

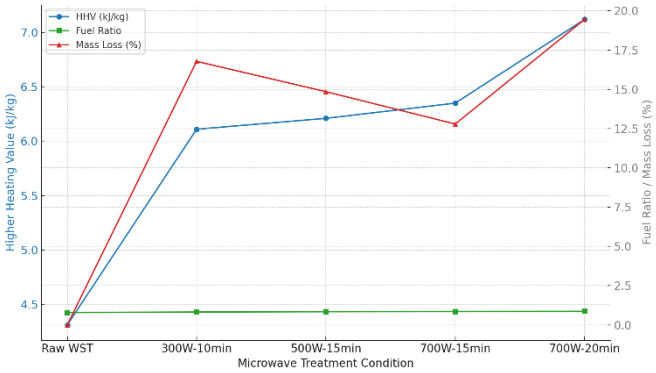

Figure 7. The effects of various microwave treatment conditions on the HHV, fuel ratio, and mass loss of WST

4. CONCLUSIONS

This study successfully demonstrated the conversion of WST into micro-fuel through the application of varying microwave power levels and irradiation times. The optimal condition was identified at 700 W and 20 minutes of irradiation, which resulted in a significant increase in the HHV from 4.31 kJ/kg to 7.12 kJ/kg, an improvement of approximately 65.2%. Additionally, the fuel ratio of WST was enhanced from 0.79 to 0.86 under the same conditions, confirming the effectiveness of the process.

The irradiation time of 20 minutes was found to be the most suitable for achieving efficient conversion. During the microwave-assisted process, several thermochemical reactions occurred, as indicated by changes in atomic ratios and the release of gaseous byproducts such as CO, CO_2, and CH_4. These gases contribute to improving the combustion characteristics of the produced micro-fuel.

The results underscore the importance of optimizing the relationship between microwave power and irradiation duration to enhance both energy content and combustion efficiency. Moreover, this process can be replicated across different scales. Furthermore, the high yield percentages (e.g., 87.21% at 700 W and 80.55% at 20 minutes) and substantial HHV enhancement (up to 7.12 kJ/kg) support the feasibility of scaling up for industrial applications.

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