Review

A Critical Review on Briquettes Developed from Spent Coffee Ground Wastes

Gokul Raghavendra Srinivasan*, Aditya Mahajan, Rajiv Seth, Rakesh Mahajan

Research and Development, Steamax Envirocare Private Limited, India

*Corresponding: gokusrinivasan@gmail.com

Abstract: Coffee is regarded as the highly consumed beverage throughout the world and has established a key spot in the world economy as an important commodity for trading. In general, they are produced by brewing their roasted and ground beans, which release aromatic coffee; as well as produce an equivalent amount of spent coffee grounds (SCG). Previously, they were discarded as wastes or used as natural pest repellent or garden fertilizer; however, in recent times, are valorized into biofuels owing to their high calorific value. In fact, SCG briquettes have gained wide attention for supplying energy renewably, especially to the rising energy demand; and also have been identified as an effective measure to reduce their pollution. With this in mind, this present chapter focuses on reviewing the availability and chemistry involved in these SCG wastes, pre-treatments and preparations required for their briquetting, compacting techniques followed, and fuel characteristics of their briquettes, from various available works of literature. Here, their availability showcases the amount of SCG wastes generated with respect to time and consumption, wherein understanding their chemistry helps in deciding the pre-treatments necessary for their briquetting. Meanwhile, preparation techniques briefs about the necessary pre-treatments undertaken before compaction by different researchers; and the fuel characteristics define the physicochemical and mechanical properties of their briquettes, developed using various compaction methods. Besides, combustion behaviors of these briquettes are explained in terms of their burning characteristics and emission levels, as reported in literatures; which help in deciding their suitability as a replacement for existing fossil coal. Eventually, all the reported data were in accordance with their permissible standards and suggested these SCG as a highly renewable solid biofuel.

Keywords: *Spent coffee grounds; SCG Briquettes; SCG Biodiesel; Caffeine; Residual Oil; Irregular Particle Size*

1. Introduction

Coffea, a genus of flowering shrubs belonging to Rubiaceae family, are mainly cultivated as agriculture crops for their seeds, having greater importance in beverage industries (Brunerová et al., 2019; Potip & Wongwuttanasatian, 2018). Amongst 70 known species, only Coffea Arabica and Coffea canephora (or) Coffea robusta are purposely cultivated, with former contributing predominantly upto 75% while latter contributing the remaining portion (Belitz et al., 2009; Etienne, 2005). These seeds have been primarily used for producing beverages, especially coffee for more than 1000 years; which have been identified as the most celebrated beverage drink in the world (Brunerová et al., 2019; Potip & Wongwuttanasatian, 2018; Park et al., 2020). Besides, they are also regarded as the second largest traded commodity in the world, falling behind petroleum products (Gómez-de la Cruz et al., 2015; Peshev et al., 2018; Park et al., 2020; Nabais et al., 2008); with over 80 countries involved in their large scale cultivation (Mussatto et al., 2011; Murthy & Naidu, 2012). Hence, they hold key significance in international trade and relationships, economics, and even politics for many developing countries (Brunerová et al., 2019). In fact, millions of people are offered with numerous job opportunities associated with different stages of coffee production; and includes cultivation of plants, harvesting of cherries, processing of beans, packaging and storage, and shipping and handling (Mussatto et al., 2006).

In general, coffee is brewed from the ground roasted coffee beans by adding hot water or steam, which extracts their soluble compounds and aromas; leaving behind a large quantity of residual wastes, commonly termed as spent coffee grounds (SCG) (Seco et al., 2020; Fehse et al., 2021). The amount of these wastes generated depends on their rate of consumption and source, which vary from domestic households to coffee shops or cafeterias, sometimes even large scale coffee beverage industries (Kang et al., 2017; Fithratullah, 2022; Blinová & Sirotiak, 2019). On average, only 40% of these beans are processed into coffee, leaving behind almost 60% of the residues as wastes (Acevedo et al., 2013; Fithratullah, 2022). Other wastes include coffee pulp produced during the removal of beans, coffee silver skin produced during roasting or hulling, and coffee wastewater obtained during handling of their beans (Blinová & Sirotiak, 2019; Nabais et al., 2008; Mussatto et al., 2006; Seco et al., 2020). Discouragingly, these wastes do not have any market value, nor have any direct application as value added products (Chen et al., 2017; Kourmentza et al., 2018; Seco et al., 2020); hence, are discarded in open environment or disposed in landfills or incinerated, which however contributes to environmental pollution due to their high pollutant potential , in addition to other concerns like odour and harbourage for insects (Brunerová et al., 2019; Lee et al., 2021; Fermoso & Mašek, 2018; Rivera et al., 2020). However, these SCG wastes have been reported calorific worthy with better thermal efficiency and permissible emission range, thus valorising them into fuel can be regarded as an ideal disposal technique (Allesina et al., 2017); besides, being used as raw material for producing numerous beneficial organic compounds, as animal feed, and as manures and composts for plants (Brunerová et al., 2019; Colantoni et al., 2021; Kang et al., 2017; Santos et al., 2017; Zhang & Sun, 2017; Pujol et al., 2013; Campos-Vega et al., 2015; Atabani et al., 2019). Following this, these wastes are subjected to various advanced chemical and biotechnological treatment processes to valorise them into different forms of biofuels, which includes biodiesel, bio-ether, biochar, bio-oil, or biogas (Karmee, 2018; Gardy et al., 2019). In specific, these wastes performed well in its solid form, especially in form of densified briquettes or pellets which have been proven to exhibit fuel characteristics almost similar to existing fossil fuel. In fact, these SCG wastes exhibited very high calorific content with minimal ash content (Fehse et al., 2021), and helped in developing low cost, highly renewable and environmental friendly solid biofuels at large scale (Chou et al., 2009; Rajaseenivasan et al., 2016).

About denisifed SCGs, these wastes are compacted into briquettes or pellets under application of high pressure that agglomerates their particles, and are held together by the binders (Moreno-Ariasa et al., 2021). Here, these binders are organic substances that hold back the SCG particles or fibres together through cohesion or adhesion, and can be any natural gum or starch; and theoretically, SCG briquettes can be developed using only their high lignin content as natural binders (Moreno-Ariasa et al., 2021; Brunerová et al., 2019). However, developing binder less or 100% raw SCG briquettes are high unsuccessful and remains as a challenge until today, especially at lower compaction pressures; and can be explained by their coarse particle morphology and its high lipid content (Vardon et al., 2013; Seco et al., 2020; Bejenari et al., 2021). Yet, this can be overcome by introducing calculated amount of these binders and moisture content to these wastes, which enables their compaction at lower pressure and temperature (Seco et al., 2020; Espuelas et al., 2020]. Besides, adding a portion of other biomasses also helps in enhancing the durability and handability of these briquettes; and accordingly, Kang et al. (2017) added appropriate proportion of spent coffee ground, coal fines, saw dust to produce eco-friendly briquettes for domestic application capable of producing very low toxic emissions (Kang et al., 2017; Brunerová et al., 2019; Roy & Corscadden, 2012; Chen et al., 2017). Worth mentioning, increasing the moisture content in the briquetting dough helps increasing the compaction efficiency by simultaneously softening the biomass and activating the binder, as a result producing highly durable briquettes (Huang et al., 2017); but are reduced post compaction by drying the compacted products (Brunerová et al., 2019). In addition, briquettes developed from SCG-biochar were also found promising for energy generation, citing their superior fuel and combustion characteristics (Lee et al., 2021).

Accounting their potential, these SCG based briquettes are expected to support and contribute a significant part to the present energy demand, rising steadily due to the modernization and exponential human population growth (Chia et al., 2018). Unfortunately, this demand have simultaneously started depleting the existing fossil fuel resources and harming the planet's atmosphere that have led to catastrophic environmental events such as

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climate change and global warming (Tan et al., 2019). Hence, relying on these SCG wastes can be seen as a fruitful option, as they are highly renewable as well as calorific, and easy available. Available in abundance, these wastes give rise to second generation solid biofuels, which this present book chapter will focus on by summarising their availability, chemistry involved in these wastes, pre-processing techniques followed to prepare them and various briquetting methods used for their compaction, along with their fuel and combustions characteristics.

2. Availability of SCG Wastes

2.1 Cultivation and consumption of Coffee

As mentioned earlier, Coffea has been used in numerous cuisine applications, besides being traded as a commodity crop globally (Fithratullah, 2022).Traditionally, Brazil, Vietnam, Colombia, and Indonesia are being considered as the global pioneers in producing coffee, collectively contributing upto 50% of world's coffee production (International Coffee Organisation, 2020; Brunerová et al., 2019; Fithratullah, 2022). Looking at their consumption rate, about 9.08 million tons of coffee beans were consumed during year 2015/2016, and about 9.44 million tons, estimated as on November 2017 (Potip & Wongwuttanasatian, 2018; International Coffee Organization, 2018). Even more, International Coffee Organization (ICO) data suggested that about 10.3 billion tonne of coffee were harvested during 2020, and about 166,628 thousand 60 kg bags of coffee beans were consumed globally during 2020/2021 (International Coffee Organization, 2021). This data also estimated that roughly 5.03 billion tons of coffee was imported to the European Union countries through marine transportations (International Coffee Organisation, 2019). In terms of consumption post brewing, almost 400 billion cups of coffee are consumed annually, and is expected to increase in coming years (Grigg, 2002).Table 1 summarises the annual worldwide coffee production during the year 2014-2017, as recorded by International Coffee Organization (ICO) (Brunerová et al., 2019). Moreover, these data displays a steady rise in their production and consumption; and can be explained by the newly found interest and taste for these beverages among the younger generation, thus increasing their demand considerably (Fithratullah, 2022).

Table 1: Annual global coffee production rate (2014-2017), along with their cultivation area and yield (FAO, 2019; ICO, 2010; Brunerová et al., 2019)

Harvest Year	Total Area used for harvesting (X 10^6 Ha)	Average Yield (in tonnes/Ha)	Amount of Green beans harvested (X 10^6 tonnes)	Amount of coffee beans produced (X 10^6 60 kg Bags)
2014	10.52	8.37	8.80	0.154
2015	10.95	8.10	8.87	0.150

2016	10.95	8.59	9.32	0.153
2017	10.84	8.50	9.21	0.159

2.2 Coffee to SCG Equivalence

It is fairly evident that brewing of coffee beans produces aromatic coffee extract, and leaves behind a large quantity of residues coffee dusts as SCG wastes. Accordingly, many studies have reported different volume of these SCG wastes, post brewing; in most cases, reported their concentration always greater than 50% depending upon their extraction process. For instance, about 550-650 grams of SCG wastes are produced while brewing 1 kg of raw coffee beans, for a moisture content added between 55 and 88% (D.B) (Gómez-de la Cruz et al., 2015; Santos et al., 2017; Acevedo et al., 2013; Potip & Wongwuttanasatian, 2018); whereas, instant coffee preparation yields only 45-50% of SCG wastes (Murthy & Naidu, 2012). On the other hand, almost 650 grams and 900 grams of SCG wastes are generated upon producing coffee from 1 kg of green coffee and ground coffee, respectively; and about 2 kilograms of wet SCG were generated for producing 1 kg of soluble or instant coffee (Luz et al., 2018; Blinová & Sirotiak, 2019).

2.3 Generation of SCG wastes

As such, almost 50% of coffee feedstock is rejected as SCG wastes; and availability of these wastes can be accounted based on this conversion value (Tsai et al., 2012).Recollecting from earlier facts, these SCGs are mostly produced in coffee stalls and shops, apart from coffee based industries (Potip & Wongwuttanasatian, 2018; Mata et al., 2018); and these wastes are rich in sugars polymerized into cellulose and hemicellulose structures (Fu and Chena, 2020). Infact, these wastes are generated in both urban and rural parts of the country citing the boom in coffee business; and are always readily available, mostly in their wet form (Potip & Wongwuttanasatian, 2018). On average, about 6-8 million tons of SCG wastes are generated annually and increased to 9.3 million tonnes during the year 2017 (Mussatto et al., 2011; Sarno & Juliano, 2018; Jang et al., 2015; Zabaniotou & Kamaterou, 2019; Echeverria & Nuti, 2017; Murthy & Naidu, 2012). About 50% of these SCG wastes are disposed directly into landfills, while the remaining portion of the wastes are usually discarded in open garbage bins and dump yards, and even in drainages (Primaz et al., 2018; Tsai et al., 2012). However, with proper waste management techniques, around 4.40-4.65 million tonnes of SCG wastes, normally disposed in landfills can be valorised into suitable biofuel (Lee et al., 2021). Research suggests about 2.3 PJ of energy; equivalent to 1.16% of bioenergy potential in Poland was contributed by these SCG wastes alone, thus signifying these SCG wastes as valuable feedstock (Ciesielczuk et al., 2015).

2.4 Chemichal Characteristics Of SCG Wastes

Besides assessing their availability, it is also equally important to understand the chemical characteristics of these SCG wastes in order to ensure their renewability. To begin with, Spent coffee grounds (SCG) wastes are primarily made up of cellulose and hemicellulose compounds (Wei et al., 2019; Ballesteros et al., 2014; Vardon et al., 2013), followed by significant amount of lignin, caffeine, fatty and amino acids, polysaccharides and polyphenols, flavonoids and Millard products, and tannins (Pujol et al., 2013; Campos-Vega et al., 2015; Atabani et al., 2019; Rivera et al., 2020; Espuelas et al., 2020; Zabaniotou & Kamaterou, 2019; Limousy et al., 2013; Mata et al., 2018; Cruz et al., 2012; Murthy & Naidu, 2012). Especially, these wastes contain 11.6%–13.2% of cellulose, 37.2%–41.0% of hemicellulose, and 22.2-34.94% of lignin (Potip & Wongwuttanasatian, 2018; Lee et al., 2017; Brunerová et al., 2019); and which varies along with coffee species and coffee preparation technique (Blinová & Sirotiak, 2019). Here, high concentration of lignin content favours their torrefaction during the conversion of these wastes into biochar; besides acting as natural binder during briquetting (Lee et al., 2017). Figure 1 depicts the distribution of lignocellulosic compounds in these SCG wastes (Lee et al., 2021).

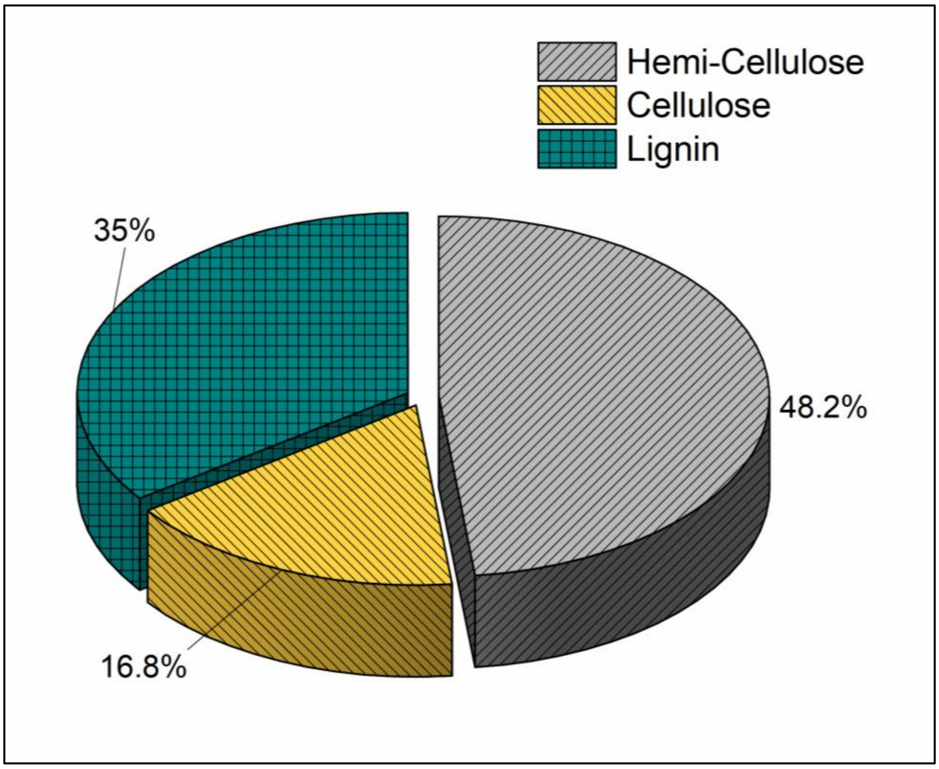

Figure 1: Distribution of lignocellulosic compounds in raw SCG wastes

Following this, proximate analysis on coffee beans, before brewing reported its water content as 2.1%, volatile matter as 76.75%, ash content as 3.88% and fixed carbon as 17.27%; while, proximate composition of dried SCG wastes were measured as follows: water content-11.69%, volatile matter-70.03%, ash content-2.06% and fixed carbon-16.22% (Kang et al., 2017).However, moisture content in these SCG wastes were reported upto 55-60%, and are always dried to 8-10%, prior to briquetting (Kang et al., 2017; Potip & Wongwuttanasatian, 2018). Meanwhile, higher heating value (HHV) of these SCG wastes ranged between 18.8 and 26.9 MJ/kg, thus making these wastes as a successful substitute for existing fossil coal (Ballesteros et al., 2014; Caetano et al., 2014; Murthy & Naidu, 2012).

About their elemental composition, SCG wastes are identified as one of the potential source for high carbon content biomass, by reporting the carbon content as 54% for both Coffee beans and dried spent coffee ground (Tsai et al., 2012). In addition, elemental composition of coffee beans, pre-brewing and dried SCG wastes were measured as hydrogen- 6.94 and 7.19%,nitrogen-1.62 and 1.45%, sulphur-0.06 and 0.05%, and oxygen-34.25% and 36.2%, respectively (Kang et al., 2017). Besides, EDX analysis on these SCG wastes also showed mixed presence and traces of numerous macronutrients like aluminium, calcium, magnesium, phosphorous, potassium, silicon, sodium, and sulphur in them; and are summarised in Table 2 along with their composition (Colantoni et al., 2021; Bejenari et al., 2021). In case of SCG biochar, concentration of carbon increased 56.25% to 78.82%, while, oxygen reduced from 29.75% to 10.59% (Lee et al., 2021).

Table 2: Micronutrients and mineral composition of SCG wastes (Colantoni et al., 2021)

Micronutrient	SCG wastes
Lithium	0.53 ± 0.5 mg/kg
Boron	10.6 ± 4.5 mg/kg
Sodium	37.15 ± 1.2 mg/kg
Magnesium	1.98 ± 0.018 g/kg
Aluminium	21.44 ± 3.6 mg/kg
Potassium	1.69 ± 0.007 g/kg
Calcium	0.25 ± 0.004 g/kg
Manganese	10.52 ± 2.6 mg/kg
Iron	9.87 ± 1.5 mg/kg
Nickel	1.23 ± 0.5 mg/kg
Copper	9.82 ± 3.5 mg/kg
Zinc	3.57 ± 1.04 mg/kg
Gallium	0.27 ± 0.3 mg/kg
Strontium	10.51 ± 2.01 mg/kg
Barium	3.17 ± 0.9 mg/kg

Looking into their particle size and morphological properties, almost 90% of SCG wastes particles are sized in between 320 and 420 μm, with irregular shapes and intra-particle gaps, thus making these wastes highly porous. On average, these pores range in between 20 and 30 μm, with extreme irregularity in the shapes; however, similar morphological characteristics were exhibited among the SCG wastes of other known coffee species (Bejenari et al., 2021). Eventually, these results were supported by the SEM images of

SCG particles, which comprised of flakes with shallow pores all over, giving sponge like appearance. Again, similar morphological characteristics were noted for the bio-chars of SCG wastes, strongly concluding that thermal degradation induced chemical alteration, without affecting their physical appearances including their particle size (Lee et al., 2021).

Next up, Thermo-gravimetric studies on raw SCG wastes generated two exothermic peaks signifying the burning of their volatile matter and fixed carbon content, with highest peak noted during the stable combustion of their fixed carbon content (Seco et al., 2020). Also, this study supported the results from proximate analysis on SCG wastes claiming the distribution of low fixed carbon and high volatile matter content in them. On the contrary, SCG with binders reported slightly reduced volatile matter and increased fixed carbon content (Espuelas et al., 2020). Moreover, this study briefed about the stability of their lignocellulosic compounds, with hemicellulose exhibiting poor stability followed by cellulose, and lignin showcasing highest stability (Fermoso & Mašek, 2018). And, significant loss of mass in the SCG wastes was noted during the volatilization and burning phase of their combustion. Here, other phases include burning of chars and burnout, and dewatering phase prior to the volatilization and burning phase (Seco et al., 2020).

Moving on, FT-IR characterization on these wastes generated few distinct peaks corresponding to various bond activities of O-H bond, aliphatic C-H bonds, C=O (esters) bonds, C=C (aromatic) bonds, and C-O bonds. Table 3 reports the various bond activities corresponding to different functional groups identified in SCG and SCG biochar wastes, along with their wavelength range and numbers. Besides, sharp peaks corresponding to polysaccharides like galactose, arabinose, glucose, mannose and other polysaccharides are noted in between the range of 950-700 cm^{-1}; and intensity of these peaks vary with coffee species analyzed. In addition, peak noted at 1637 cm^{-1} region relates to stretching of C=O bond, C=C bond of cyclic hydrocarbons, and C=N bond corresponding to caffeine; and is used as an indicator for determining the residual caffeine content in the SCG wastes from its intensity (Atabani et al., 2018; Zarrinbakhsh et al., 2016; Ramos-Andrés et al., 2019; Paradkar & Irudayaraj, 2002).

Table 3: Chemical functional groups detected in SCG and optimised SCG-Biochar, as reported by Lee et al., 2021

Designated and Noted wavenumber range (in cm^{-1})	Reported bond activities of functional groups
Range: 3600-3400; **Raw SCG:** 3331; **SCG char:** 3404	Strong stretching of O-H bonds in Alcohols and Phenols
Range: 3000-2850; **Raw SCG:** 2929-2852; **SCG char:** 2989	Stretching of C-H bonds in Alkanes
Range:2140-2100;	stretching of C≡C bonds

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Raw SCG: not noted; **SCG char:** 2143	in Alkynes
Range: 2000-1660; **Raw SCG:** 1679-1775; **SCG char:** 1947	Bending of C-H bonds in Aromatic Compounds
Range:1610-1550; **Raw SCG:** not noted; **SCG char:** 1554	Medium stretching of C=O bonds in Carboxylic Acids
Range:1555-1485; **Raw SCG:** 1492; **SCG char:** not noted	Strong stretching of N-O bonds in Aromatic Nitro Compounds
Range:1470-1350; **Raw SCG:** 1410; **SCG char:** 1359	Bending of C-H bonds in alkanes
Range:1340-1250; **Raw SCG:** not noted; **SCG char:** 1302	Strong stretching of C-N bonds in aromatic amines
Range:1350-1000; **Raw SCG:** 1209-1290; **SCG char:** 1151	Strong stretching of C-F bonds in alkyl fluoro compounds
Range:1320-1000; **Raw SCG:** 1084; **SCG char:** 1077	Strong stretching of C-O bonds in primary alcohols and phenols
Range: 995-850; **Raw SCG:** 925; **SCG char:** 985	Stretching of P-O-C bonds in aromatic phosphate compounds
Range: 865-810; **Raw SCG:** 859; **SCG char:** 854	Medium Bending of C-H bonds in aromatic compounds, towards out of plane
Range:850-750; **Raw SCG:** 774; **SCG char:** 735	Strong stretching of C-Cl bonds in alkyl chloro compounds
Range:680-500; **Raw SCG:** not noted; **SCG char:** 573	Strong stretching of C-Br bonds in alkyl bromo compounds

Owing to these unique chemical characteristics, these SCG wastes are used for producing biodiesel accounting their high bio-oil content (upto 16.12%)(Fehse et al., 2021; Gonçalves et al., 2020; Goh et al., 2020), bio hydrogen or ethanol (Sendzikiene et al., 2004; Kondamudi et al., 2008), adsorbents and sorbent for metal removal (Colantoni et al., 2021), anti-bacterial devices, to increase conductivity of lithium-ions batteries (Luna-Lama et al., 2019). Here, Figure 2 portrays the Proximate (PC), and elemental composition, using EDX and Ultimate analysis (UC) of Raw SCG wastes and SCG bio-char produced under optimised carbonization. Besides, Table 4 tabulates the additional thermal and physicochemical properties of SCG and optimised SCG-Biochar (Lee et al., 2021).

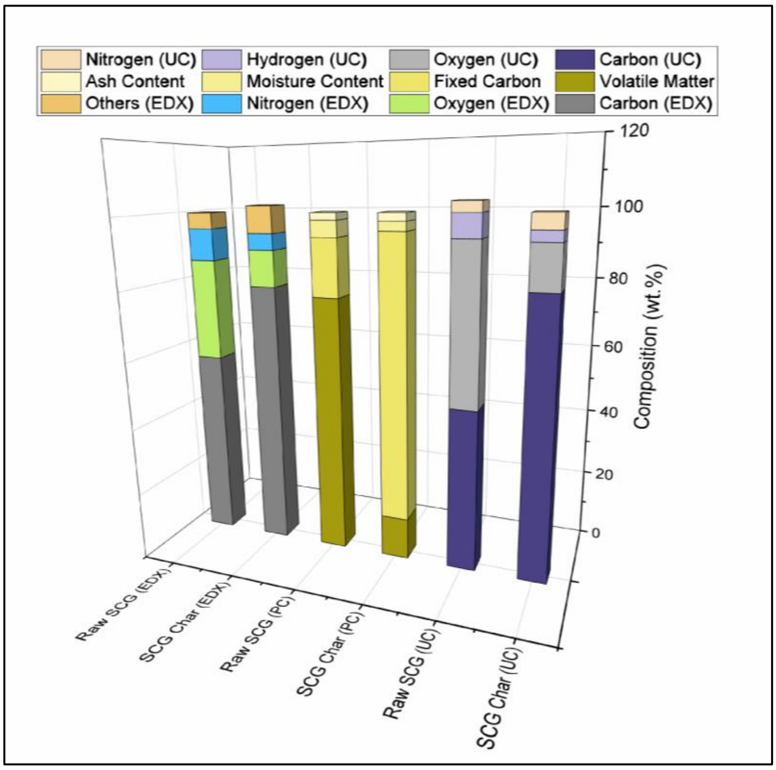

Figure 2: Proximate (PC), and elemental composition, using EDX and Ultimate analysis (UC) of Raw SCG wastes and SCG bio-char produced under optimised carbonization

Table 4: Physicochemical characteristics of SCG and optimised SCG-Biochar (Lee et al., 2021)

	SCG	**Optimised SCG-biochar**
Biochar yield (%)	-	29.94
HHV (MJ/kg)	22.59	31.41
Energy yield (%)	-	41.6
Volatile matter/fixed carbon	4.55	0.15
H/C atomic ratio	1.65	0.44
O/C atomic ratio	0.68	0.12
Fuel ratio	0.22	6.75

2.5 Pre-treatment and Processing of SCG Wastes

Any biomass feedstock needs to under certain processing or pre-treatments or both, prior to briquetting in order to develop high quality briquettes. Even, SCG also needs certain pre-treatment before being compacted into briquettes, owing to their irregular morphology and residual oil content that hinders proper binding between their particles (Bejenari et al., 2021). Any pre-treatment of SCG begins with roasting of its coffee beans, prior to brewing at 200-230 ^{0}C for 10-15 minutes, until their colour changes from bluish green to dark down (Colantoni et al., 2021). Post brewing, the residual wet SCG wastes are dried at 105 ^{0}C, in hot air oven for 24 hours to reduce their overall moisture content below 8-10% (Seco et al., 2020). Meanwhile, large scale drying are carried out at slightly higher temperatures (~ 200 ^{0}C), accounting the large quantity of SCG wastes to be dehydrated (Setiawan et al., 2016). Following this, the dehydrated SCG wastes are treated with solvents like hexane or toluene to remove their lipid fraction (Fehse et al., 2021; Tongcumpou et al., 2019; Setter et al., 2020), which later on can be used in the production of SCG oil biodiesel (Bui et al., 2022). In general, these wastes are refluxed with these solvents for 4-6 hours, at temperatures maintained slightly above the corresponding boiling point of the solvent used; and are treated in a Soxhlet extractor for lab scale studies. However, solvent based pre-treatments are least considered for large scale processing due to the requirement of heavy operating cost and highly organised operational techniques, including solvent recovery and storage.

Yet, this can be overcome by converting these SCG wastes into high calorific bio-chars through pyrolysis (Lee et al., 2021), which later on can be compacted into briquettes adding suitable additives. Most commonly practised pyrolysis techniques includes low and high temperature pyrolysis, fast and slow pyrolysis, and catalytic pyrolysis (Romeiro et al., 2012; Bok et al., 2012; Kelkar et al., 2015; Kan et al., 2014); are decided based on the availability of resources, and volume of SCG wastes needs to be processed. To begin with, Setiawan et al. (2016) carbonated these SCG wastes via low temperature pyrolysis, by heat treating them at 250 ^{0}C inside a hot air oven in the absence of oxygen for 120 minutes (Setiawan et al., 2016); whilst, Cho et al. (2015) carried out the pyrolysis of SCG again, in the absence of oxygen, using CO_2 instead of air/N_2 for promoting the pyrolysis yield (Cho et al., 2015). Likewise, Lee et al. (2021) carbonized these SCG wastes into bio-char through pyrolysis, for the following parameters: Pyrolysis temp- 500.00; Pyrolysis time- 30.00 mins; Heating rate- 6.00 ^{0}C/min; Nitrogen flow rate- 250.00 mL/min; and recorded their biochar yield and high energy yield as 29.94% and 41.60%, respectively. Eventually, these bio-chars exhibited superior elemental composition (carbon- 80.35%, oxygen- 12.43%, H/C ratio- 0.44, O/C-0.12 and fuel ratio- 6.75), and high thermal efficiencies with low activation energies (63.24–122.93 kJ/mol)(Lee et al., 2021).

With both SCG wastes and SCG bio-chars already existing in their pulverised form, they do not require any further milling or crushing processes (Brunerová et al., 2019); and can be directly compacted into briquettes using different additives, techniques and process parameters, as discussed in the following section.

2.6 Briquetting of SCG Wastes

Briquetting of SCG wastes deals with densifying and agglomerating their particles into solids, which in turn enhances their handability and fuel quality. Generally, these briquettes are developed by compacting the SCG wastes along with binder and additives (if any), under optimum compaction pressure and temperature, and moisture content; and are carried out with help of various tools that includes, manual compaction tool, hydraulic and pneumatic press, briquetting machines, and screw press. Most importantly, the quality of these briquettes depend entirely on compaction pressure, binder dosage and particle size; and vary with respect to compaction technique followed (Chen et al., 2015; Kaliyan & Morey, 2009; Roy & Corscadden, 2012). Following this, numerous researchers have developed these SCG briquettes; and works related to their briquetting have been tabulated in Table 5, comprising details related to briquette type, additive and binder added, compaction technique and conditions, and key highlights in their work.

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Table 5: Tabulated summary of briquette type, additive and binder added, compaction technique and parameters, and key highlights of different studies reported in the literature related to SCG briquettes

Briquette type	Feedstock	Additives	Binder	Briquetting Technique	Briquetting Conditions	Remarks	References
Compound / Composite	25% of SCG	75% of Larch sawdust	Lignin (natural binder)	High-pressure hydraulic briquetting press	Compaction pressure: 80 -100 MPa	• Mass ratios (Larch sawdust + SCG): (100% + 0%), (50% + 50%), (75% + 25%) • Briquette dimensions: diameter- 50.51 ± 0.20 mm; height-53.94 ± 4.19 mm; mass: 113.76 ± 14.39 g	Brunerová et al., 2019
Compound / Composite	50% of SCG	50% of Spruce shavings	Lignin (natural binder)	High-pressure hydraulic briquetting press	Compaction pressure: 80 -100 MPa	• Mass ratios (Larch sawdust + SCG): (100% + 0%), (50% + 50%), (75% + 25%) • Briquette dimensions: diameter- 50.51 ± 0.20 mm; height-53.94 ± 4.19 mm; mass: 113.76 ± 14.39 g	Brunerová et al., 2019
Homogeneous	SCG	-	Lignin (natural binder)	High-pressure hydraulic briquetting press	Compaction pressure: 80 -100 MPa	• Briquette dimensions: diameter- 50.51 ± 0.20 mm; height-53.94 ± 4.19 mm; mass: 113.76 ± 14.39 g • Failed mechanically owing to their weak binding forces amongst their particles	Brunerová et al., 2019
Homogeneous	90% of SCG	-	10% of crude glycerol	Hydraulic Briquettizer	Compaction pressure: 10 MPa; Moisture content: 1.5%	• Mass ratios (SCG: crude glycerol)-100:0 (G0), 95:5 (G5) and 90:10 (G10) • Briquette dimensions: diameter- 53 mm; length-52 mm; mass: 100 g • SCG-glycerol briquettes recorded their highest temperature and combustion rate of 533.4°C and 0.20 g/s, respectively	Potip & Wongwuttanasatian, 2018
Homogeneous	90% of SCG	-	10% of Xanthan gum	Laboratory press	compaction pressure: 12 MPa;	• Moisture content: 10, 15, 20, 25, and 30% • Compaction pressure: 8 MPa, 10 MPa, and 12 MPa	Seco et al., 2020

					compaction temperature: 30-35 ^{0}C (room temperature); moisture content: 15%	• Briquette dimensions: diameter- 65 mm; cylindrical mold • Sample size: 100 g of SCG+ glycerol slurry mix • Drying of briquettes: dried at room temperature for 24 h	
Homogeneous	SCG	5% of water	-	Hydraulic stamp press (Zeulenroda Presstechnik PYXE 250 F and PYE 100SS)	Compaction pressure: 140 MPa; compaction temperature: 60◦C; compression rate: 10 mm/s; Briquetting time: 3 seconds	• Briquettes developed without any binder • Moisture content: 5-10%; • Compaction pressure: 120-160 MPa; • Briquette dimensions: diameter- 50 mm; height-20 mm; mass: 40 g • Optimum moisture content: 5%	Fehse et al., 2021
Homogeneous	SCG	-	5% of cellulose	Hydraulic stamp press (Zeulenroda Presstechnik PYXE 250 F and PYE 100SS)	Compaction pressure: 140 MPa; compaction temperature: 60 ◦C; compression rate: 10 mm/s; Briquetting time:	• Optimum moisture content:5% • Compaction pressure: 120-160 MPa • Briquette dimensions: diameter- 50 mm; height-20 mm; mass: 40 g	Fehse et al., 2021

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					3 seconds		
Homogeneous	SCG (Extracted using percolation extractor-Fischer Extraction plant)	-	-	Hydraulic stamp press (Zeulenroda Presstechnik PYXE 250 F and PYE 100SS)	Compaction pressure: 140 MPa; compaction temperature: 60 ◦C; compression rate: 10 mm/s; Briquetting time: 3 seconds	• Optimum moisture content:5% • 5 Litres of toluene added into the percolation extractor, and refluxed with SCG for 3 hours • Moisture content: 5-10% • Optimum moisture content:5% • Compaction pressure: 120-160 MPa • Briquette dimensions: diameter- 50 mm; height-20 mm; mass: 40 g	Fehse et al., 2021
Homogeneous	SCG biochar (pyrolyzed SCG)	-	10% of Tapioca starch	Hydraulic stamp press (Zeulenroda Presstechnik PYXE 250 F and PYE 100SS)	Compaction pressure: 140 MPa; compaction temperature: 60 ◦C; compression rate: 10 mm/s; Briquetting time: 3 seconds	• Carbonization of SCG at 850 ◦C for 1 hour (rise in temperature by 0.83 ◦C/min upto 320 ◦C, and 2.85 ◦C/min upto 850 ◦C) • Moisture content: 5-10% • Optimum moisture content:5% • Compaction pressure: 120-160 MPa • Briquette dimensions: diameter- 50 mm; height-20 mm; mass: 40 g	Fehse et al., 2021
Homogeneous	SCG biochar (pyrolyzed SCG)	-	40% of Tapioca starch	Manual compaction (Hand held hammer)	-	• Carbonization at 500 ^{0}C • Starch:Water- 2:1 • Bio-char:tapioca starch- (40% w/v) @ mass ratio of 4:1 • Briquette dimensions: diameter- 35 mm;	Tongcumpou et al., 2019

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						height-45 mm • Drying of briquettes: dried in hot air oven at 105 °C for 24 hours	
Homogeneous	SCG	-	5% of Xanthan gum	Laboratory press	Compaction pressure: 12 MPa; Compaction temperature: 30-35 ^{0}C (room temperature); Optimum moisture content: 30%	• Moisture content: 15%, 20%, 25% and 30% • Compaction pressure 8 MPa, 10 MPa and 12 MPa • Binder dosage: 5 and 10% • Briquette dimensions: diameter- 65 mm; height- 12 mm; mass: 100 g	Espuelas et al., 2020
Homogeneous	SCG	-	5% of Guar gum	Laboratory press	Compaction pressure: 12 MPa; Compaction temperature: 30-35 ^{0}C (room temperature); Optimum moisture content: 30%	• Moisture content: 15%, 20%, 25% and 30% • Compaction pressure 8 MPa, 10 MPa and 12 MPa • Binder dosage: 5 and 10% • Briquette dimensions: diameter- 65 mm; height- 12 mm; mass: 100 g	Espuelas et al., 2020
Homogeneous	SCG	10% of Sodium chloride (NaCl)	Lignin (natural binder)	Molding machine (HEBI; XL140118, China)	Compaction pressure: 0.1 MPa; Compaction temperature:	• Briquette dimensions: diameter- 40 mm; height- 5 mm; mass: 5 ± 0.1 g • Drying time of SCG + NaCl briquettes reduced by 18%, compared to raw SCG briquettes	Fu & Chen, 2020

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					30-35 ⁰C (room temperature)		
Homogeneous	SCG	10% of Sodium sulphate (Na2SO4)	Lignin (natural binder)	Molding machine (HEBI; XL140118, China)	Compaction pressure: 0.1 MPa; Compaction temperature: 30-35 ⁰C (room temperature)	• Briquette dimensions: diameter- 40 mm; height- 5 mm; mass: 5 ± 0.1 g • Drying time of SCG + Na2SO4 briquettes reduced by 38%, compared to raw SCG briquettes	Fu & Chen, 2020
Homogeneous	SCG	10% of Lignite dust	Lignin (natural binder)	Molding machine (HEBI; XL140118, China)	Compaction pressure: 0.1 MPa; Compaction temperature: 30-35 ⁰C (room temperature)	• Briquette dimensions: diameter- 40 mm; height- 5 mm; mass: 5 ± 0.1 g • Drying time of SCG + lignite briquettes increased by 9%, compared to raw SCG briquettes • Here, lignite had negative effect on drying kinetics of SCG briquette	Fu & Chen, 2020
Homogeneous	SCG	-	Lignin (natural binder)	Molding machine (HEBI; XL140118, China)	Compaction pressure: 0.1 MPa; Compaction temperature: 30-35 ⁰C (room temperature)	• Briquette dimensions: diameter- 40 mm; height- 5 mm; mass: 5 ± 0.1 g • Microwave drying was proposed as an efficient technique for drying the SCG briquettes • During microwave drying, two distinct falling rates were reported, with moisture diffusivities reported as 7.89 x 10-9 to 1.75 x 10-8 m2/s during first falling rate period, and 1.09 x 10-9 to 1.81 x 10-8 m2/s during second falling rate period; and average	Fu & Chen, 2020

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						activation energy of both falling rate period as 24.43 W/g • Besides, microwave drying provided sterilization effect, which prolonged the storage of these briquettes for a very long time without any contamination	

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2.7 Fuel Characteristics of SCG Briquettes

Post drying, the compacted briquettes are evaluated for their fuel characteristics, to ensure their compatibility and similarity to existing fossil coals; and in general, are assessed as per international testing standards. Though, these results vary with different testing standards, the suitability of these briquettes are decided, if found in between their permissible range. Likewise, SCG briquettes are also assessed as per international standards, especially ASTM standards, to ensure their fuel characteristics meet the essential requirements of a commercial biofuel.

To begin with, moisture content of the dried compacted SCG briquettes ranged in between 10-15%, depending on the particle size, water absorptivity, brewing technique and drying method (Kang et al., 2017; Brunerová et al., 2019; Ciesielczuk et al., 2015). Though, SCG wastes are dried after brewing, adequate amount of water is added again during compaction for activating the binders (Seco et al., 2020). Even though, wet SCG wastes and briquettes report their moisture content between 20 and 60%, they required less drying time (on average 24 hours) owing to their morphological characteristics; however, binders used for binding these SCG particles required more time drying (Ciesielczuk et al., 2015). Again, this porous morphology of the SCG particles resulted in the low absorption rates of their briquettes. Moreover, briquettes with high moisture content reports high density, performs poorly during combustion, and consumes more time and energy for drying; besides losing their durability (Seco et al., 2020).

Moving on, SCG briquettes are widely recognised for their very low ash content; and on average, report about 1-3%, depending on the particle size and rate of combustion (Kang et al., 2017; Allesina et al., 2017; Ciesielczuk et al., 2015; Somnuk et al., 2017; Caetano et al., 2012). In general, ash content of these SCG wastes is around 1.5%, and tends to increase with addition of binders or additives (Brunerová et al., 2019). Supporting this, addition of xanthum gum as binder increased the ash content of the SCG briquettes from 0.66% to 0.97% (Seco et al., 2020); and, increased from 0.81% to 0.97%, upon increasing the binder concentration from 5% to 10%. Meanwhile, SCG briquettes noted reduction in their ash content from 0.66% to 0.57% and 0.52%, when added 5% and 10% of Guar gum as binder (Espuelas et al., 2020). In short, reduced ash content for these SCG briquettes can be explained by their low metal concentrations (Colantoni et al., 2021); and is predominantly contributed by their binders or additives, instead.

Next up, fixed carbon content and volatile matter of these SCG briquettes were found in the range of 18-20% and 75-77%, respectively (Espuelas et al., 2020), and were primarily responsible for their stable combustion. Studies reported that addition of organic binders increased the fixed carbon content and reduced the volatile matter of these briquettes slightly, which however, favoured their steady burning and heat release rate. Illustrating this, Espuelas et al. (2020) noted rise in fixed carbon content from 18.00% to 19.01% and

19.05%, and reduction in volatile matter to 76.35% and 75.85%, while adding 5% and 10% of xanthan gum during compaction. Likewise, similar concentration of guar gum resulted in increased fixed carbon content to 19.07% and 19.20%, and reduced volatile matter to 76.43% and 76.33%, respectively (Espuelas et al., 2020).

About their calorific content, SCG wastes recorded their heating value between 18.8–26.9 MJ/kg (Haile, 2014; Sołowiej & Neugebauer, 2016; Zuorro & Lavecchia, 2012; Pujol et al., 2013; Mhilu, 2014; Potip & Wongwuttanasatian, 2018; Colantoni et al., 2021; Mata et al., 2018; Sermyagina et al., 2021), while, SCG briquettes maintained their heating value above 22 MJ/kg (Espuelas et al., 2020; Kang et al., 2017). Amongst known biomasses, SCG wastes and their briquettes exhibit fuel characteristics equivalent to lignite (Fu & Chen, 2020); and produce very limited emission levels during emission. Inspite of this, slight reduction in calorific content were noted upon adding binders; yet, their impact is least regarded accounting their contribution in developing high quality briquettes with good durability and strength (Espuelas et al., 2020). For instance, addition of xanthum gum reduced the calorific value of these SCG briquettes from 25.399 MJ/kg to 23.503 MJ/kg (Seco et al., 2020). Supporting this, Figure 3 portrays the reduction in calorific value of these SCG briquettes, with addition of xanthum (XG) and guar (GG) gum (Espuelas et al., 2020). Besides, addition of SCG increased the overall calorific content of the compound briquettes, as their counterparts like sugarcane bagasse, rice husk, saw dust reported inferior CV (Pallavi et al., 2013; Colantoni et al., 2021).

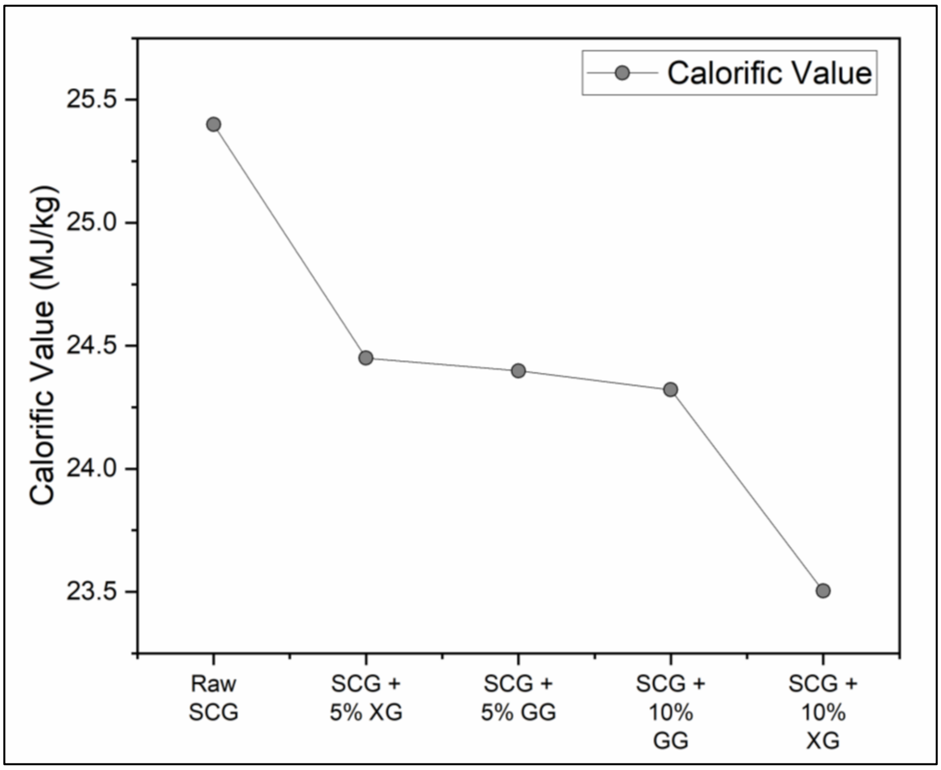

Figure 3: Variation in calorific values of raw SCG briquettes, Xanthan and Guar gum binded briquettes

Following this, density of SCG briquettes were measured in between 669 and 1078 kg/m^3; and was influenced by compaction pressure, moisture content, type of binder, and particle size (Seco et al., 2020; Espuelas et al., 2020; Brunerová et al., 2019). In specific, pure SCG briquettes with 10% moisture content reported their density in between 669 and 735 kg/m^3, while SCG briquettes with 10% organic binders reported in between 672 and 819 kg/m^3 (Seco et al., 2020; Espuelas et al., 2020); and compound briquettes developed from SCG wastes with saw dust and wood shavings reported in between 899.44-1077.49 kg/m^3 (Brunerová et al., 2019). Plainly evident, high moisture content and compaction pressure yielded high density briquettes, and briquettes with low moisture content or poor compaction crumbled during testing and handling.

Besides this, these SCG briquettes reported their durability upto 98% (Brunerová et al., 2019); and were also, again influenced by compaction pressure, binder concentration, moisture content, and particle size. Here, both water and binder content helps establishing van der Waals' forces between the SCG particles under compaction; thus explaining the impossibility of developing raw SCG briquettes with good durability and strength (Rajaseenivasan et al., 2016; Kaliyan & Morey, 2010). Infact, briquettes developed by adding 10% of moisture content failed completely even before the testing; while, binded briquettes held back for a majority portion of the durability test (Seco et al., 2020). Supporting this, Espuelas et al. (2020) revealed that SCG briquettes compacted using 5% of xanthan and 30% of moisture, at 12 MPa withstood for 300 seconds with a minimal loss of mass of 3.9% (Espuelas et al., 2020). Likewise, another study recommended using 10% tapioca starch as binder, and compaction pressure of 140 MPa for developing briquettes with high durability, beyond which resulted in reduced durability (Fehse et al., 2021).

About their elemental composition, pure SCG briquettes reported their carbon, hydrogen, oxygen, and nitrogen as 57.29%, 7.52%, 33.18%, and 2.01%, respectively. Studies reported that carbonized SCG biochar exhibited increased carbon content; while, SCG wastes blended with binders reported briquettes with reduced nitrogen content. Supporting this, Espuelas et al. (2020) concluded that average reduction in nitrogen content for xanthan gum and guar gum were estimated to be 13.93 % and 16.42 %, respectively. Figure 4 illustrates the proximate and elemental composition of briquettes developed from raw SCG, SCG with xanthan gum, and SCG with guar gum (Espuelas et al., 2020).

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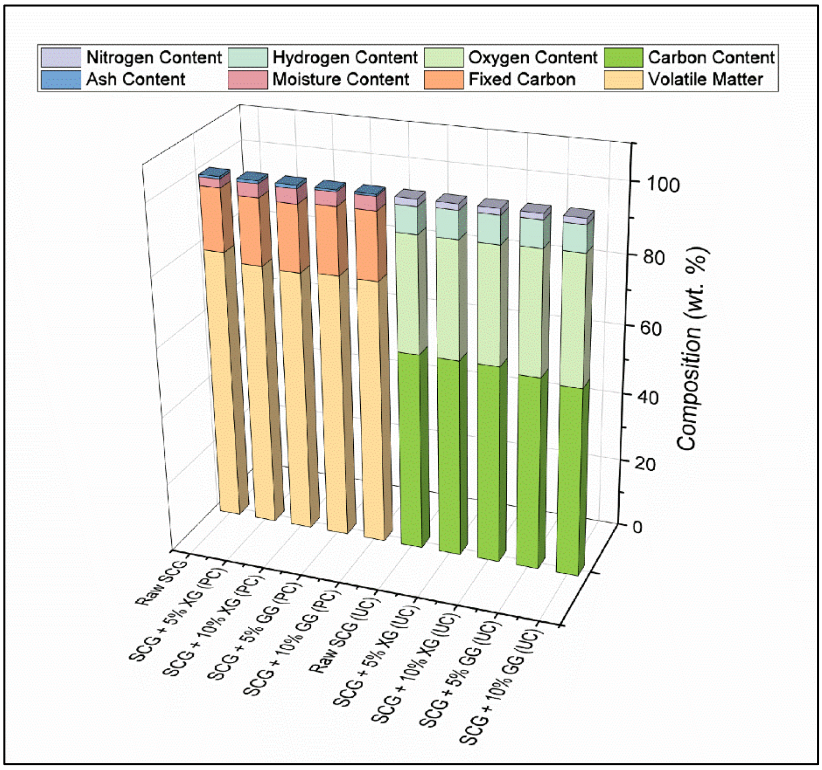

Figure 4: Proximate and elemental composition of raw SCG briquettes, Xanthan and Guar gum binded briquettes

2.8 Combustion Characteristics of SCG Briquettes

Standardly, combustion of any briquettes takes places in three different phases, namely the pre-heating phase, degassing phase and charcoal phase, as defined by Smit and Meincken, 2012; and similar phases were noted for SCG based briquettes, and even pellets (Smit and Meincken, 2012). Recollecting from earlier facts, it is impossible to produce 100% raw SCG briquettes without any additives and binders; yet, it is important to understand the behaviour of their combustion, especially accounting their commercial and large scale applications. However, this can be accomplished by studying the combustion characteristics of these briquettes developed from raw SCG with minimal amount of additive or binder. Responding to this, Potip & Wongwuttanasatian (2018) studied the combustion behaviour of the briquettes, produced by compacting raw SCG wastes with 10% of crude glycerol, for varied inlet air supply (Potip & Wongwuttanasatian, 2018). Here, this study varied the inlet air supply for combustion of these briquettes at 550%, 700%, 850% and 1000% theoretical air; and chose 850% theoretical air as the most ideal inlet air supply. Preliminary results suggested that these SCG briquettes required inlet air supply higher than 500% theoretical air for effective combustion, and was influenced by both SCG and glycerol molecules (Limousy et al., 2015; Pilusa et al., 2013). This was because, briquettes reporting density between 400 and 700 kg/m3 uses only 150%–250% theoretical air; whereas, density of these briquettes ranged in between 870-880 kg/m3, thus seeking high inlet air supply (Mitchell et al., 2016; Wakchaure & Sharma, 2007). Besides, rate and temperature of the combustion increased propotionally with concentration of crude glycerol. And, phases of SCG-glycerol briquettes' combustion conveyed that the preheating phase lasted for about 28–35 minutes, while, degassing phase lasted for about 15-25 minutes, with highest rate of combustion noted during the preheating phase, after 9-18 minutes.

Looking into the stoichiometric combustion equation for 100g SCG (equation 1) and 1 mole of crude glycerol (equation 2) at 100% theoretical air, 200 g of each sample would require an air flow rate of 2.259 and 1.684 m3/h, respectively, and 32 minutes for their complete combustion (Potip & Wongwuttanasatian, 2018). Figure 5 depicts the calculated air flow rate required for SCG-glycerol briquettes for their varying mixing ratios and inlet air supply.

$$(4.551C + 3.295H_2 + 1.088O_2 + 0.142N_2) + 5.111(O_2 + 3.76N_2) + Ash \rightarrow 4.551CO_2 + 3.295H_2O + 19.359N_2 + Ash \quad \text{(Equation 1)}$$

$$C_3H_8O_3 + 3.5\,(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 13.16N_2 \quad \text{(Equation 2)}$$

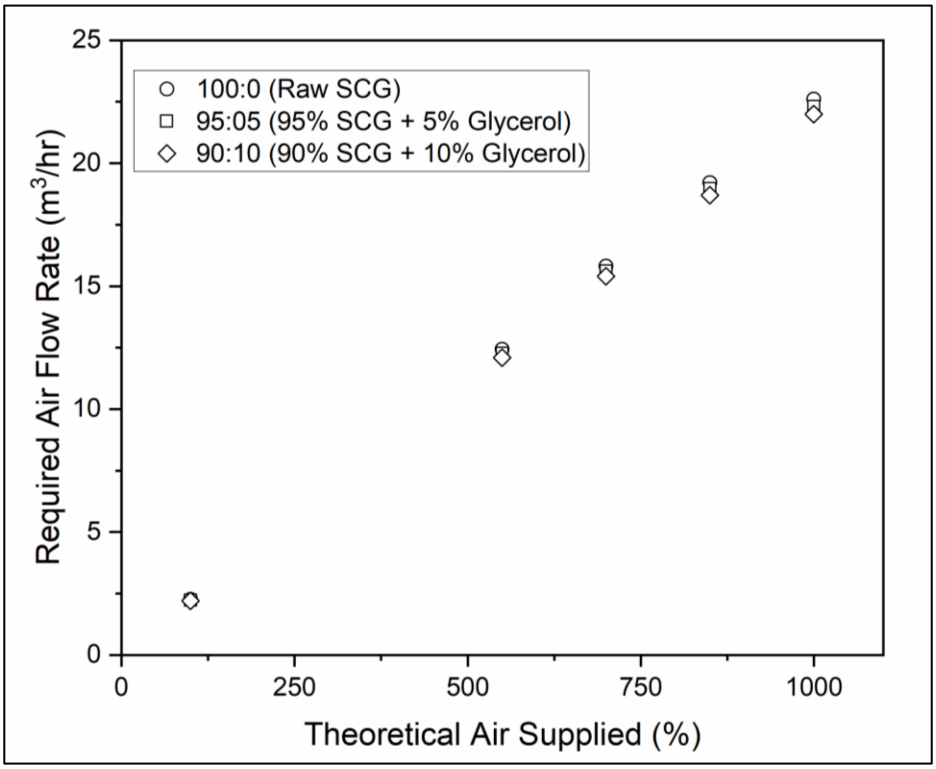

Figure 5: Required air flow rate, as computed with respect to theoretical air supply, for SCG + glycerol briquettes (Potip and Wongwuttanasatian, 2018)

Furthermore, heating value of these SCG briquettes were measured as 21.14-21.55 MJ/kg, and their combustion rate and temperatures (Figure 6a and 6b), for varying inlet air supply, were reported in between 0.09 and 0.18 g/s, and 463 and 533°C, respectively. Similar results were noted upon studying the combustion characteristics of briquettes developed from SCG wastes mixed with 10% of xanthan gum; which reported superior rate of combustion along with minimal amount of ash content (Seco et al., 2020). Moreover, addition of binders, especially organic gums reduced the calorific content of the SCG briquettes; nevertheless, favoured for their steady combustion (Espuelas et al., 2020). Moving on, study on combustion performance of SCG-anthracite briquettes, blended in 60:40 ratio suggested the deformation temperature, softening temperature, hemispherical temperature and flow temperature of the raw SCG wastes as 1252.85 ⁰C (1526 K), 1352.85 ⁰C (1626 K), 1413.85 ⁰C (1687 K) and 1517.85 ⁰C (1791 K), respectively, and were improved by introducing anthracite along with it. In addition, burning characteristics (Figure 7a and 7b) depicted that raw SCG briquettes exhibited higher rate of burning than anthracite at all temperatures, owing to their high volatile content.

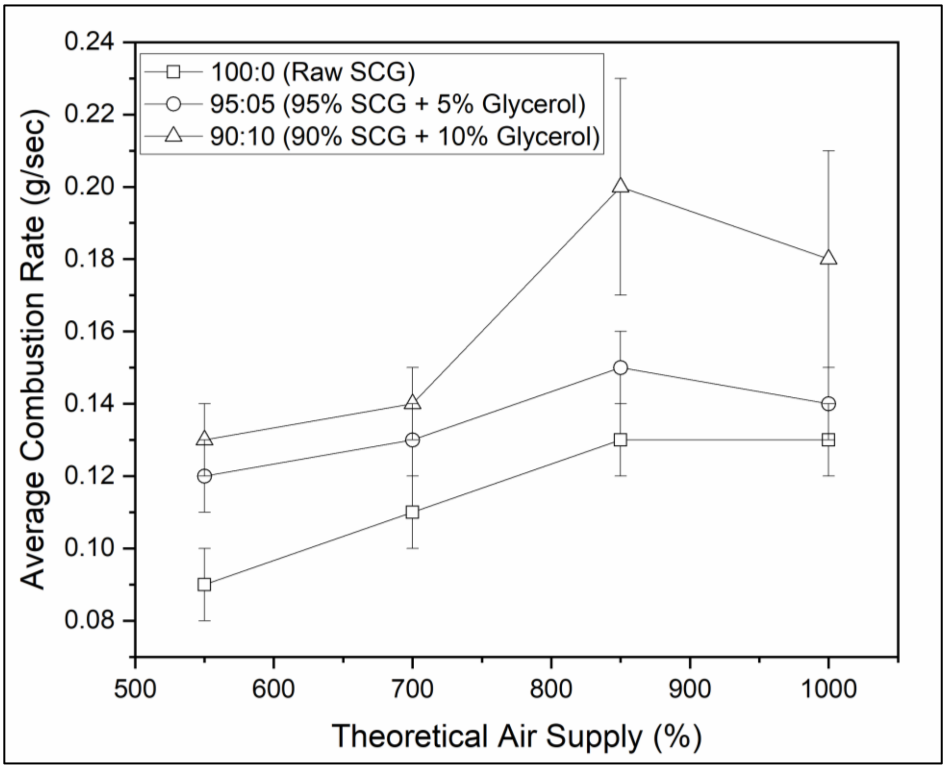

Figure 6a: Average combustion rate of SCG, and SCG-Glycerol briquettes (Potip and Wongwuttanasatian, 2018)

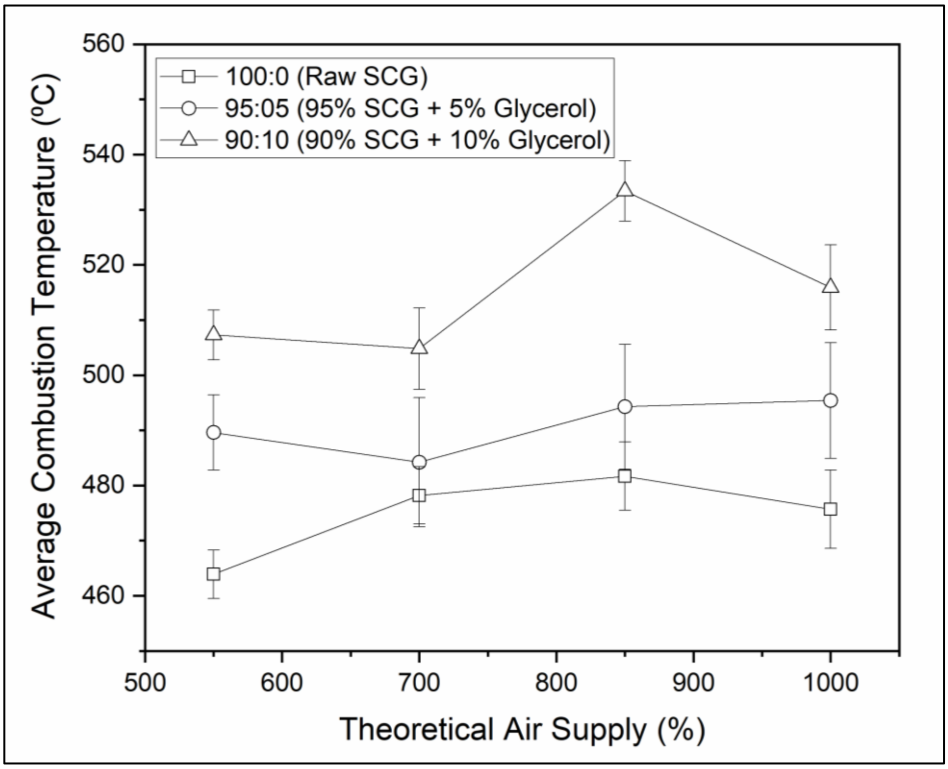

Figure 6b: Average combustion temperature of SCG, and SCG-Glycerol briquettes (Potip and Wongwuttanasatian, 2018)

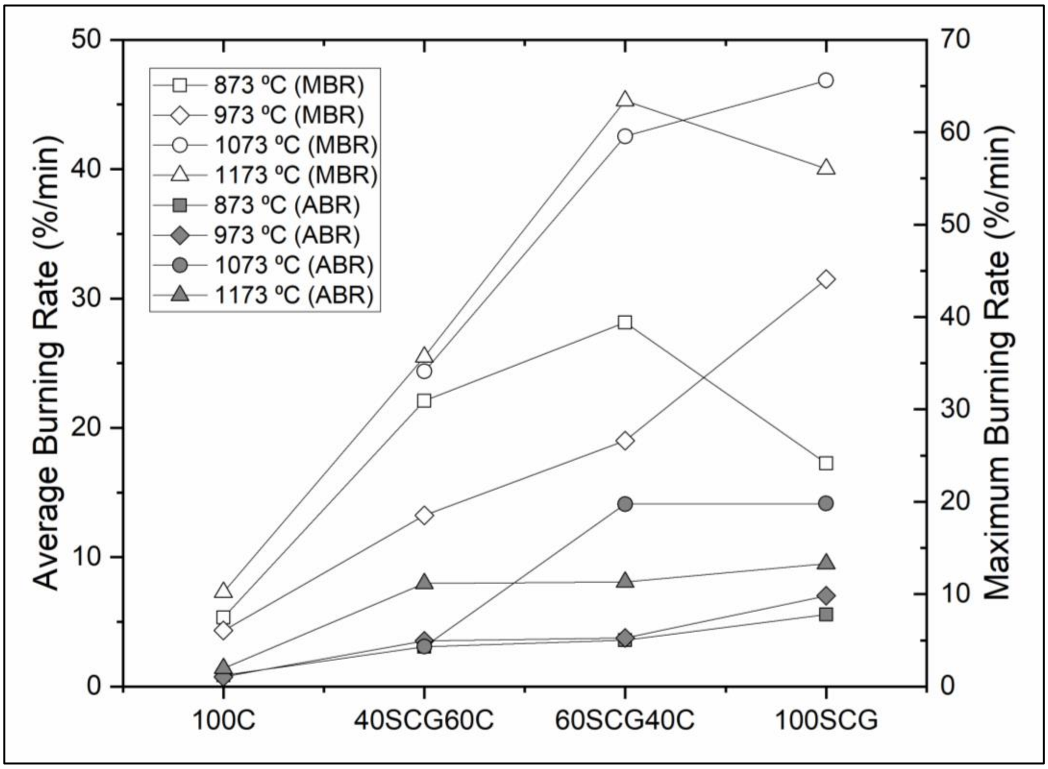

Figure 7a: Average and Maximum Burning rates of raw SCG and SCG-Anthracite briquettes
(Wei et al., 2019)

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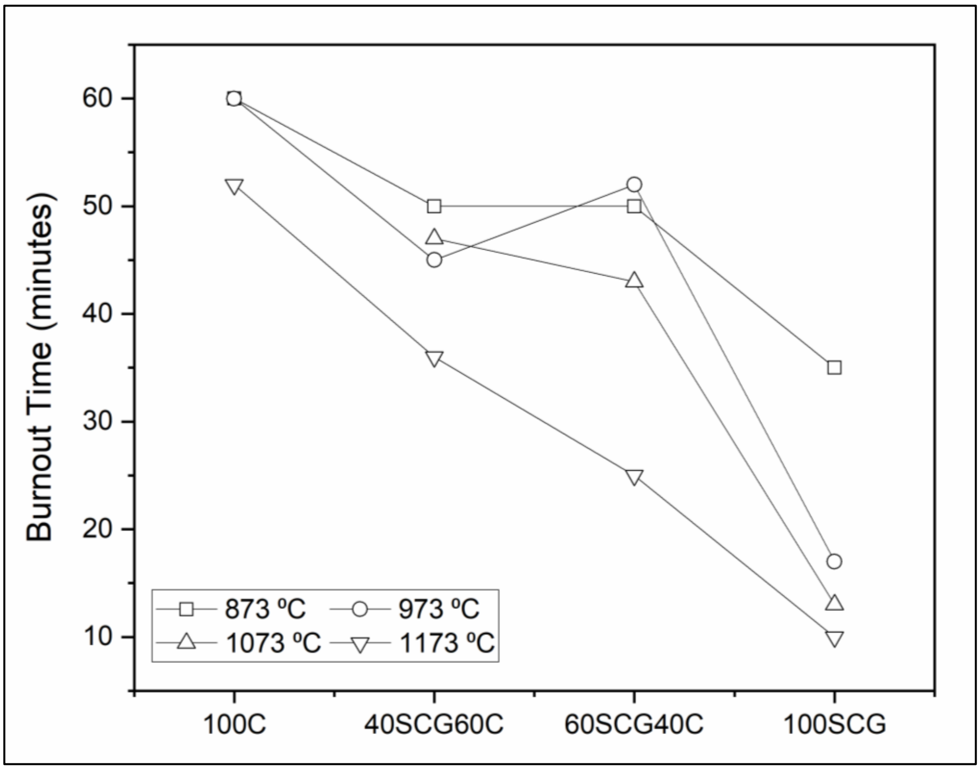

Figure 7b: Burnout time of raw SCG and SCG-Anthracite briquettes (Wei et al., 2019)

Looking into their emission characteristics, SCG briquettes reported better emission (CO_2, O_2, CO and NOx) levels than compared to commercial gas and wooden briquettes (Kang et al., 2017); and were well within the MCP, ELVs and REL-STEL (NIOSH) Standards (Potip & Wongwuttanasatian, 2018). Table 6 consolidates the concentrations of different emissions from the SCG briquettes and even pellets, measured within their permissible range as per international standards (Potip & Wongwuttanasatian, 2018; Kim et al., 2022; Limousy et al., 2013). Here, high concentration of NOx and CO2 emissions were contributed by the fuel bound carbon and nitrogen molecules; whereas, zero sulphur emissions signified the absence of sulphur content in the SCG molecules (Potip & Wongwuttanasatian, 2018). Meanwhile, all blends of SCG-anthracite briquettes reported rise in NOx emission in between 2.80 and 20.98 PPM, and reduction in SOx emissions, with increase in concentration of SCG wastes. Again, reduced ash content were noticed in raw SCG briquettes, and increased with rising anthracite concentrations. Figure 8 demonstrates the composition of different metal oxides characterised from the residual ash content of anthracite and SCG (Wei et al., 2019).

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Table 6: Emission levels in flue gas emission of SCG briquettes and pellets, ranging within the permissible standards

Emission	SCG + 10% Glycerol	SCG Char with bottom ash and kaolinite clay Briquettes	100% SCG Char Pellets	100% SCG Char Pellets	50% SCG + 50% Pine Dust Pellets	50% SCG + 50% Pine Dust Pellets
	(Potip and Wongwuttanasatian, 2018)	(Kim et al., 2022)	(Limousy et al., 2013)	(Limousy et al., 2013)	(Limousy et al., 2013)	(Limousy et al., 2013)
CO Emission	1262 mg/m^3	8-48 ppm	1785 ppm	3069 ppm	353 ppm	606 ppm
CO_2 Emission	19%	929-2180 ppm	-	-	-	-
NO_x Emission	38 mg/m^3	3.7-0.7 ppm	178 ppm	79 ppm	8 ppm	22 ppm
O_2 Emission	21%	-	-	-	-	-
HC Emission	270 mg/m^3	-	1071 mg/m^3	1472 mg/m^3	310 mg/m^3	426 mg/m^3
SO_2 Emission	0	7-1.4 ppm	0	0	0	0

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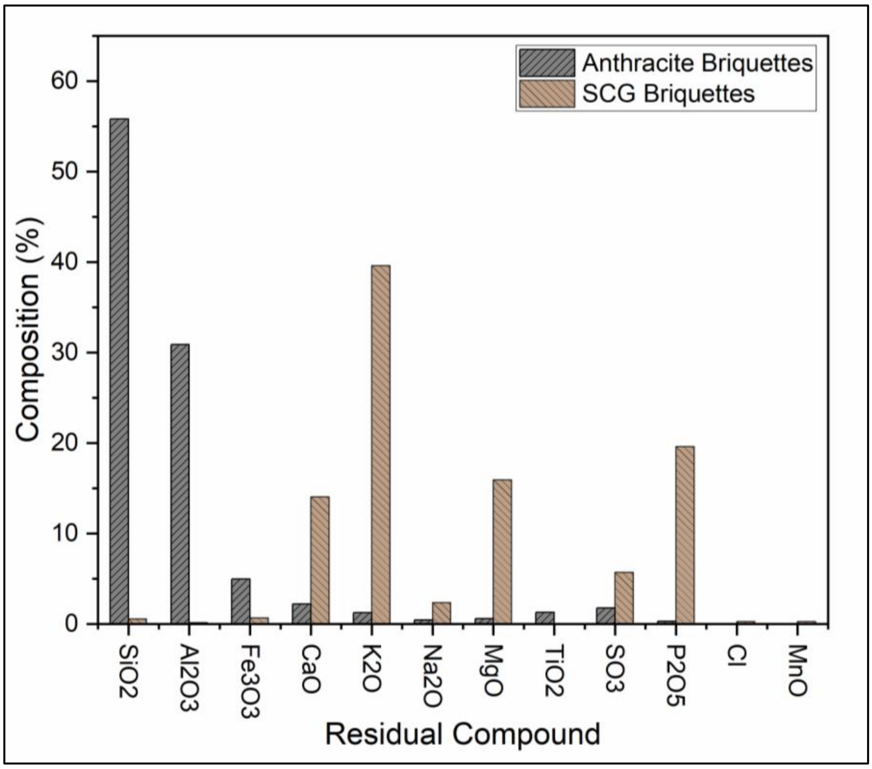

Figure 8: Residual composition of ash (in %) from pure anthracite and raw SCG briquettes

3. Conclusion

Thus, a comprehensive review comprising of summarised list of data relevant to the availability and chemistry, pre-treatments and productions, fuel and burning characteristics of SCG wastes and their briquettes have been compiled successfully. Following are the key conclusions deduced from this literature study:

(i) SCG wastes are abundantly available biomass, having good potential as raw feedstock for valorising into biofuels, with least concerns over food vs. fuel conflict

(ii) With high carbon and hydrogen content, these wastes reported high calorific content, almost similar to that of existing fossil coal

(iii) Owing to their oil content and irregular morphology, it is always highly impossible to develop 100% raw SCG briquettes with their fuel characteristics meeting the standards; inspite of their high lignin content.

(iv) Citing this, these SCG wastes were either carbonised or mixed with additive for compaction into briquettes, which required both binder and water content to establish higher level of bonding between their particles.

(v) Besides, increase in binder dosage and reduction in particle size had significant effect on fuel properties of the SCG briquettes; and resulted in increased moisture and ash content, fixed carbon content, density and compressive strength.

(vi) About their combustion charactertsitcs, high volatility and fixed carbon content favoured stable combustion of these briquettes; and reported superior rate of combustion along with minimal amount of ash content.

(vii) Summing up this, it was fairly evident that these briquettes can be regarded as successful replacement or supplement for fossil coals; and is expected to cut short the fuel demand and also impact to environment.

Besides, this chapter also shares knowledge related to the entire life cycle of these SCG briquettes, helps individual in identifying the possible opportunities in terms of employment, capital investment and trading, and educates the readers about choosing these SCG briquettes for right application. As always, introducing renewable biofuels for meeting the energy demand helps in preserving the environment safely and develop sustainably.

Author Contributions: Conceptualization: SGR and AM; Methodology: SCG and RS; Software: SGR; Data curation: SGR and AM; Resources: AM and RM; Writing-original draft preparation: SGR and AM; Writing—review and editing: SGR, RS and RM; Supervision: RS; Project administration: RM. All authors have read and agreed to the published version of the manuscript."

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