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Characteristics Evaluation of Torrefaction Effects on Spent Coffee Ground Derived Biochar

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Abstract

A number of technological factors, primarily the kind of feedstock and temperature of thermal treatment can influence the characteristics of biochar by differentiating products having a broad variety of pH, specific surface area, pore volume, volatile matter, ash, and carbon content etc. This study investigated comparative analysis of spend coffee ground biomass of three different cities Jaipur, Kolkata and New Delhi (originally produced Ratnagiri Estate, Orissa and Karnataka respectively). TGA-DTG analysis of all SCGs biomass were performed to find their thermal decomposition range. Biochar was produced from SCGs at torrefaction range between 250°C to 350°C. SCGs derived biochar produced from all three biomass, were then characterized by different analytical methods, Brunauer-Emmet-Teller, Fourier transform infrared for investigation of total surface area, porosity and functional groups attached on the biochar surface respectively. Surface morphology of the biochar with highest surface area was further characterized using Scanning electron microscopy. The results of this study revealed that the biochar produced after torrefaction at 300° C derived from Kolkata state's biomass, offered a maximum surface area of 20.686 m^2/g with biochar yield of 63% and maximum functional groups presence on its surface which makes its suitable for bioremediation.

Key Words: *SCGs Feedstock, Torrefaction, Biochar, Comparative analysis, Surface area.*

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1. INTRODUCTION

Production of coffee takes place in almost 80 countries, making it the second most traded commodity and one of the most drank beverages globally. The coffee bean was the second most traded financial derivative internationally. According to International Coffee Organization (ICO) there were over 8 million tons of coffee beans transacted globally. About 0.91 grams of spent coffee grounds (SCG) are produced for every gram of coffee produced, meaning that at least 6 million tons of SCGs are produced annually worldwide. The herbaceous plant that yields coffee beans has lignin, hemicelluloses, cellulose, and fats in addition to caffeine [1]. After coffee beans are pulverized and soaked to produce energy, they are eventually converted into SCGs. The potential of SCGs for use as fertilizers [2], solid fuels [3], adsorbents for the removal of metal ions and gases [4], and many other applications has already been the subject of research. Biochar formed from SCGs has many benefits, such as low cost, high hydrophobicity, and environmental friendliness. It may be used for a variety of tasks, such as soil amendment, water treatment, environmental cleanup, and as a coal substitute fuel [5]. Three temperature ranges have been recorded for the thermochemical conversion of SCG biomass, according to the literature survey: torrefaction (200–300 °C), pyrolysis (350–800 °C), and gasification (750–1000 °C). Pyrolysis is primarily utilized to create liquid biofuels like bio-oil, whereas torrefaction is typically used to create solid fuels like charcoal [6]. Therefore, regulating the thermochemical reaction temperature of biomass is necessary to produce varied quality and yield of manufactured products. The yields of solid and liquid products often decrease as temperature rises [7]. The process of torrefaction, whether applied to biomass in an oxygen-depleted environment or with continuous N_2 flow, can optimize the retention of lipids in the biomass and improve the yield of lipid-rich biochar.

Torrefaction is a thermochemical process that turns biomass into a substance that resembles coal by gradually heating it. The findings of both the preliminary and final analyses indicated that torrefaction had a beneficial effect on the biomass samples[8]. By torrefaction, SCG can be transformed into high-value fuel. More sugars, fibers, proteins, and substances like fatty acids, aldehydes, ketones, alcohols, hemicelluloses, cellulose, or lignin are present in higher concentrations for this conversion. Torrefaction occurs in an oxygen-deficient atmosphere at a moderate temperature of 200 to 300 °C. Reduced heating rates are another feature of torrefaction that is added to this temperature parameter[9]. Torrefaction's primary advantage is the turn of biomass samples into premium fuels with higher energy densities and lower atomic ratios. The hydrophobic qualities of torrefied biomass facilitate effective handling, storage, and long-distance transportation. Research showed that the fixed carbon content improved with increasing torrefaction temperature (200–300 °C) and residence time (0.5–1 h)[10]. Additionally, the torrefaction of SCG biomass improve SCG's specific surface area and hydrophobic nature. Furthermore, the torrefied process's H/C and O/C atomic ratios for SCG biomass were found to be between 0.93 and 1.0 and 0.19 and 0.20, respectively. Between 250 and 300 °C, a notable rise in the output of volatile compounds was noted. The C content rose from 52.8 weight percent at 200 °C with 0.5 hours of residence time to 69.5 wt % when the torrefaction temperature raised to 300 °C with 1 hour[10]. The elimination of volatiles, tars, lignin degradation, and oxygenated species loss from the pores with the formation of a network of pores may have contributed to an improved porous structure throughout the torrefaction process of SCG samples [11]. This article mostly concentrated on the torrefaction procedure for thermal treatment of SCGs biomass because of all these previously achieved results. The physiochemical features of carbon-based products derived from biomass are clearly influenced by the source biomass feedstock's characteristics, the biomass conversion methods used, and the processing parameters [12].

The phrase "spent coffee grounds" can be used to describe both the coffee grounds obtained from the soluble coffee industry and those made after brewing at home or in cafeterias. Compared to wasted coffee that is acquired after brewing in homes or cafeterias, industrial used coffee components are eliminated much more successfully, producing residues that are more chemically depleted[13]. Even though the genus Coffea has 130 species and seven intraspecific taxa[14], the two species that dominate the global coffee trade are Arabica (Coffea arabica), which accounts for over 60% of traded coffee, and robusta (Coffea canephore), which accounts for the remaining 40%[15]. India is one of the world's leading producers of coffee, with an estimated 3.74 lakh metric tons produced in 2023–2024[16]. It is believed that Indian coffee is the best coffee in the world, produced in shade instead of direct sunshine[17]. With a staggering output of 2.66 lakh metric tons, the southern Indian state of Karnataka is the country's greatest producer of coffee. India produces 71.3% of its coffee in Karnataka alone. A Rainforest Alliance-certified farm, Ratnagiri Estate is located in the South Indian Western Ghats, close to Bababudangiri, the birthplace of coffee in India. The farm is home to Arabica and pepper with a diverse and rich ecosystem. State of Orissa produces Arabica coffee. The majority of the coffee cultivated here comes from forests, which use sustainable methods like growing in the shadow of big trees. As with most biological feedstocks, it should be noted that the compositions of SCGs vary greatly according on a variety of parameters, including the brewing technique, growing circumstances, and kind of coffee. Previous research has focused on understanding how reaction conditions and biomass parameters affect the production, yield, and efficiency of biochar and hydrochar. On the other hand, some earlier studies assessed the properties of biochar produced from SCGs for various uses. The characteristics of the SCG feedstock that was gathered from three different cities Jaipur, Kolkata and New Delhi (originally produced Ratnagiri Estate, Orissa and Karnataka respectively) and used to make biochar by torrefaction have been the main subject of this paper. Analysis of the comparative features of three distinct SCGs' biomass-derived biochar produced by torrefaction, which hasn't been frequently documented in the literature before.

2. MATERIALS & METHODS

SCGs sample were collected from Ministry of Roster House Coffee Shop, Malviya Nagar, Jaipur, Flurys Acropolis mall, Kolkata and Starbucks New Delhi. After collection SCGs were dried to remove residual moisture. The SCGs which was producing at these three coffee houses, were receiving raw coffee beans from three different states. Jaipur's coffee house from Ratnagiri Estate, Kolkata's coffee house from Orissa and North Eastern Region and New Delhi's Starbucks from Karnataka. All coffee waste samples were gathered, air dried, and then oven dried for the entire night at 105 °C in a Sanco, India, hot air oven. The dried samples were crushed to a particle size 2-3 mm and stored in the air tight poly bags for further use. Before experiment the dried SCGs biomass were screened using a 0.5 mm mess sieve to make the particles uniform. During the study all collected biomasses were assign the samples name as SCGR, SCGK, and SCGD for Rajasthan, Kolkata and Delhi samples respectively. After torrefaction process at desired temperature, produced biochar has been indicated in this study as SCGR250, SCGK300, and SCGD350 for Rajasthan, Kolkata and Delhi samples respectively.

3. Characterization of SCGs biomass

3.1 Analysis of the Proximate and Ultimate

The proximate, ultimate, and pH study results demonstrate that SCGs' chemical composition varies both before and after torrefaction exposure. The presence of carbon, hydrogen, nitrogen and oxygen compositions of SCGs is typical of lignocellulosic biomass materials [18]. Since SCG has a carbon content of about 50.26% wt, it is regarded as a typical lignocellulosic biomass. Additionally, SCG has a lower range of nitrogen (1.77% wt.) and a larger content of hydrogen (6.29% wt.), both of which are advantageous for thermochemical conversion processes. Reduced nitrogen concentrations result in less nitrous compound emissions during the thermochemical conversion process.

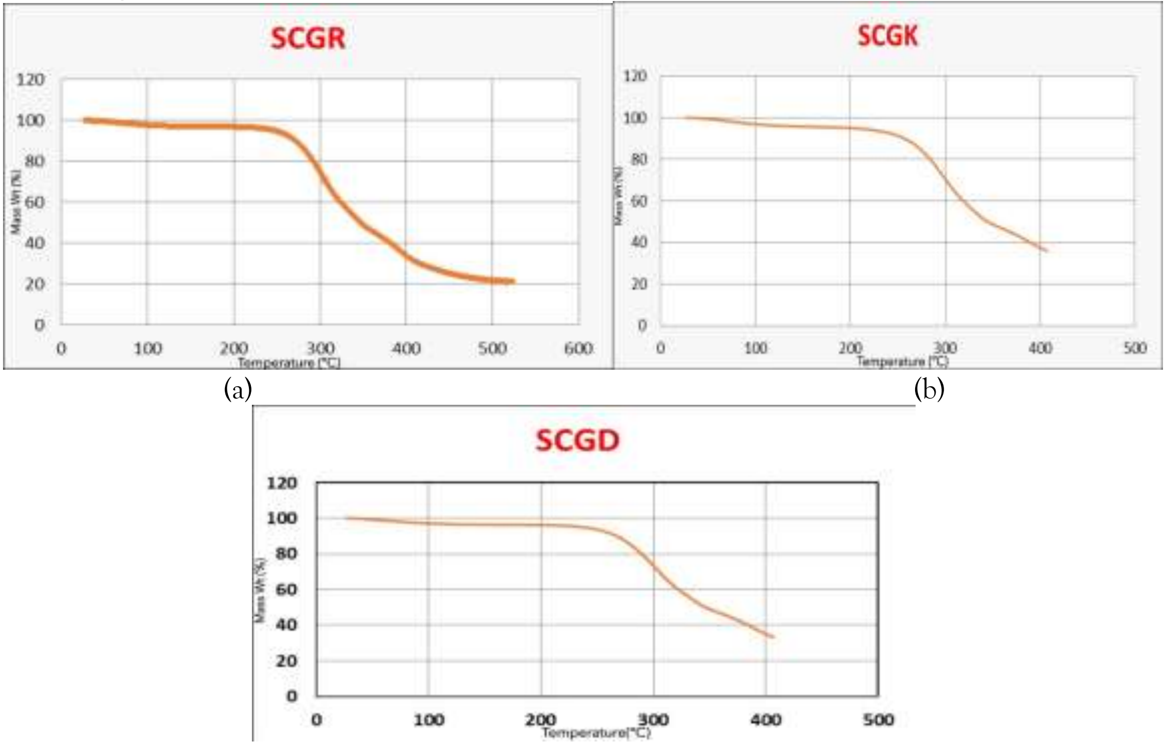
3.2 Impact of pH on Product 's Quality

The pH of the produced biochar was measured by using a calibrated pH meter (Eutech, 2019). Sample of SCGs was mixed with water at a 1:10 and shaked for 1 hr at 150 rpm before measuring pH. The SCGs biochar formed at all three-torrefaction temperature, were found alkaline in nature with the pH range SCGR250 (7.2), SCGK300 (8) and SCGD350 (9.3) respectively while the raw samples of biomass were acidic with pH value SCGR (pH 5.2), SCGK (5.6) and SCGD (4.8) respectively. pH has a specific effect on the charge on the adsorbent surface, the degree of dissociation of different functional groups on the adsorbent, and the ionization of the adsorbate [19]. The reason why alkaline biochar works so well at eliminating cations is because it maintains negatively charged surface sites in a range of neutral and acidic water solutions.

3.3 Thermal stability and composition analysis using TGA and DTG Techniques

The most widely used thermal analysis method for lignocellulosic materials is thermogravimetric analysis (TGA), which typically aims to determine the mass changes and thermal degradation of the organic materials. Understanding a substance's behaviour during thermal degradation is a crucial skill. To ascertain the thermal stability of all SCG biomass samples—SCGR, SCGK, and SCGD—collected from three distinct cities, thermogravimetric analysis (TGA) (Toledo-Mettler, USA) was carried out (Figure.1).

The decomposition rate of the SCG's biomass increased linearly with increasing heating rate, indicating that the heating rate had a substantial impact on the biomass thermal decomposition. SCG biomass was subjected to thermal analysis in a nitrogen environment. at 25 °C to 400 °C, heating at a rate of 10 °C per minute. The residual mass percentage plotted over a range of temperatures yielded the TGA curves. After the decomposition of volatile materials occurred between 200 and 400 °C, the first mass loss in the biomass sample was determined using the moisture content in the biomass from 150 to 200 °C. At temperatures as high as 200° C, the stage takes place, indicating the dehydration and elimination of the precursors' mild volatile matter content.



(a) (b)

(c)

Fig. 1 TGA-DTG analysis of SCG biomass, (a)SCGR, (b)SCGK and (c) SCGD samples

A biomass sample of approximately 23 mg of SCGs was tested for every TGA assay. There is an additional phase that happens when the temperature rises above 200° C. This phase is known as the active phase and is defined by pyrolytic volatile combustion. At these stages, hemicellulose (220-315 °C), cellulose (315-400 °C), and lignin (160-900 °C) broke down as the fundamental lignocellulosic building components [20]. To carry out the torrefaction of biomass samples, three distinct thermal decomposition ranges were found based on the TGA-DTG analysis

3.4 Torrefaction processes and characterization of produced biochar

The scientific community has come to favour the thermochemical process of torrefaction due to its ability to enhance the performance of biomass-based products while consuming less energy. N_2 is often utilized as an inert gas during the torrefaction process to prevent oxidation. In these circumstances, two factors that significantly affect the quality of biochar are temperature and length of stay. To remove any moisture, the SCG samples were dried in an oven for an entire night at 105 °C before to torrefaction. After undergoing a temperature torrefaction in an inert environment, the biomass of SCGs was converted into biochar. The Torrefaction process was used in a quartz tube furnace (Model TF/21092023, Ants Innovation (Mumbai). About 20 g of SCG biomass were loaded into an alumina crucible for each experiment, and it was then placed in the tube furnace's hot zone (hot zone size (mm) ID: 70, L 300, uniform hot zone length 100). In varying time intervals, the samples were torrefied at 250, 300, and 350 °C. For the duration of the torrefaction process, the heating rate and residence time were maintained at 10 °C per minute and 60 minutes, respectively. Samples were held in the furnace for 60 minutes, after that they were allowed to cool to 100 °C while N_2 was continuously supplied.

Fig .2 Production Methodology of Biochar derived from SCGs Biomasses

The resulting biochar was then stored in desiccators to continue cooling. After every experiment involving torrefaction, the biochar was weighed, cleaned to eliminate any ash residue, and dried for two hours at 105 °C. Finally, after getting cooled it was collected for characterisation. The torrefaction process is schematically depicted in Figure .2.

3.5 Effect of temperature on biochar yield

To determine the distribution and composition of other products, the yield of biochar must be computed. Fixed carbon and lignin concentration are directly correlated in biomass [21] yet, both lignin and fixed carbon values are essential for determining the potential biochar yield for any given biomass [22]. Furthermore, the ultimate biochar yield is determined by a combination of the operating temperature and the heating rate during the pyrolysis process. In contrast to gas flow rate, a recent study found that temperature and heating rate were the most important determinants of biochar production [23]. Because the lignin and cellulose content of biomass varied and organic matter was converted to ash, which decreased the carbon content of the biochar, the production of biochar dropped as the temperature rose due to the higher burning rate[24]. The following formula was used to determine the biochar's conversion efficiency [25].

$$Yield\ of\ Biochar\ = \frac{Weight\ of\ Biochar(g)}{Weight\ of\ dry\ SCG\ feedstock(g)} \times 100$$

The yield percentage of biochar varied from 51 to 88%, and it showed a declining tendency as temperature increased. A temperature of 250 °C produced the highest biochar output (88%). The torrefaction process's higher temperature range (300) resulted in a significant reduction in charcoal yield (63%) and the largest reduction (51%) at 350 °C. The temperature range of 250 to 300 °C, which is significant for torrefaction, was shown to have a rapid yield loss rate (Figure 3).

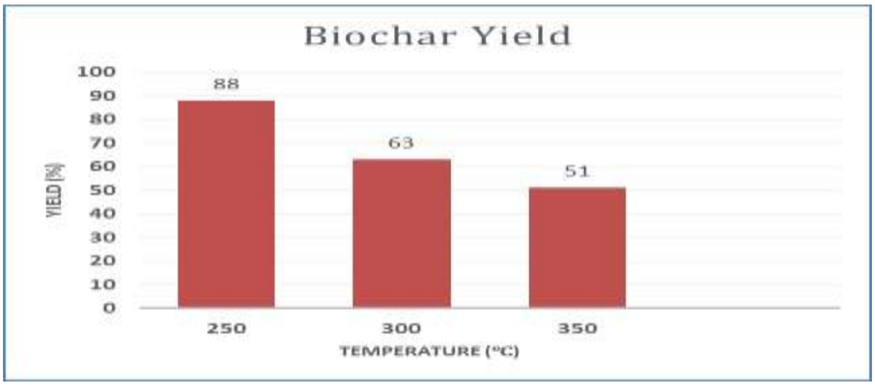


Fig.3 Biochar yield variation at different temperature

3.6 Identification of functional groups present on surface

The first stage in material analysis is frequently Fourier transform infrared (FT-IR) spectroscopy. A shift in the spectrometer's absorption band characteristic patterns points to a potential contamination or a change in the material's composition. Using measurements of the samples' diffuse reflection of infrared light, which provides the surface polarity or surface charge for chemisorption, surface functional groups were identified based on the radiation's absorption at particular frequencies [26]. With FT-IR Spectrum 2 (Perkin Elmer), the chemical functional groups present in different biochar samples of SCGs were assessed. To improve homogeneity and provide a finely powdered powder with the right size particles for examination, the biochar samples were manually ground before the experiment started. Images in the 400–4000 cm^{-1} wave number range were acquired, and a small amount of powdered material was used for examination.

3.7 BET Surface area and pore volume analysis

Numerous biochar characteristics are connected to surface area and porosity. According to [27], surface area influences surface charge accessibility, which in turn dictates cation exchange capacity. The amount of water that biochar can hold onto is mostly dependent on its porosity and interconnectivity of pores. Although there is a high correlation between biochar reactivity and active sites, many active sites necessitate a large accessible surface area [28]. Applications for biochar are also significantly impacted by surface area and porosity. For instance, biochar is widely employed as a sorbent, and surface area and porosity have a direct impact on its sorption capacity [29]. Pour filling in the sorption process is made easier by the porous structure of biochar.

One important factor in any adsorbent material is its specific surface area, which is often referred to as its Brunauer-Emmet-Teller, or BET surface area [30]. N_2 adsorption and desorption processes are assessed using St 2 on NOVA touch 4LX [s/n: 000000], which was used to measure the BET surface area, overall volume, and pore size distribution in this work. Every run of the assay used a biochar sample weighing roughly 0.1210 g, and each sample was tested repeatedly. The material was degassed for 6.0 hours at 200 °C before to each assay. The total pore volume and pore size were determined using the Barrett-Joyner-Halenda (BJH) adsorption model, and the specific surface area was determined using the BET model.

3.8 Study of surface morphology

After SCGK biomass was torrefied at 300 °C, a SEM image of the biochar produced by SCGs was examined. This range of torrefaction treatment was most advantageous for producing SCG-derived adsorbent with greater specific surface area, pore size, pore volume, and surface functional groups when compared to other temperature ranges in the current study. The Zeiss ULTRA Plus high-resolution field emission scanning electron microscope (HRFESEM) was used for SEM imaging.

4. RESULTS

4.1 Impact of torrefaction temperature on elemental and proximate analysis

Each torrefied sample underwent proximate and final examination of the produced biochar by measuring the amount of ash, moisture, volatile matter, and fixed carbon. Table 1 summarizes the average outcomes of the proximate and ultimate analyses.

As previously noted, the average biomass of SCGs is mostly composed of carbon (50.26 wt.) and oxygen (42.37% wt.). Moisture contributed 8.62% wt., with ash contents coming in at 0.65% wt. (Jeníček et al., 2022). Proximate analytical results in this study suggest that during heat operations, SCGs exhibit a high content in the volatile matter (VM) range of 64.08 – 81.02 % wt. With a rise in process severity, the amount of moisture and volatile substances dropped due to the precursors' torrefaction. SCGs' volatile matter reduces as the thermos degradation temperature rises, while their fixed carbon (FC) tends to do the reverse. A decrease in ash content is ideal for the process of thermochemical conversion. It is preferred that the torrefied solid residues have a low ash concentration.

Nitrogen (N) increased from 1.77 % to 1.83% and carbon (C) from 50.26% to 59.54% when the torrefaction range of SCGs was raised from 0 to 250 °C. Due to a considerable loss of several oxygen-rich functional groups and compounds, oxygen (O) decreased from 42.37% to 23.16% and hydrogen (H) decreased from 6.29% to 6.03%. Additionally, a comparison of the composition of the biochar formed after the temperature was raised from 250 °C to 350 °C revealed a rise in carbon from 59.04% to 74.89%, nitrogen from 1.83 % to 1.93 %, a reduction in hydration from 6.03% to 4.95%, and an oxygen from 23.16 to 8.15 %.

Table 1 Proximate and Ultimate analysis of SCG at different torrefaction condition.

Torrefaction conditions of SCG (°C)	**Carbon** (% wt.)	**Hydrogen** % wt.)	**Oxygen** (% wt.)	**Nitrogen** (% wt.)	**Ash** (% wt.)	**Fixed carbon** (% wt.)	**Volatile material** (% wt.)	**Moisture (% wt.)**	**Reference**
SCG 0	50.26	6.29	42.37	1.77	0.65	14.06	75.71	8.62	(Jeníček e al., 2022)
SCGR250	59.04	6.03	23.16	1.83	0.83	18.02	81.02	1.79	
SCGK300	69.05	5.75	14.78	1.87	1.98	29.00	67.08	1.20	Data as per present study
SCGD350	74.89.	4.95	8.15	1.93	2.49	31.25	64.08	0.98	

4.2 FTIR with impact of Torrefaction

The original SCG was characterized for FTIR and found functional group on the surface as –OH (3335 cm^{-1}), C-H (2920 & 2850 cm^{-1}), C=O ($^{\sim}$1700 cm^{-1}), C=C (1605 cm^{-1}), C-O-C (1161 cm^{-1}), C-N (1097 cm^{-1}), C-O (1027 cm^{-1}) [31], which were comparable to present study. The spectral peaks evident within the wave number range of 3570-3200 cm^{-1} (broad) corresponding to the hydroxyl group, H- Bonded O-H stretch observed at 3433.57cm^{-1}, 3433.46 cm^{-1} and 3436.49 cm^{-1} for SCG torrefied at 250, 300 and 350 °C respectively, present mainly in the lignocellulosic component (cellulose). Biochar produced at these different torrefied rages of temperature showed peaks at 2925.86, 1743.37, 1453.82 cm^{-1}, which can be attributed to the presence of saturated aliphatic (alkene/alkyl) C-H groups, carbonyl compounds, and aromatic C-H stretching respectively. The findings showed that torrefaction-produced biochar had many functional groups, indicating the presence of many organic molecules in the biochar. For instance, biochar that was created at 300 °C had extra peaks at 1373 and 1100 cm^{-1}, respectively, which may indicate the presence of alcoholic groups that contain oxygen. However, it was found that as temperature increased, the number of functional groups in the biochar continually decreased, indicating that organic molecules were volatilizing and producing pyrolytic gasses.

Since different functional groups in biochar might come from lower temperatures of thermal decomposition, it is important to use these lower temperatures for the creation of biochar with more adsorption sites. The O-H stretching vibration of the methyl compounds in lignin is represented by an enhanced band within the 2935–2915 cm^{-1} spectra, as demonstrated by previously published data for SCG thermal degradation. These spectra likewise indicate an increase with process temperature and residence time. The breakdown of amorphous carbohydrates, especially cellulose and hemicelluloses, was suggested due to the observed rise in lignin content in biochar [32]. Moreover, [10] reported that the spectral peaks detected at 1740 cm^{-1} were caused by the breakdown of carbonyl groups in the hemicelluloses found in biochar and might be related to the carbonyl stretching (C=C) of acetyl, carboxylic acid, aldehyde, or ketone groups in hemicelluloses. The C=O aromatic skeletal vibration is shown by the peak at 1630–1600 cm^{-1}. According to the trend, biochar's thermal stability improves as torrefaction increases cellulose breakdown [33]. Additionally, the decrease in the 1090 cm^{-1} peaks during torrefaction at 250 °C, which corresponds to the C-N stretch in the finger print area, followed by the disulfides (S-S stretch) at 605 cm^{-1}. Peaks with 581 and 461 cm^{-1} are reduced upon reaching 300 °C, after which they vanish at elevated temperatures (Table 2). Because of its low degree of crystallinity and polymerization, hemicellulose is the most reactive biopolymer found in biomass. Less pronounced peaks at 300 ^{o}C in torrefied samples indicate that hemicellulose undergoes the most significant breakdown mechanisms during torrefaction. Figure 4 illustrates that, severe torrefaction conditions (300 ^{o}C) for one hour cause significant changes in the spectra of the substances under investigation while mild torrefaction conditions at 250 ^{o}C retail peaks do not. The changes result from partial disintegration of cellulose and entire breakdown of hemicelluloses, which releases oxygenated species.

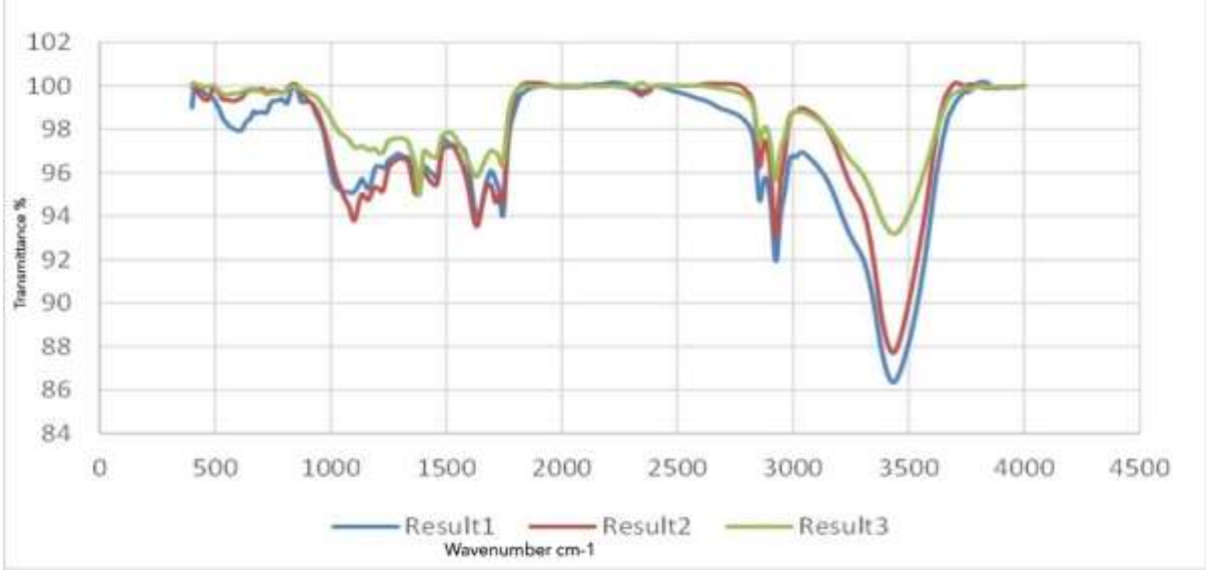


Fig. 4 FTIR analysis of torrefied samples at different temperatures Result 1(SCGR250), Result 2(SCGK300) and Result 3 (SCGD350)

Table 2 Functional group and its quantified frequencies

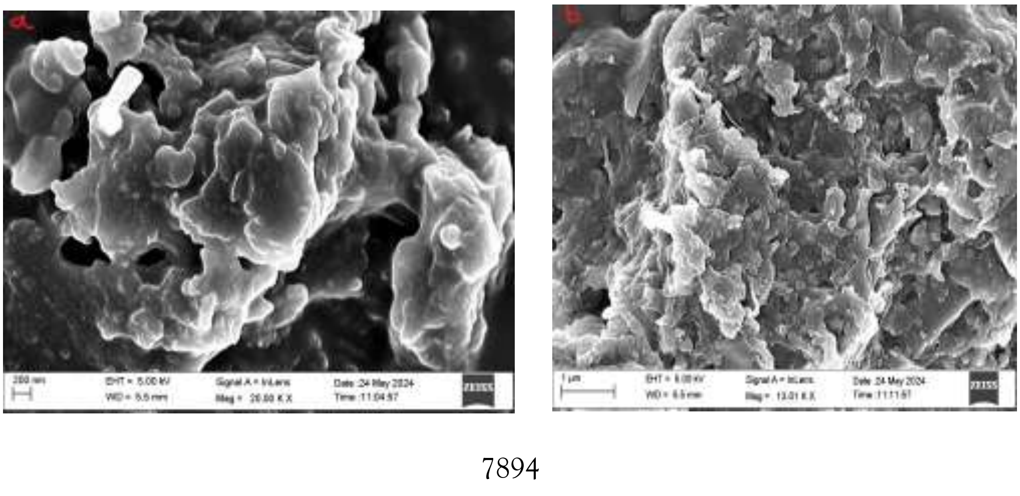
Produced Biochar	**Peaks at Wave number(cm^{-1})**	**Functional Group present**
SCGR250	3433	Alcohol and Hydroxyl compound O-H
	2925	Methylene stretch C-H
	1743	Carbonyl Compounds
	1457	Methylene C-H Bend
	1090	CN Stretch
	605	Disulfides (S-S stretch)
SCGK300	3433	Alcohol and Hydroxyl compound O-H
	2925	Methylene stretch C-H
	2343	Bend of triple bond compounds C≡C
	1741	Carbonyl Compounds
	1453	Methyl C-H Bend
	1373	Alcohol and Hydroxy Compound
	1100	Aliphatic organ halogen compound
	581	Disulfides (S-S stretch)
	461	Polysulfide (S-S stretch)
SCGD350	3436	Alcohol and Hydroxyl compound O-H
	2924	Methylene stretch C-H
	1740	Carbonyl Compounds
	1630	Alkenyl C=C stretch
	1382	gem-Dimethyl stretch
	1216	P-O-C stretch

4.3 BET Analysis of Torrefied biochar

Previous rsearch by Yang et al. 2023, reported original SCG with a surface area of 8.05 m^2/g [31], which was higher value than reported by other researchers. A surface area of 2.5 m^2/g and 0.4 m^2/g were reported [34]. In the present work specific surface areas of SCGs biochar were reported to range from 7.79012 m^2/g to 20.686 m^2/g. However, these recorded values are lower as compared to other studies for SCGs biochar. Islam et al and Zhang, et al reported Specific surface areas of SCGs as 40.1 and 1.46 m^2/g respectively after the pyrolysis at 500^{0}C and 1000°C respectively [35, 36]. According to another study BET surface area of SCGs derived biochar was reported only 1.53 m^2/g with after pyrolysis at 550^{0}C [37]. The pore volume in other studies was reported 0.019 cc/g Islam et al., 2022 [35], and 0.008 cc/g [36]. The properties of the feedstock and the thermochemical conversion conditions, such as temperature, oxygen content, and reaction time (residence time), affect the specific surface area of biochar. Variations in specific surface area could be caused by less micropores in the biochar matrix. In this study all SCGs biomasses were torrefied at 250, 300 and 350^{0}C provide a BET specific surface area of 8.096 m^2/g, 20.686 m^2/g and 9.093 m^2/g. respectively. A pore volume of 0.00848268 cc/g with 1.52837 nm pore radius dV(r) (r), 0.0160632 cc/g with 1.69423 nm Pore radius dV(r) and 0.00860349 cc/g with 1.53545 nm pore radius dV(r) was recorded at 250, 300 and 350 °C respectively. Through the BET surface area of raw material was recorded considerably low as <0.1 m^2/g [37], the Surface area of the biochar was increased from 8.096 m^2/g up to 20.686 m^2/g after torrefied SCG on 250, 300 and 350 °C respectively. According to the specific surface area (BET), pore volume and pore size results, SCG biomass taken from the Kolkata region has the highest surface area (20.686 m^2/g) to adsorb heavy metals from aqueous streams when compared to SCG biomass samples from Delhi and Rajasthan. Previously reported findings showed that SCGs have only 1.46 m2/g specific surface area after being paralyzed at 500 °C [36]. SCGs biochar with this surface area was found suitable for adsorption of Sulfonamide antibiotics (SAs) from waste water stream. Results of BET analysis by X. Zhang et al., is very low compare to findings of present study reports. The reduced quantity of micropores in the biochar matrix could be one of the causes. Additionally, biochar produced at 300 °C had a maximum pore volume of 0.0160632 cc/g, which were significantly very close to 0.019 cc/g, maximum finding of previous study [36]. The results of this study in terms of specific surface area were considerably more than in the earlier investigation, where the pore volume and specific surface area were recorded 11.0 m^2/g and 0.009 cc/g, respectively after pyrolysis conditions at 500 °C. In comparison to other biochars, this reduced surface area SCG biochar demonstrated a greater maximum adsorption capacity for Sr^{2+} (Q_{max} = 51.81 mg/g) [38]. Furthermore, a study showed the BET analysis for modified SCG derived biochar provided thermal decomposition at 400° C, the specific surface area and pore volume were 3.60 m^2/g and 0.015 cm^3/g respectively, which was much lower than present work. This biochar with lower surface area and pore volume was found with maximum removal efficiency of Cd (II) with ~ 96% [39]. However, increased temperature up to 500° C under slow pyrolysis conditions, resulted in a decrease in biochar surface area (4.17 m^2/g), but an increase in pore size (2.24 nm) when compared to present treatment process. Zhang, et al. evaluated SCG biochar formed at various temperatures and discovered that higher temperature (>400° C) damaged the tiny pores, resulting in a decrease in surface area [36]. These observations are compatible with the present the present study.

4.4 Surface characteristics of produced biochar using SEM imaging

The SEM image of the SCGK derived biochar produced at 300° C for 1 hr is shown in Figure.5 displaying their morphologies and offering a more thorough understanding of the sample structure. As is prominent the SCGK exhibits a coarser texture and fractures caused by lignin degradation and hemicellulose depletion, which are consistent with findings from other studies. Additionally, when gaps and openings grow in number, the structure becomes more fragile. Torrefaction disintrigates solid surfaces, which results in observable cell-wall distortion and macroapertures, especially when it occurs at 300° C for an hour. Additionally, carbonization and the release of volatile compounds are caused by torrefaction, which produces brittle and porous biochar samples. Surface microstructure, such as microfibers brought on by structural disruption of biomass, may be visible. According to [11], a torrefied SCG biomass sample at 300° C showed a comparable change in morphology.



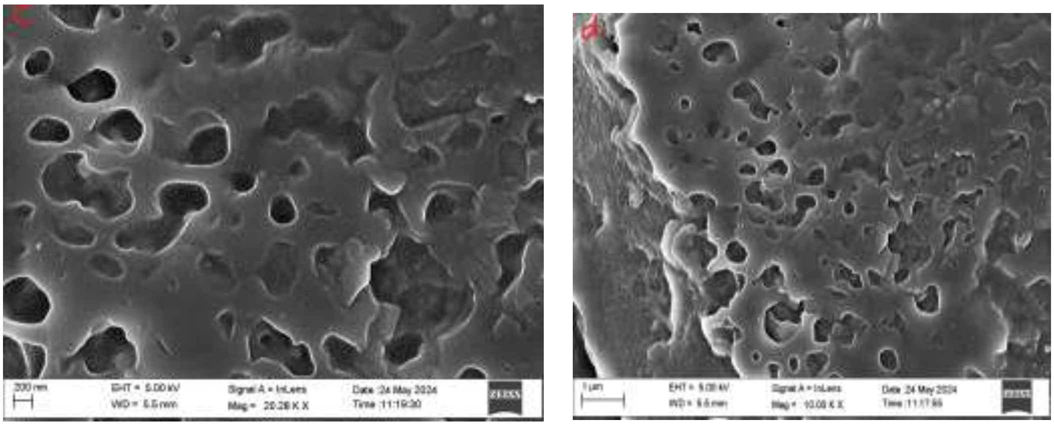


Fig. 5 SEM image (a)&(b) for depletion and degradation on surface (c) &(d) for porous and brittle biochar for SCGK300 biochar sample with highest pore size and surface area

5. Production efficiency of Biochar at different thermal process

The process of thermal degradation of biomass can take several forms, including drying, torrefaction, carbonization, pyrolysis, gasification, and combustion, depending on the temperature and oxygen content. The torrefaction procedures utilized in SCG thermal decompositions have been the main focus of this research, with findings compared to biomass from previously torrefied and paralyzed SCGs. Fast and slow pyrolysis are the two types that exist. The manufacture of liquid fuel is not a good fit for slow pyrolysis, which typically takes several hours and yields a high solid byproduct. In contrast, fast pyrolysis breaks down solid biomass quickly at temperatures between 400 and 600° C, releasing a volatile combination of water, CO/CO_2, and other organic chemicals. The part of this vapor that can condense is bio-oil. The torrefaction procedure has been used in this article to create biochar. Whereas pyrolysis is used to create liquid biofuels (bio-oil), torrefaction is used to create solid fuels (biochar). In the absence of oxygen, torrefaction is a thermochemical process that usually occurs at 200–300° C, atmospheric pressure, modest particle heating rates, and an hour-long reactor period (Intermediate products). In biomass, hemicelluloses and cellulose pyrolyze between 200 and 315 ° C and between 315 and 400 °C, respectively, but lignin pyrolyzes between 160 and 900 ° C [40]. When Zhang et al. examined SCG biochar produced at different temperatures, they found that higher temperatures (over 400° C) harmed the small pores, reducing the surface area. Therefore, it is possible to achieve the desired product quality and yield by carefully controlling the thermochemical reaction temperature with specific biomass. In contrast to pyrolysis, torrefaction lowers handling costs by making the biomass brittle and easy to grind. Because it produces high-quality solid fuels (biochar) with lower atomic ratios and higher energy densities from biomass samples, torrefaction has an advantage over other thermal breakdown processes. According to [41], the hydrophobic properties of torrefied biomass make it easier to handle, store, and transport across long distances. Owing to these and other factors, the current study concentrated on the torrefaction process in order to create effective biochar.

6. CONCLUSION

This makes sense, since several studies may employ SCG from notably different coffee beans and brewing methods. This study assessed how different kinds of produced biochar material's characteristics and related applications were affected by the production process. However, the outcomes were also contrasted with those of previous thermal degradation processes of various types. The results obtained indicated that the biochar generated using SCGK biomass taken from the Kolkata region through torrefaction (300 °C) has the highest surface area (20.686 m^2/g) and also large number of functional groups as per FTIR, present on biochar surface which show its efficient applicability to adsorb heavy metals from aqueous streams compared to SCG biomass samples from Delhi and Jaipur. The results also indicated that the thermal process used in this work provided a high-quality biochar with good amount of yield (51%) at 300 °C torrefaction range as compared to obtained results after pyrolysis by other researchers. SEM images indicated highly porous and brittle nature of SCG300K biochar samples. In the previous research it was observed that increased temperature up to 500° C under slow pyrolysis conditions, resulted in a decrease in biochar surface area (4.17 m^2/g), but an increase in pore size (2.24 nm) when compared to present treatment process. According to previous research higher temperature (>400° C) resulting in a decrease in surface area. Hence torrefaction has utilized in this study to obtain higher surface area of SCG with good range of yield and maximum porosity with capability to adsorb heavy metals from aqueous solution. It is also concluded that SCG biomass collected from Kolkata region and cultivated in Darjeeling, found with best results as compared to coffee of Delhi region (cultivated in Karnataka) and Jaipur region (cultivated in Ratnagiri).

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Data availability All data are available upon request as our research data includes sensitive or confidential information such as patient data.

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