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Short Communication

Rapid conversion of wet spent coffee grounds into high-calorific biochar via drying-free flame plasma pyrolysis for process intensification

Taejun Park [a,b,*], Gideok Park [c], Hyunseung Shin [c]

[a] Resources Utilization Division, Korea Institute of Geoscience & Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon, 34132, Republic of Korea
[b] Resource Engineering, University of Science Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, 34113, Republic of Korea
[c] Got tech co., Ltd., 301 busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 46241, Republic of Korea

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ABSTRACT

Conventional valorization of high-moisture biomass is economically constrained by energy-intensive pre-drying steps and prolonged residence times required by traditional pyrolysis. Herein, we report a novel process intensification strategy utilizing an atmospheric flame plasma to directly convert wet spent coffee grounds (moisture ~55%) into high-grade biochar within 90 s, entirely eliminating the need for dehydration or de-oiling pre-treatments. The intense heat flux from the LPG-based plasma jet triggered flash evaporation of the inherent moisture, inducing an in-situ steam activation mechanism termed the popcorn effect, which facilitated the development of a highly porous structure with a peak specific surface area of 115.4 m^2/g. Under the peak phenomenological condition (90 s), the process achieved a mass reduction of 83.3% and yielded a sulfur-free biochar with a higher heating value of 29.0 MJ/kg, surpassing that of standard anthracite. This study demonstrates that flame plasma pyrolysis provides a sustainable, energy-efficient, and ultra-fast pathway for waste-to-energy conversion, effectively turning the intrinsic moisture of biomass from a thermal burden into a functional activation agent.

1. Introduction

With the global surge in coffee consumption, over 10 million tons of spent coffee grounds (SCG) are generated annually [1]. Owing to their high carbon content and calorific value, SCG possess considerable potential as an energy resource. However, the majority of SCG are currently landfilled or incinerated, leading to environmental concerns such as greenhouse gas emissions and soil contamination [2]. Accordingly, to address the dual challenges of sustainable waste management and energy recovery, active research and optimization of various advanced thermochemical conversion technologies have recently been underway to efficiently convert diverse and complex biomass feedstocks into high-value energy [3,4,5,6,7].

Currently, established SCG valorization technologies such as torrefaction [8,10], hydrothermal carbonization (HTC) [3,10], and pyrolysis [11] face critical limitations when processing high-moisture (~55–60%) biomass. Torrefaction and conventional pyrolysis require extended residence times and energy-intensive pre-drying to reduce moisture, drastically increasing overall costs [4]. Similarly, fast pyrolysis strictly requires dried feedstocks to prevent excess water in the target liquid products. Although HTC directly processes wet biomass, it suffers from prolonged residence times (1–6 h) and extreme high-pressure operations, leading to high capital costs and complexity [3,12]. Furthermore, the intrinsic lipid content of SCG often promotes tar formation, necessitating additional defatting steps [13]. Plasma technology offers high energy density and rapid kinetics for biomass conversion [14,15]. However, previous plasma applications for SCG activation [16,17] and gasification [15,18] predominantly relied on pre-dried feedstocks and prolonged treatment times.

In this study propose a novel flame plasma pyrolysis (FPP) process that directly upgrades wet SCG (~55% moisture) into high-calorific biochar within 90s, completely bypassing conventional pre-drying. The high-enthalpy plasma triggers flash evaporation, utilizing the inherent moisture as an in-situ steam-activation agent to rapidly develop a porous structure. This study elucidates this mechanism and evaluates the resulting biochar properties for sustainable waste-to-energy conversion.

* Corresponding author at: Resources Utilization Division, Korea Institute of Geoscience & Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon, 34132, Republic of Korea.
E-mail address: tjpark@kigam.re.kr (T. Park).

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2. Materials and methods

2.1. Raw materials

SCG were collected from a cafeteria at the Korea Institute of Geoscience and Mineral Resources. The initial moisture content of the SCG was approximately 55 wt%. Unlike conventional pyrolysis studies, the SCG were used in their raw, wet state without any pretreatment. Proximate analysis (LECO TGA701) of the raw SCG revealed a composition of 74.55% volatile matter, 15.64% fixed carbon, and 1.13% ash, with a calorific value (LECO AC500) of 21.8 MJ/kg (Table 2). It should be noted that while the as-received SCG with ~55% moisture was directly used for plasma treatments, the sample was air-dried (8.68% moisture) solely for the standard proximate and calorific analyses. (See Table 1.)

2.2. Flame plasma carbonization of SCG

An atmospheric-pressure flame plasma system was employed for the rapid drying and carbonization of the SCG (Fig. 1). The flame plasma was generated using a commercial atmospheric pressure flame plasma device. Unlike conventional electrically-driven plasma torches, this system generates a high-temperature plasma jet by combusting a nearly ideal mixture of liquefied petroleum gas (LPG) and compressed air, thereby requiring minimal electrical energy consumption. The experiments were conducted in batch mode, with 30 g of wet SCG placed on the reactor stage for each run. The working distance between the plasma torch nozzle tip and the sample surface was fixed at 10.5 cm, maintaining the flame plasma temperature applied to the sample within the range of approximately 800–900 °C. To investigate the evolution of fuel properties over time, the treatment durations were 50, 70, 90, and 110 s.

2.3. Characterization of SCG-derived biochar

Process efficiency was evaluated via the weight loss of the plasma-treated SCG. The produced biochar was characterized using proximate analysis and calorific value measurements. Microstructural changes and pore formation were examined using scanning electron microscopy (SEM; JEOL JSM-IT200). Pore characteristics were determined by N2 adsorption–desorption isotherms at −196 °C (ASAP 2020, Micromeritics). Samples (~0.2 g) were degassed under vacuum at 300 °C for 4 h prior to analysis. The specific surface area (SBET) was calculated using the Brunauer–Emmett–Teller (BET) equation within a relative pressure (P/P0) range of 0.05–0.30. Total pore volume (Vtotal) and pore size distribution were determined at P/P0 = 0.99 and using the Barrett–Joyner–Halenda (BJH) method, respectively. All fundamental property evaluations were performed in triplicate (n = 3) to ensure reproducibility. The results are reported as mean values ± standard deviations.

3. Results and discussion

3.1. Reaction mechanism involving the synergistic effect of flame and plasma

Unlike conventional indirect heating, flame plasma carbonization simultaneously delivers an ultra-high heat flux and reactive radicals. While slow pyrolysis favors tar formation, direct plasma heating rapidly elevates biomass temperatures. As Kang et al. [1] demonstrated, such high heating rates fundamentally alter cellulose and lignin pyrolysis pathways, favoring syngas generation over condensable products (e.g., tar). This theoretically supports our observation that smoke and bio-oil generation were effectively inhibited during the process. Furthermore, the plasma plume provides abundant highly reactive radicals (e.g., O·, H·, and OH·). Materazzi et al. [12] indicated that these radicals aggressively attack the carbon bonds of volatile organics and nascent tar, causing immediate cracking and reforming. Specifically, oxygen radicals oxidatively decompose soot precursors (e.g., aromatics) into CO and H_2, effectively suppressing secondary pollutants while enhancing overall carbonization efficiency.

Table 1
Proximate analysis and calorific value of SCG (Air-dried basis).

Moisture	Volatile Matter	Ash	Fixed carbon	Calorific value
8.68%	74.55%	1.13%	15.64%	21.8 MJ/kg

3.2. Ultrafast conversion of SCG into high-calorific fuel

The most notable finding of this study is that wet SCG, with a high moisture content of 55 wt%, were converted into a high-calorific solid fuel in just 90 s without requiring any additional drying process. Remarkably, the plasma heat treatment solely achieved a weight reduction of approximately 83.3% without prior pretreatment. Additionally, the process proceeding in a clean manner, with almost no smoke or oil observed during treatment (Fig. 2). Unlike conventional pyrolysis which predominantly yields condensable heavy tars, the ultrafast heating rate and extreme temperatures of the flame plasma promote instantaneous secondary thermal cracking and in-situ steam reforming. Consequently, the volatile product distribution drastically shifts from heavy bio-oils to non-condensable, high-value syngas (H_2, CO).

Fig. 3 shows the changes in proximate analysis and calorific value as a function of plasma treatment time. As the plasma treatment time increased from 0 to 110 s, the volatile matter content decreased sharply from 74.6% to 39.1%, whereas the fixed carbon increased approximately threefold from 15.6% to 46.2%. Although the observed fixed carbon content is lower than that of anthracite (~80%), it is significantly higher than that obtained via conventional torrefaction (280 °C, 30 min, fixed carbon ~27%) [8] or hydrothermal carbonization results [4]. These findings suggest that the plasma treatment achieves higher carbon densification with significantly faster reaction kinetics.

The HHV of raw SCG (21.8 MJ/kg) peaked at 29.0 MJ/kg after 90 s of flame plasma treatment—an approximately 33% increase. This enhanced HHV is highly comparable to standard anthracite coal (25.1–29.3 MJ/kg) [9], highlighting the biochar's superior quality as a solid fuel. This ultra-fast conversion contrasts sharply with conventional torrefaction, which requires >30 min and pre-dried feedstocks to achieve a similar HHV (~28.5 MJ/kg) [21], clearly exemplifying process intensification. However, extending the treatment to 110 s decreased the HHV to 26.6 MJ/kg. This reduction implies a thermal overdose, causing oxidative burn-off of the carbon skeleton and a relative increase in non-combustible ash content (from 1.1% to 8.3%). Consequently, 90 s was identified as the targeted operating time for maximizing both energy yield and fuel quality.

The ultimate analysis of carbon, nitrogen, hydrogen, sulfur, and oxygen contents, presented in Table 2, provide quantitative evidence of the rapid carbonization and compositional upgrading of SCG induced by flame plasma treatment. The elemental oxygen (O) content was calculated by difference on a dry basis using the following equation: O (wt%) = 100 - C - H - N - S - Ash.

Marked carbon densification was observed as treatment time increased to 110 s, with carbon content rising from 53.0% to 67.1%. This ~1.27-fold enrichment drives the enhanced calorific value, as intense plasma heat flux and radicals cleave weak bonds in hemicellulose and cellulose, releasing volatiles and concentrating fixed carbon [23]. Concurrently, oxygen content substantially decreased from 32.9% to 18.0%, indicating improved fuel stability and energy density. The resulting reductions in H/C and O/C ratios signify a shift from the biomass to the coal region (e.g., lignite or anthracite) in the Van Krevelen diagram [24]. This rapid deoxygenation confirms the conversion of SCG into a coal-like fuel via the effective removal of oxygenated volatiles [25]. Environmentally, the initial sulfur content (0.19%) was completely volatilized and eliminated (0.0%) by the high-temperature

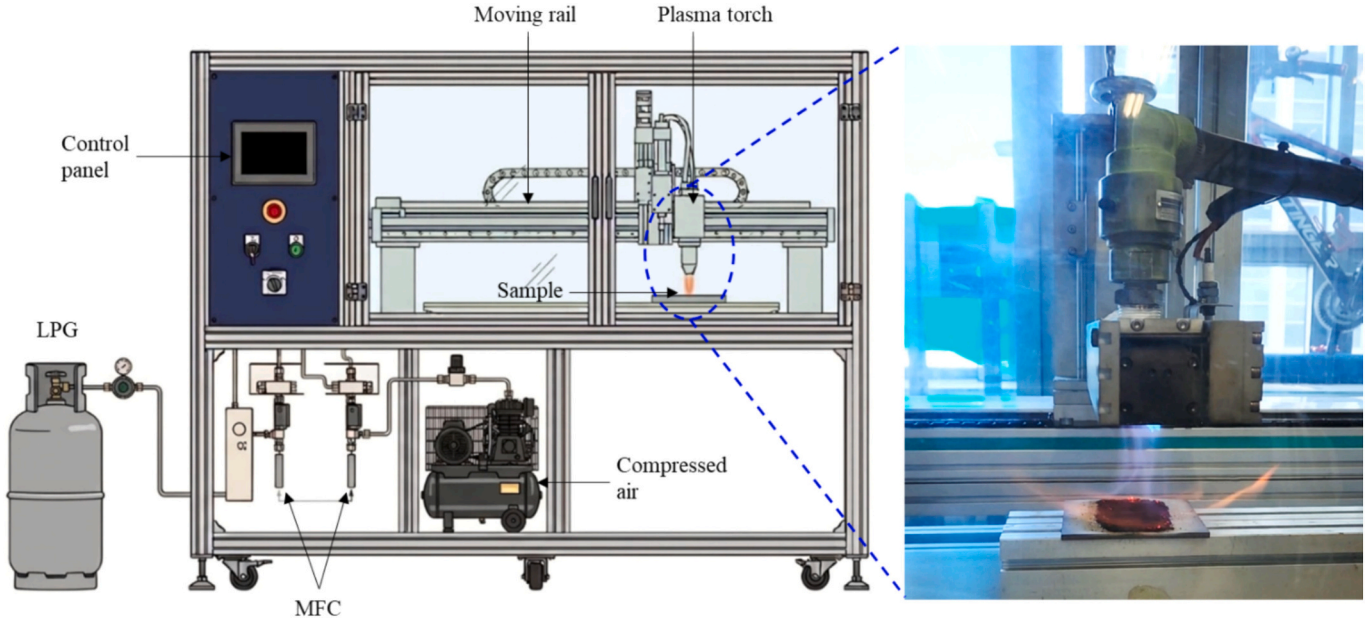

Fig. 1. Atmospheric-pressure flame plasma system.

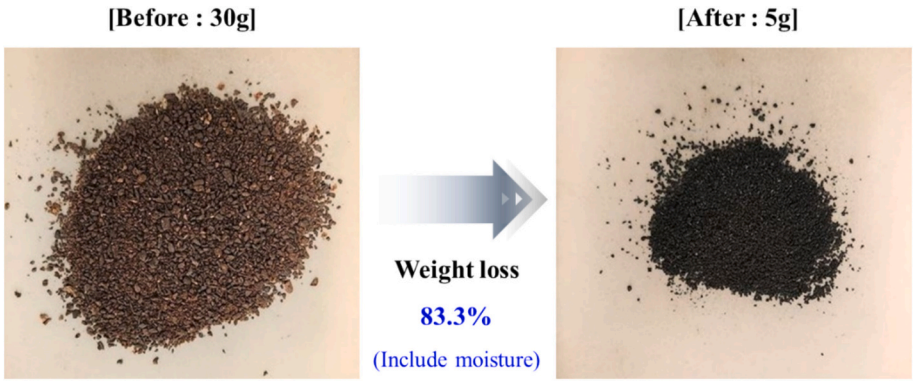

Fig. 2. Weight reduction of SCG after heat treatment using flame plasma.

plasma. Consequently, the produced biochar promises negligible SOx emissions during combustion. Collectively, these results demonstrate that flame plasma treatment rapidly (< 2 min) restructures SCG into a cleaner, carbon-rich, oxygen-poor, and sulfur-free solid fuel.

3.3. Devolatilization-driven pore formation and morphological evolution

The exposure time to the flame plasma induced a drastic morphological evolution of the SCG particle surface. SEM images (Fig. 4 **(a)**) clearly illustrate the structural distinction between untreated and plasma-treated SCG. While raw SCG retained a smooth, closed, and nonporous surface, the plasma-treated sample exhibited an open structure characterized by numerous macropores and surface cracks.

The development of porosity can be attributed to rapid devolatilization. The high heat flux delivered by the flame plasma instantaneously vaporizes internal moisture and oils, causing the internal pressure to increase beyond a critical threshold [18]. This process triggers a "popcorn effect" or "micro-explosion," resulting in the explosive ejection of gases from the particle interior [19,20]. This phenomenon not only increases the specific surface area but also lowers the mass-transfer resistance of oxygen during combustion (Fig. 4 **(b)**). These observations are consistent with reports on increased surface roughness is plasma-treated coffee grounds [1], suggesting that the resulting porous structure may be suitable for use as a functional carbon material, such as activated carbon or adsorbents. Although the successful formation of pores at the moisture content at the time of collection (~55 wt%) demonstrates the validity of this non-drying approach, future studies require comprehensive comparative research across various moisture concentration ranges to rigorously identify the optimal moisture threshold that maximizes this pore-activating "popcorn effect" relative to the thermal loss caused by water vapor evaporation.

Table 3 summarizes the BET analysis results for all treatment intervals. The specific surface area and pore evolution of flame-plasma-treated SCG were estimated in correlation with the observed SEM morphologies. In the initial stage (0–50 s), raw SCG exhibited a nonporous, smooth surface with a negligible specific surface area (~1.5 m^2/g), consistent with the characteristics of untreated biomass precursors reported in the literature [25]. Upon plasma flame exposure for 50 s, rapid moisture evaporation and initial devolatilization induced mechanical stress on the particle surface, likely initiating surface cracking and increasing the BET surface area to approximately 24.5 m^2/g.

During the activation stage (70–90 s), the treatment yielded a peak BET surface area of 115.4 m2/g at 90 s. An unpaired Student's *t*-test confirmed this phenomenological peak as significantly higher ($p < 0.05$) than adjacent timeframes (70 s and 110 s). This increase is driven by the

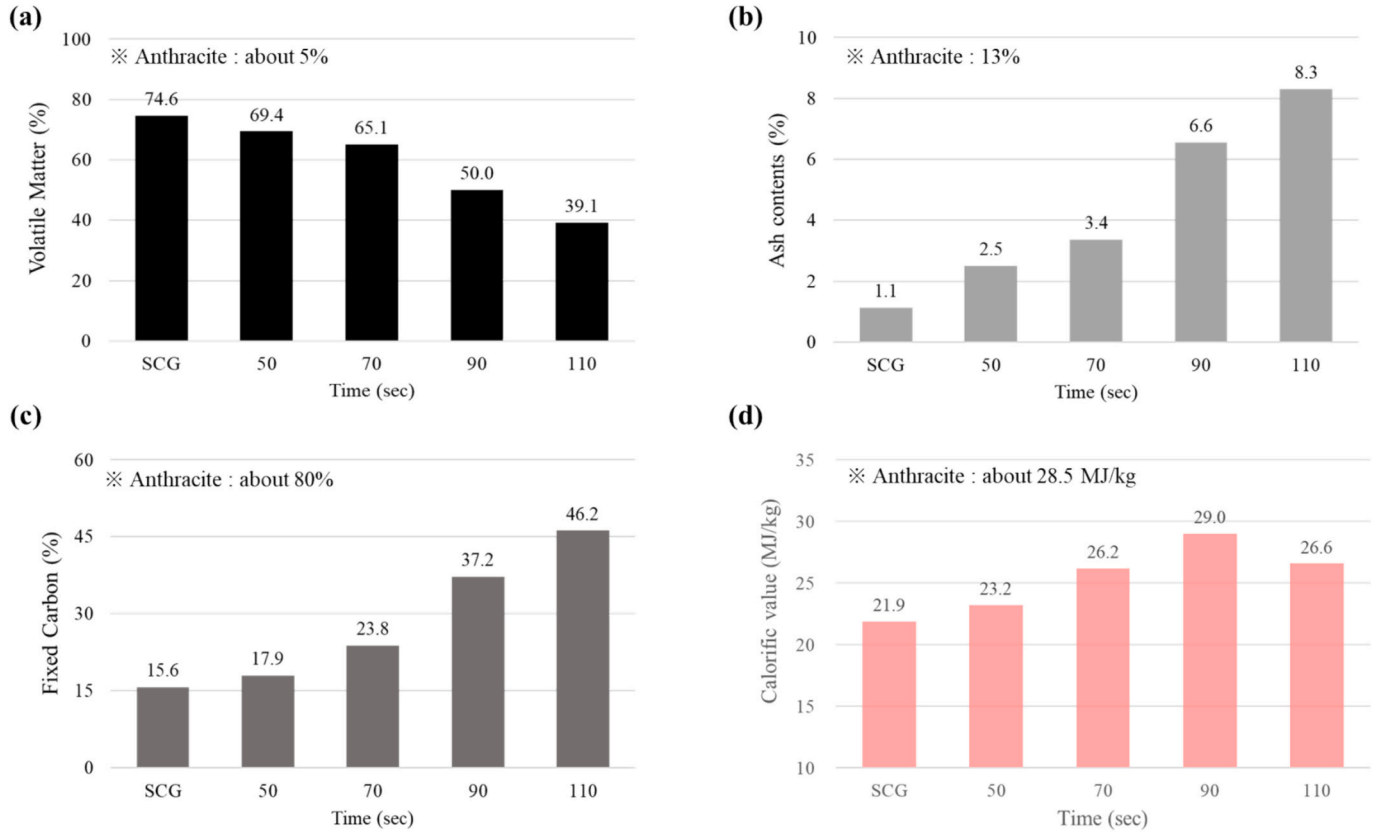

Fig. 3. Proximate analysis of SCG as a function of plasma treatment time: (a) Volatile matter content, (b) ash content, (c) fixed carbon content, and (d) calorific value.

Table 2
Ultimate analysis results of flame plasma treatment of SCG.

Time (*sec*)	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Ash (wt%)	Oxygen* (%)
Raw SCG	53.0 ± 0.5	7.0 ± 0.3	2.4 ± 0.2	0.19 ± 0.1	1.13 ± 0.3	36.28 ± 0.7
50	44.8 ± 0.3	0.03 ± 0.01	0.0 ± 0.0	0.10 ± 0.1	2.50 ± 0.2	52.57 ± 0.4
70	54.0 ± 0.4	0.08 ± 0.01	0.0 ± 0.0	0.10 ± 0.1	3.40 ± 0.3	42.42 ± 0.5
90	62.8 ± 0.2	0.10 ± 0.01	0.0 ± 0.0	0.10 ± 0.1	6.60 ± 0.5	30.40 ± 0.5
110	67.1 ± 0.5	0.01 ± 0.01	0.0 ± 0.0	0.00 ± 0.1	8.30 ± 0.6	24.59 ± 0.8

* Oxygen was calculated by difference.

intense plasma heat flux, which accelerates volatile emission and triggers a "popcorn effect." The rapid release generates internal pressure, expanding the carbon matrix to form a well-developed porous network. This aligns with Kosheleva et al. [22], who observed significant porosity improvements in optimized food-waste biochar. Consequently, 90 s represents the targeted carbonization point, maximizing the removal of pore-blocking materials without compromising structural integrity. Finally, during the degradation stage (110 s), the surface area decreased to 65.5 m2/g, although SEM images revealed larger, more distinct pores.

This apparent discrepancy can be attributed to a "pore widening and collapse" mechanism caused by over-carbonization. Previous studies [18,22,25,26] have suggested that excessive heat exposure or prolonged residence time triggers severe ablation of the carbon walls, causing micropores (< 2 nm), which contribute most to the specific surface area, to merge into mesopores or macropores (> 50 nm). Consequently, while the macropores became more visible in SEM images, the total available surface area drastically decreases owing to the loss of microporosity. Furthermore, the increased ash content (8.3%) at 110 s suggests that mineral sintering may have occurred. At high plasma temperatures, accumulated minerals can melt or agglomerate, block pore entrances, and physically obstruct access to the internal pore network, thereby reducing the measured surface area.

3.4. Quantitative metrics for process intensification and scale-up feasibility

To substantiate the process intensification of drying-free FPP, quantitative metrics were evaluated at the targeted 90 s treatment. The process achieved a mass yield of 37.0%, an energy yield of 49.1%, an energy density enhancement of 32.8%, and a carbon yield of 51.7%. This ultra-fast reaction represents a 90–120 fold reduction in residence time compared to conventional methods [12], exponentially magnifying throughput. Furthermore, by completely bypassing the massive latent heat penalty of pre-drying, the system achieved a competitive specific energy consumption (SEC) of ~154 MJ/kg$_{char}$. For industrial scaling (e.g., continuous rotary kilns), integrating sensible heat recovery from exhaust and in-situ steam will further minimize SEC and OPEX. Ultimately, the compact FPP system enables decentralized, on-site integration, eliminating high-moisture waste transportation burdens. Detailed energy balances and SEC calculations are provided in the Supplementary Information (Text S1, Table S1).

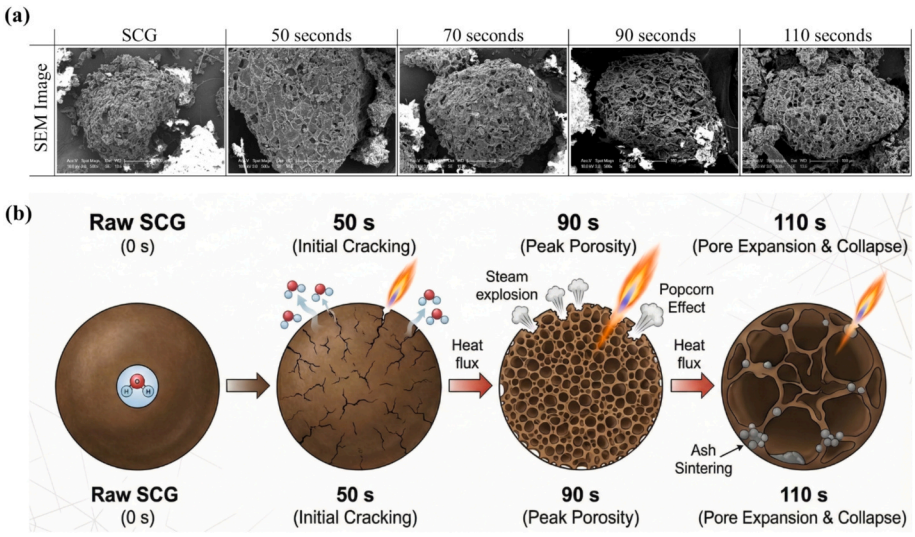

Fig. 4. Pore structure evolution of SCG as a function of exposure time under flame plasma treatment. (a) SEM images at different exposure times. (b) Schematic illustrating the transformation from non-porous raw SCG to peak porosity and eventual collapse with extended treatment.

Table 3
Surface area and pore characteristics of flame-plasma-treated SCG as a function of treatment time.

Treatment time (s)	Surface area (m^2/g)	Pore characteristics and evolution
SCG	1.5 ± 0.2	**Nonporous structure** (Smooth surface with closed pores before pretreatment)
50	24.5 ± 1.1	**Devolatilization onset** (Microcrack formation due to moisture evaporation and initial release of volatile matter)
70	72.0 ± 2.4	**Pore development** (Accelerated mesopore formation with active release of volatile substances)
90	115.4 ± 3.5	**Peak activation (Maximum porosity)** (Maximization of porosity due to rapid gas emission)
110	65.6 ± 2.5	**Structure collapse and ash blockage** (Excessive thermal shock leading to pore coalescence)

4. Conclusion

This study demonstrated a breakthrough process intensification strategy that utilizes flame plasma to directly convert wet SCG (moisture ~55%) into high-quality biochar without any pre-drying or de-oiling steps. The process was completed within a remarkably short time (< 2 min), achieving a mass reduction of 83.3%. The biochar produced under the optimal condition (90 s) exhibited a superior calorific value of 29.0 MJ/kg, surpassing that of anthracite, with complete removal of sulfur content. The results elucidated that the inherent moisture in the biomass acted not as a hindrance but as an agent for flash evaporation and in situ steam activation under a high-enthalpy plasma jet. This mechanism facilitated the development of a highly porous structure and accelerated the carbonization reaction. Consequently, the proposed flame plasma pyrolysis method offers a sustainable and energy-efficient pathway for the valorization of high-moisture organic waste, effectively overcoming the economic and technical bottlenecks associated with conventional drying-based processes.

CRediT authorship contribution statement

Taejun Park: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Gideok Park:** Writing – original draft, Methodology, Investigation, Data curation. **Hyunseung Shin:** Validation, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cej.2026.176452.

Data availability

Data will be made available on request.

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