# CHARACTERIZATION OF BIOMASS BRIQUETTES FROM SPENT COFFEE GROUNDS AND XANTHAN GUM USING LOW PRESSURE AND TEMPERATURE

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## ABSTRACT

This paper analyzes the ability of the SCG for briquettes production based on the use of xanthan gum as binder under low pressure and low temperature biomass manufacturing conditions. Briquettes were manufactured at room temperature, at 10, 15, 20, 25 and 30% of moisture content and 8, 10 and 12 MPa of compaction pressure. Raw SCG samples reached dry densities between 0.669 and 0.735 g/cm$^3$ for the samples with a moisture content of 15% and 8 MPa, and 10% and 12 MPa, respectively. Samples treated with 10% of xanthan gum got densities between 0.672 and 0.819 g/cm$^3$ depending on the moisture content and the compaction pressure. No one of the raw SCG combinations passed the durability test meanwhile xanthan ones with 30% of moisture content obtained the best results with a loss of mass of 9.1% for the combination compacted at 10 MPa. Raw SCG samples showed water absorption values between 0.498% and 0.846% meanwhile xanthan samples water absorption oscillated between 0.427% and 1.065%. Xanthan gum increased the SCG ashes content from 0.66% to 0.97% and decreased the Lower Heating Value (LHV) from 25,399 J/g of the pure raw SCG to 23,503 J/g. Thermogravimetric tests showed that xanthan gum mix compared to the raw SCG increased as well the volatile peak from 61.54 mW to 81.94 mW as the mass loss rate in the volatile stage from -0.0178 mg/s to -0.0184 mg/s.

## KEYWORDS

Spent coffee grounds; fuel; biomass; briquette; xanthan gum

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## 1. INTRODUCTION

Coffee is the most popular beverage in the world and the second traded commodity after petroleum [1]. International Coffee Organization estimated in November 2017 a yearly world coffee beans consumption of 9.44 millions of tonnes, with an increase since 2014 of 1.9% [2]. For the preparation of this beverage, grinded toasted coffee beans are contacted with hot water or steam to extract the soluble compounds and aromas. After the extraction, solid Spent Coffee Grounds (SCG) remains as a wet solid waste. From 1 tonne of raw coffee beans are produced about 550-650 kg of SCG, with a moisture content between 55 and 88% in dry basis, depending on the extraction process used [3, 4]. SCG has a high pollutant potential because of the toxic nature of substances contained like caffeine, tannins or polyphenols and requires high quantities of oxygen to degrade it [5, 6]. The large SCG amounts generated everyday around the world, its low market value and the lack of any effective big scale solutions, turn this waste into a global environmental issue [7, 8]. Its management must be solved in a circular economy thinking way, considering SCG not as a waste but as a valuable resource. New valorization ways are required to take advantage of this resource, avoiding the disposal in landfills, the nowadays main management solution [9–12]. More than a half of the SCG are generated in industry or coffee shops, what could favor the implementation of large scale valorization solutions in advantageous conditions [6]. Santos et al. [4] and Zhang and Sun [13] stated the convenience of this waste for composting in plants. Other authors demonstrated the potential of SCG for the extraction of caffeine and phenolic compounds or for the synthesis of sugars, biodiesel and ethanol, among others high added value products [1, 12, 14, 15]. The manufacture of solid biomass fuels is other application of the SCG with big environmental and economic benefits. Dried coffee grounds have a Lower Heating Value (LHV) of 18.8-26.9 MJ/kg which is comparable with other biomasses like wood sawdust or wheat straw [5, 6, 12, 14, 16]. SCG could become a large scale, low cost and low environmental impact renewable energy resource [17, 18]. SCG densification is required to produce a higher calorific biomass fuel, suitable as a commodity product because of the transport, handling, feeding and combustion equipment requirements [19–21]. This process would require the raw SCG moisture content reduction to increase the compaction efficiency and obtaining a good quality and durable product [22]. Densification is usually carried out by means of different high pressure and high temperature processes, eventually accompanied by biomass torrefaction or the use of binding additives, that create solid bridges and cohesion forces between biomass particles [5, 17, 19, 21, 23–31]. Some authors have demonstrated the ability of the SCG for the pellets production [5, 10, 15, 16]. Limousy et al. [32], stated the ability of the wood chips briquettes manufacturing containing 20% of SCG. Nowadays the 100% SCG briquettes production remains as a challenge. Few investigations about low energy fuel manufacturing systems have been carried out. This could suppose a potential increase of the sustainability of solid biomass fuels as renewable energy source. Thabuot et al. [33] demonstrated the convenience of briquettes of biomass wastes treated with 20% of palm fiber and 20% of molasses under low pressure at room temperature. Rajaseenivasan et al. [18] stated that sawdust briquettes manufactured at 33 MPa compacting pressure, increasing considerably their strength when they were treated with neem powder, with only a little reduction in burning rate. Yank et al. [34] investigated the use of different organic binders for the rice husk low pressure briquettes manufacturing reaching good results for binder dosages between 10-15%. Soleimani et al. [35] stated the effectiveness of the carbohydrates as binders in the biomass pellets densification at high pressure manufacturing conditions and suggested the convenience of reducing the densification pressure.

This paper analyzes the ability of the SCG raw and treated with xanthan gum for the low pressure and low temperature briquettes manufacturing. Xanthan gum, widely used as food thickener, has a polysaccharide structure and is easily soluble in water. It was chosen for laboratory investigation because of the following reasons: (i) It is a renewable resource because is produced by fermentation of sugar monomers, (ii) it lacks of Nitrogen, Sulfur or Chlorine which could generate emissions and (iii) as its hydration consumes water, it could allow the processing of SCG with a high moisture content, decreasing the drying needs. Low pressure and low temperature briquettes manufacturing could help to decrease the biomass fuel production energy consumption as well to simplify the manufacturing facilities. Briquettes physical as well as combustion essential characteristics were considered. Density determines the fuel heating power by volume unit and transport expenses. Abrasion was considered as indicator of briquettes durability during the storage and handling as well as of the dust production. Water absorption was used to estimate the stability of briquettes against environmental moisture. Proximate analysis, ultimate analysis, Lower Heating Value (LHV) and thermogravimetric analysis were considered for briquettes combustion quality characterization.

## 2. MATERIALS AND METHODS

### 2.1. MATERIALS

For this research development, a sample of one tonne of SCG from an instant coffee production factory, was provided by BIOPAR S.L. This company is specialized in biomass pellets manufacturing. The sample was collected in the company outdoor storage where the incoming material is stored and air dried. The sample was homogenized and physically and chemically characterized in laboratory.

A commercial xanthan gum powder was used as binder for the briquettes manufacturing. This sample was provided by the company Leylas Dely (UK).

## 2.2. PREPARATION OF BIOMASS BRIQUETTES

The SCG moisture content was obtained by drying of a sample in an oven at 105 ºC during 24 hours, showing a moisture content of 19.8%. Raw SCG was oven dried to homogenize the initial moisture content of all the mixes at 8%. Briquettes manufacturing moisture content, binder dosage and compaction pressure for the experimental investigation were selected based on previous published works [15–17, 20, 21, 23, 25, 30–34, 36]. Manufacturing was carried out in laboratory at room conditions. When a combination comprised the use of binder, this was added to the dry SCG and carefully mixed in a laboratory mixer for 5 minutes. After that it was added slowly the water required to reach the defined mix moisture content and mixed for 5 minutes again to guarantee the correct homogenization. After these processes the mixes were densified by compaction. For the briquettes densification a laboratory press and a 65 mm diameter cylindrical mold were used. Each sample was prepared with 100 g of mix and introduced through the upper part of the mold. The compaction process was carried out by means of the press piston at a constant speed of 50 mm/minute. The compaction pressures considered for the briquettes manufacturing were 8, 10, and12 MPa. 30, 45 and 60 MPa pressures were also tested to state the compaction energy required to get the SCG maximum dry density limit. Once the compaction pressure was reached, the samples were immediately unmolded. A sample of each combinations were used to determine the water content after manufacturing by drying for 24 hours and weighting. The rest of the briquettes were maintained at room conditions one week before testing.  A total of 30 briquette combinations were manufactured. The codification used for their managing was as follows: (GK)-(MC)W-(PR) being:

GK the SCG kind, in this investigation raw SCG, (R)

MC the percentage of moisture content

PR the compaction pressure

## 2.3. BRIQUETTES QUALITY TESTING

The characterization of the ability of SCG for the functional briquettes manufacturing was carried out by means of dry density, durability and water absorption tests. Dry density was obtained dividing the briquette dry mass by its apparent volume obtained by measuring 10 briquettes with an electronic caliper. Durability was characterized by means of an abrasion and knocking test adapted from the European Standard UNE EN ISO 17831-2. It consisted on the determination of briquettes mass loss, at different test times, along 5 minutes under rotation in a 600 mm of diameter rotatory drum 45 degrees tilted. To favor the knocking and avoid the briquettes rolling, two 200 mm high plates were placed into the rotatory drum. Briquettes water absorption test was carried out in a wet chamber at 20 ºC and 100% of relative humidity along 6 hours. Briquettes were weighted at different testing times to measure the weight increases which was expressed as percentage of the initial briquette mass. Durability and water absorption tests were carried out with a set of 10 briquettes at the same time to avoid the results dispersion. Proximate analyses were carried out in a METTLER-TOLEDO TG-DSC2 system. Tests were conducted with 10 mg of sample under an air flux of 100 ml/min and a heating rate of 10 C/min. A $N_2$ atmosphere was used from room temperature to 600 ºC and a $N_2$:$O_2$ (4:1) atmosphere from 600 ºC to 900 ºC. Combustion test were carried out in the same equipment and the same conditions from room temperature to 900 ºC, with a $N_2$:$O_2$ (4:1) oxidizing atmosphere. The element compositions of the raw materials were analyzed by means of a ThermoFinnigan FlashEA 1112 analyzer. Tests were conducted in Helium atmosphere at 900 ºC with oxygen injection and chromatographic columns gases separation. The LHV were determined using an IKA C5003 calorimeter.

## 3. RESULTS AND DISCUSSION

### 3.1. DRY DENSITY

Figure 1 shows the relationship between compaction energy and the briquettes dry density reached when SCG, with a moisture content of 10%, was compressed up to 60 MPa. 10% was chosen as reference because this moisture content was the lowest that allowed the briquettes unmolding and handling during this test.

FIGURE 1

SCG dry density showed a direct relationship with the compaction energy up to 30 MPa. These results agree with those obtained by Rajaseenivasan et al.[18], Muazu and Stegeman [26] or Rahaman and Salam [27] who obtained a direct relationship between the briquettes dry density and the compaction pressure. For higher pressures, dry density maintained steady, pointing up the limit of the SCG particles for its densification, with a maximum dry density of 0.899 g/cm$^3$. Above this compaction pressure SCG shows an elastic behavior and briquettes density improvement is saturated probably due to the existence of only weak particle surface-bonds [38, 39].

Figure 2 shows the briquettes dry densities obtained by pure SCG and containing xanthan gum combinations, with different moisture contents and compaction energies. Raw SCG combination with a moisture content of 10% (R10W) was added in Figure 2-b as reference.

FIGURE 2

Pure SCG briquette dry densities as expected showed a direct relationship with the compaction energies of 8, 10 and 12 MPa. An indirect relationship between the moisture content and the sample dry densities was observed. Water partially fills the pores of the mix, avoiding the occupation of these pores by the SCG particles during the compaction. Thus, the maximum dry density of 0.735 g/cm$^3$, was obtained by the combination with 10% of moisture at a 12 MPa compaction energy. On xanthan combinations higher densities were observed compared to SCG combinations because of the presence of the binder in the mixes. The lower moisture content that allowed the briquettes testing was 15%. Samples with 10% of moisture were not functional as they collapsed during handling for testing process. Xanthan combinations also showed a direct relationship with the compaction energy and an indirect relationship with the moisture content. The highest dry density was obtained by the samples with 15% of moisture content, with 0.819 g/cm$^3$.

**3.2. DURABILITY**

Figure 3 shows the results obtained by the SCG and the xanthan combinations in the durability test, expressed as percentage of lost mass of the initial value.

FIGURE 3

SCG combinations with 10% of moisture were not considered as they were completely destroyed before 5 seconds of testing time. The other combinations of SCG showed low durability that slightly increased as moisture content and compaction energy did demonstrating a beneficial effect of moisture and the compaction pressure on the briquettes durability. Water acts as both a binding agent and a lubricant and helps develop van der Waals' forces by increasing the area of contact between particles [18, 40]. All the combinations manufactured at 8 MPa were completely destroyed at 20 seconds of testing time, showing a loss of mass at 10 seconds inversely related to the briquettes moisture content. At 10 MPa a similar behavior was observed, although the combination with 30% of moisture overcame the 20 seconds of testing time maintaining 17% of the origin mass. In the case of 12 MPa manufacturing pressures, combinations with 15, 20 and 25% of moisture overcame 20 seconds of testing time, being R30W12 the best pure SCG combination, reaching the 30 seconds with a remaining mass of 19%.

For the xanthan combinations at all the compaction pressures, lost mass during this test decreased as moisture content increased. In these combinations water not only acts as binder and particles lubricant but it also solubilizes the xanthan gum developing its binding ability [40]. This improvement of the samples durability was clearer for 25 and 30% of water content. These high moisture contents compared to the usual values published in the literature are required for the xanthan gum solubilization [21] The combinations with 25% of moisture showed a direct relationship between durability and compaction pressure. Thus, the final losses of mass were 65.6, 56.6 and 52.7% for 8, 10 and 12 MPa respectively. Combinations containing 30% of moisture reached 22.5 and 21.9% of mass lost for 8 and 12 MPa compaction pressures, showing the best durability result of 9.10% of mass loss at an optimum compaction of 10 MPa.

## 3.3. WATER ABSORPTION

Figure 4 shows the results obtained in the water absorption test by the raw SCG and the xanthan briquettes.

FIGURE 4

Water absorption showed a direct relationship with the testing time for all the combinations. Nevertheless significant differences were observed between pure SCG and xanthan samples, among water absorption patterns as well as final values. Pure SCG samples in general showed lower water absorption pattern variability between combinations than the xanthan ones. No relationships were observed between the water absorption patterns and the sample moisture contents or the manufacturing pressures. Pure SCG samples final water absorption values showed lower variability than the xanthan ones. Thus, for 8MPa of compaction pressure, pure SCG and xanthan samples final water absorption values oscillated between 0.75 and 0.85% and from 0.45 to 1.10% respectively. For 10 MPa, the same samples reached from 0.50 to 0.84% and from 0.32 to 1.01% and for 12 MPa from 0.71 to 0.44% and from 0.43 to 0.92% respectively. As well as in the case of the water absorption patterns, final values did not show any relationships with the sample moisture contents or the manufacturing pressures.

## 3.4. COMBUSTION CHARACTERISTICS

Proximate analysis, ultimate analysis and LHV of pure SCG and the SCG with 10% of xanthan gum are shown in Table 1.

TABLE 1

SCG shows adequate combustion characteristics compared to other biomasses, specially its low ashes content [18, 26, 41–44]. Compared to pure SCG briquettes xanthan gum containing combinations showed a lower volatile matter content and a higher fixed carbon that could facilitate a more stable combustion. On the other hand, xanthan gum increased the ash content from 0.66% to 0.97%, pointing up a slight decrease of the quality as solid fuel, but maintaining the ash content lower than 6% required by the ISO 17225-7 Standard for the non-woody briquettes. Ultimate analysis showed a decrease of the Nitrogen content from 2.01% in the pure SCG combination to 1.72% when xanthan gum was added. This would potentially decrease the pollutant $NO_x$ combustion emissions of these combinations. LHV decreased from 25,399 J/g of the pure raw SCG to 23,503 J/g, revealing a loss of heating power of 7.5% because of the partial substitution in the briquettes of SCG by xanthan gum.

Figure 5 shows the thermogravimetric analysis of the pure SCG and xanthan containing mixes.

FIGURE 5

Thermogravimetric curves (TG) show the typical four stages in the combustion processes: (1) dewatering, (2) volatilization and burning, (3) char burning and (4) burnout. These curves suggest a lower content of volatiles and fixed carbon of the binder combinations compared to the raw SCG in apparent contradiction with the values showed in Table 1. This was attributed to the close results obtained for each combinations, the instrumental errors and the inhomogeneities of the small samples size (about 40 mg). As DTG shows, the combustion of raw SCG and the xanthan mixes generate two exothermic peaks due to the burning of volatile and fixed carbon. In the case of the raw SCG, the fixed carbon peak is higher than the one due to the volatiles burning and could be related to a more stable combustion. Opposite of what was expected based on the proximate analysis, xanthan gum mix increased the volatile peak and decreased the fixed carbon one. These results, who could suggest a lower quality of the combustion of the gum containing combinations, do not match with the volatile contents shown in Table 1 by the same reasons that the TG curve. Finally DTA curves showed a slight increase in the mass loss rate in the volatile stage for the xanthan combination compared to the raw SCG one.

## 4. CONCLUSIONS

This experimental investigation demonstrated the low ability of the pure raw SCG for the low energy functional briquette manufacturing. It is mainly due to the high water content of this material, its low densification possibilities and its low hardening properties under pressure. Raw SCG briquettes showed low durability against handling, storage or feeding. On the other hand, combinations containing 10% of xanthan gum demonstrated their ability to produce briquettes that reached required commercial dry densities, showed low water absorption capacity and high durability. Results of the water absorption and durability tests improved as briquette water content increased, because of the xanthan gum hydration needs. This would facilitate the use of SCG with a high moisture content, close to the generation one, eventually reducing the energy required or the time in open air drying. The combustion test results demonstrated that xanthan gum slightly decreased the mixes LHV, increased the ashes content, and potentially reduced the $NO_x$ pollutant emissions. Volatile and fixed carbon contents showed contradictory results depending on the tests carried out, demonstrating slight differences between combinations. These combustion results in addition to the clear improvement of the mechanical properties shows the high potential of the xanthan based, low temperature and low pressure SCG fuel briquettes manufacturing.

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## REFERENCES

1. Peshev D, Mitev D, Peeva L, Peev G (2018) Valorization of spent coffee grounds – A new approach. Sep Purif Technol 192:271–277. https://doi.org/10.1016/j.seppur.2017.10.021
2. International Coffee Organization (2018) Coffee market recovers slightly from December slump. In: http://www.ico.org/. http://www.ico.org/
3. Gómez-De La Cruz FJ, Cruz-Peragón F, Casanova-Peláez PJ, Palomar-Carnicero JM (2015) A vital stage in the large-scale production of biofuels from spent coffee grounds: The drying kinetics. Fuel Process Technol 130:188–196. https://doi.org/10.1016/j.fuproc.2014.10.012
4. Santos C, Fonseca J, Aires A, et al (2017) Effect of different rates of spent coffee grounds (SCG) on composting process, gaseous emissions and quality of end-product. Waste Manag 59:37–47. https://doi.org/10.1016/j.wasman.2016.10.020
5. Limousy L, Jeguirim M, Dutournié P, et al (2013) Gaseous products and particulate matter emissions of biomass residential boiler fired with spent coffee grounds pellets. Fuel 107:323–329. https://doi.org/10.1016/j.fuel.2012.10.019
6. Mata TM, Martins AA, Caetano NS (2018) Bio-refinery approach for spent coffee grounds valorization. Bioresour Technol 247:1077–1084. https://doi.org/10.1016/j.biortech.2017.09.106
7. Chen J, Liu J, He Y, et al (2017) Investigation of co-combustion characteristics of sewage sludge and coffee grounds mixtures using thermogravimetric analysis coupled to artificial neural networks modeling. Bioresour Technol 225:234–245. https://doi.org/10.1016/j.biortech.2016.11.069
8. Kourmentza C, Economou CN, Tsafrakidou P, Kornaros M (2018) Spent coffee grounds make much more than waste: Exploring recent advances and future exploitation strategies for the valorization of an emerging food waste stream. J Clean Prod 172:980–992. https://doi.org/10.1016/j.jclepro.2017.10.088
9. Zuorro A, Lavecchia R (2012) Spent coffee grounds as a valuable source of phenolic compounds and bioenergy. J Clean Prod 34:49–56.

https://doi.org/10.1016/j.jclepro.2011.12.003

10. Allesina G, Pedrazzi S, Allegretti F, Tartarini P (2017) Spent coffee grounds as heat source for coffee roasting plants: Experimental validation and case study. Appl Therm Eng 126:730–736. https://doi.org/10.1016/j.applthermaleng.2017.07.202

11. Goglio P, Smith WN, Worth DE, et al (2017) Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems A Canadian scenario assessment.pdf. J Clean Prod 1–11. https://doi.org/10.1016/j.jclepro.2017.06.175

12. Karmee SK (2017) A spent coffee grounds based biorefinery for the production of biofuels, biopolymers, antioxidants and biocomposites. Waste Manag 72:240–254. https://doi.org/10.1016/j.wasman.2017.10.042

13. Zhang L, Sun X (2017) Using cow dung and spent coffee grounds to enhance the two-stage co-composting of green waste. Bioresour Technol 245:152–161. https://doi.org/10.1016/j.biortech.2017.08.147

14. Mussatto SI, Carneiro LM, Silva JPA, et al (2011) A study on chemical constituents and sugars extraction from spent coffee grounds. Carbohydr Polym 83:368–374. https://doi.org/10.1016/j.carbpol.2010.07.063

15. Haile M (2014) Integrated volarization of spent coffee grounds to biofuels. Biofuel Res J 1:65–69. https://doi.org/10.18331/BRJ2015.1.2.6

16. Kang SB, Oh HY, Kim JJ, Choi KS (2017) Characteristics of spent coffee ground as a fuel and combustion test in a small boiler (6.5 kW). Renew Energy 113:1208–1214. https://doi.org/10.1016/j.renene.2017.06.092

17. Chou CS, Lin SH, Peng CC, Lu WC (2009) The optimum conditions for preparing solid fuel briquette of rice straw by a piston-mold process using the Taguchi method. Fuel Process Technol 90:1041–1046. https://doi.org/10.1016/j.fuproc.2009.04.007

18. Rajaseenivasan T, Srinivasan V, Syed Mohamed Qadir G, Srithar K (2016) An investigation on the performance of sawdust briquette blending with neem powder. Alexandria Eng J 55:2833–2838. https://doi.org/10.1016/j.aej.2016.07.009

19. Kaliyan N, Vance Morey R (2009) Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 33:337–359. https://doi.org/10.1016/j.biombioe.2008.08.005

20. Muazu RI, Stegemann JA (2017) Biosolids and microalgae as alternative binders for biomass fuel briquetting. Fuel 194:339–347. https://doi.org/10.1016/j.fuel.2017.01.019

21. Shankar T., Christopher T. Wright JRH and KLK (2011) A review of biomass densifi cation systems to develop uniform feedstock commodities for bioenergy application. Biofuels, Bioprod Biorefining 5:683–707. https://doi.org/10.1002/bbb

22. Huang Y, Finell M, Larsson S, et al (2017) Biofuel pellets made at low moisture content – Influence of water in the binding mechanism of densified biomass.

Biomass and Bioenergy 98:8–14. https://doi.org/10.1016/j.biombioe.2017.01.002

23. da Silva CMS, Carneiro A de CO, Vital BR, et al (2018) Biomass torrefaction for energy purposes – Definitions and an overview of challenges and opportunities in Brazil. Renew Sustain Energy Rev 82:2426–2432. https://doi.org/10.1016/j.rser.2017.08.095

24. Chen D, Gao A, Cen K, et al (2018) Investigation of biomass torrefaction based on three major components: Hemicellulose, cellulose, and lignin. Energy Convers Manag 169:228–237. https://doi.org/10.1016/j.enconman.2018.05.063

25. Kaur A, Roy M, Kundu K (2017) Densification of biomass by briquetting: A review. 8:20561–20568. https://doi.org/10.24327/IJRSR

26. Muazu RI, Stegemann JA (2015) Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. Fuel Process Technol 133:137–145. https://doi.org/10.1016/j.fuproc.2015.01.022

27. Rahaman SA, Salam PA (2017) Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. Fuel Process Technol 158:9–19. https://doi.org/10.1016/j.fuproc.2016.12.008

28. Jackson J, Turner A, Mark T, Montross M (2016) Densification of biomass using a pilot scale flat ring roller pellet mill. Fuel Process Technol 148:43–49. https://doi.org/10.1016/j.fuproc.2016.02.024

29. Mikulandrić R, Vermeulen B, Nicolai B, Saeys W (2016) Modelling of thermal processes during extrusion based densification of agricultural biomass residues. Appl Energy 184:1316–1331. https://doi.org/10.1016/j.apenergy.2016.03.067

30. Okot DK, Bilsborrow PE, Phan AN (2018) Effects of operating parameters on maize COB briquette quality. Biomass and Bioenergy 112:61–72. https://doi.org/10.1016/j.biombioe.2018.02.015

31. Zabava B, Voicu G, Dinca M, et al (2018) Durability of pellets obtained from energy plants: review. 1838–1843. https://doi.org/10.22616/ERDev2018.17.N419

32. Limousy L, Jeguirim M, Labbe S, et al (2015) Performance and emissions characteristics of compressed spent coffee ground/wood chip logs in a residential stove. Energy Sustain Dev 28:52–59. https://doi.org/10.1016/j.esd.2015.07.002

33. Thabuot M, Pagketanang T, Panyacharoen K, et al (2015) Effect of Applied Pressure and Binder Proportion on the Fuel Properties of Holey Bio-Briquettes. Elsevier B.V.

34. Yank A, Ngadi M, Kok R (2016) Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. Biomass and Bioenergy 84:22–30. https://doi.org/10.1016/j.biombioe.2015.09.015

35. Soleimani M, Tabil XL, Grewal R, Tabil LG (2017) Carbohydrates as binders in biomass densification for biochemical and thermochemical processes. Fuel 193:134–141. https://doi.org/10.1016/j.fuel.2016.12.053

36. Chen WH, Lin BJ, Colin B, et al (2018) Hygroscopic transformation of woody biomass torrefaction for carbon storage. Appl Energy 231:768–776. https://doi.org/10.1016/j.apenergy.2018.09.135

37. Kautsch P, Häupl P, Hengsberger H, Streicher W (2005) Zellulose-Innendämmung ohne Dampfsperre. Berichte aus Energie-und Umweltforschung, Wien 112

38. Rahaman SA, Salam PA (2017) Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. Fuel Process Technol 158:9–19. https://doi.org/10.1016/j.fuproc.2016.12.008

39. Ndiema CKW, Manga PN, Ruttoh CR (2002) Influence of die pressure on relaxation characteristics of briquetted biomass. Energy Convers Manag 43:2157–2161. https://doi.org/10.1016/S0196-8904(01)00165-0

40. Kaliyan N, Morey RV (2010) Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. Bioresour Technol 101:1082–1090. https://doi.org/10.1016/j.biortech.2009.08.064

41. Lubwama M, Yiga VA (2018) Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda. Renew Energy 118:43–55. https://doi.org/10.1016/j.renene.2017.11.003

42. Ndindeng SA, Mbassi JEG, Mbacham WF, et al (2015) Quality optimization in briquettes made from rice milling by-products. Energy Sustain Dev 29:24–31. https://doi.org/10.1016/j.esd.2015.09.003

43. Jenkins BM, Baxter LL, Miles TR, Miles TR (1998) Combustion properties of biomass. Fuel Process Technol 54:17–46. https://doi.org/10.1016/S0378-3820(97)00059-3

44. Brand MA, Jacinto RC, Antunes R, da Cunha AB (2017) Production of briquettes as a tool to optimize the use of waste from rice cultivation and industrial processing. Renew Energy 111:116–123. https://doi.org/10.1016/j.renene.2017.03.084

TABLE 1. Chemical characterization of the briquettes combinations and lower heating value.

| Analysis | Raw SCG | SCG+10% of xanthan |
|---|---|---|
| Proximate analysis (% wt.) | | |
| Moisture | 2.46 | 4.14 |
| Volatiles | 78.88 | 75.85 |
| Fixed carbon | 18.00 | 19.05 |
| Ash | 0.66 | 0.97 |
| Ultimate analysis (% wt.) | | |
| N | 2.01 | 1.72 |
| C | 57.29 | 57.20 |
| H | 7.52 | 7.84 |
| S | 0.00 | 0.00 |
| O | 33.18 | 33.24 |
| Lower heating value (J/g) | 25399 | 23503 |

FIGURE 1. Relationship between dry density and compaction pressure of raw SCG.

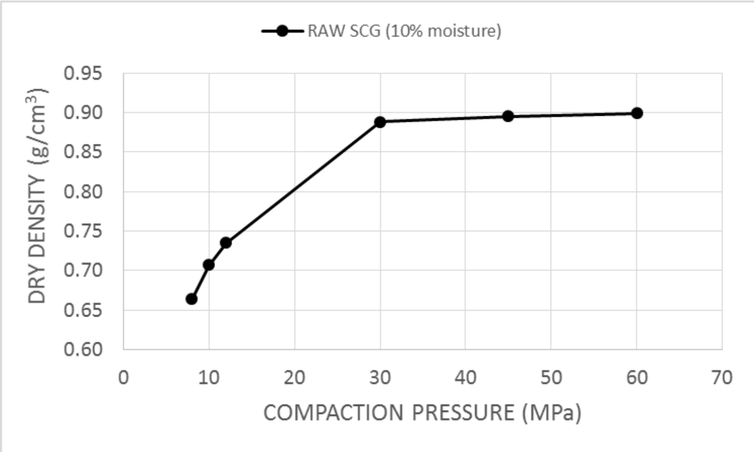
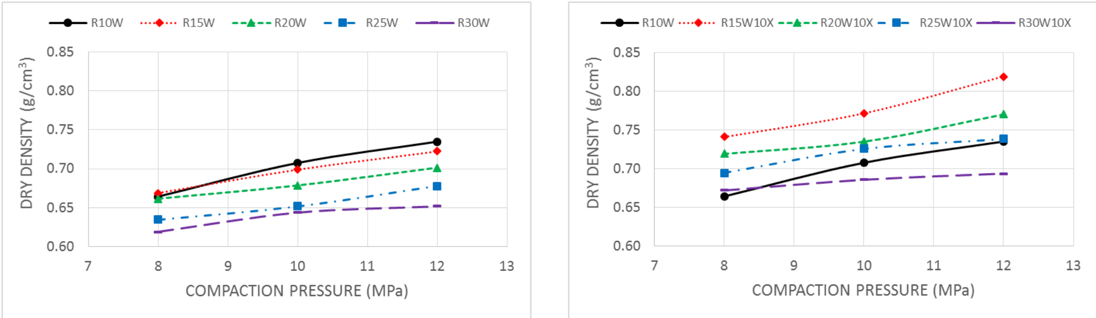
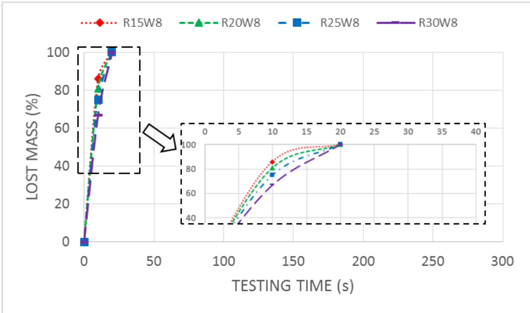


FIGURE 2. Relationship between dry density and compaction pressure of a) pure SCG and b) SCG mixed with xanthan gum.

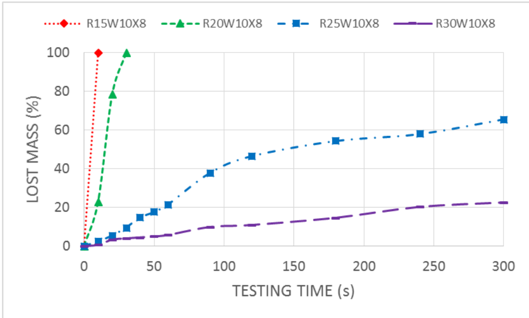



a) b)

FIGURE 3. Durability test: a) SCG at 8 MPa, b) SCG at 10 MPa, c) SCG at 12 MPa, d) xanthan at 8 MPa, e) xanthan at 10 MPa and f) xanthan at 12 MPa.




a)

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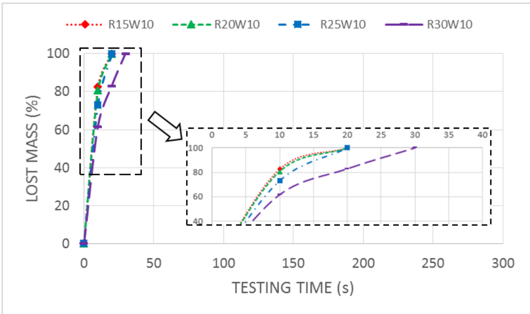


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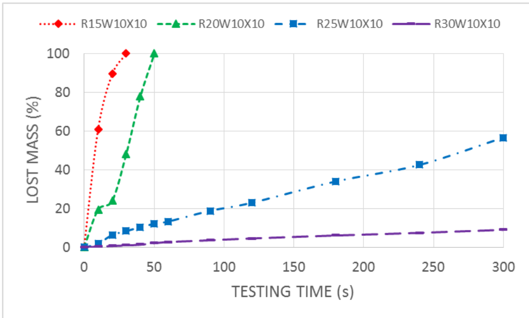


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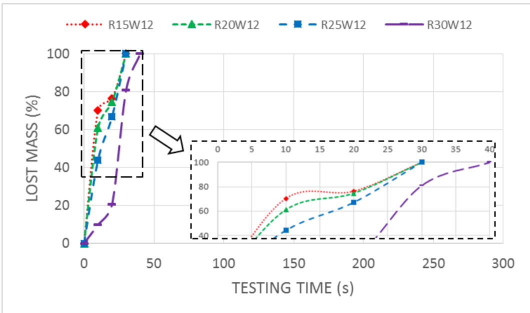


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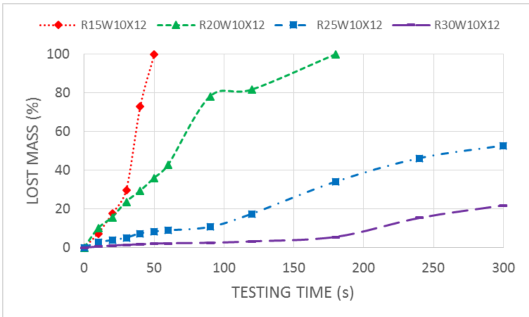
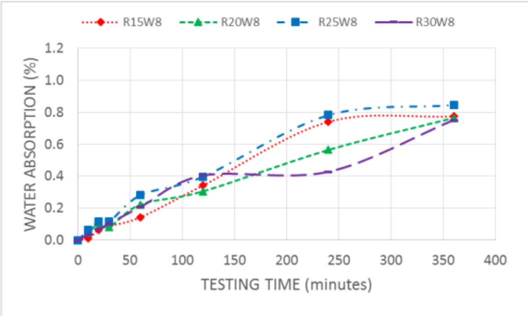



f)

c)

FIGURE 4. Water absorption test: a) SCG at 8 MPa, b) SCG at 10 MPa, c) SCG at 12 MPa, d) xanthan at 8 MPa, e) xanthan at 10 MPa and f) xanthan at 12 MPa.

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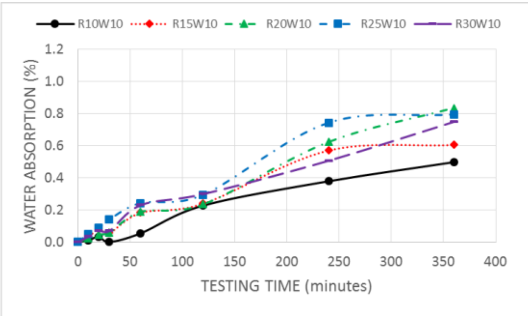


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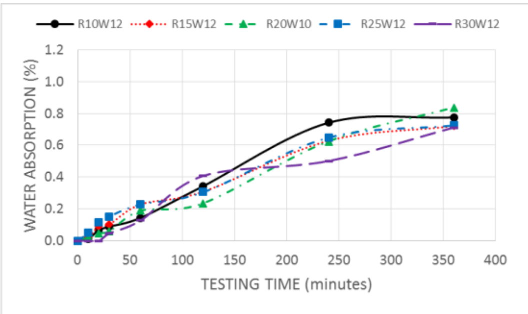


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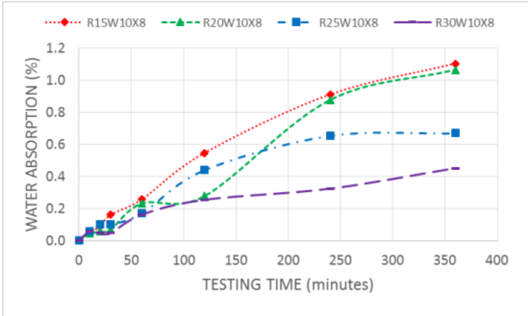


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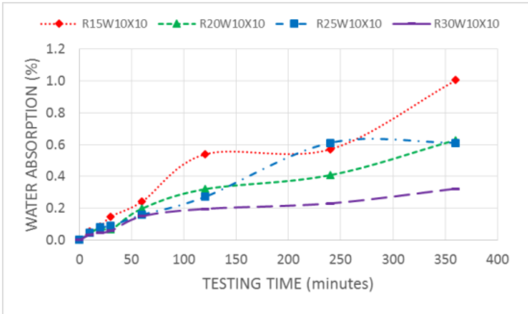


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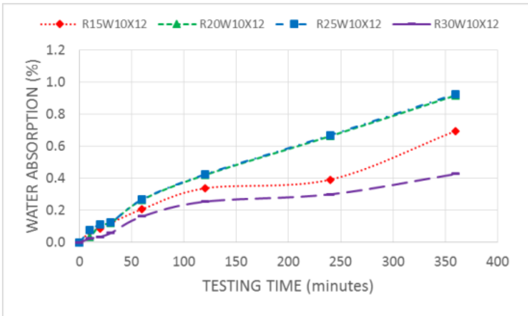
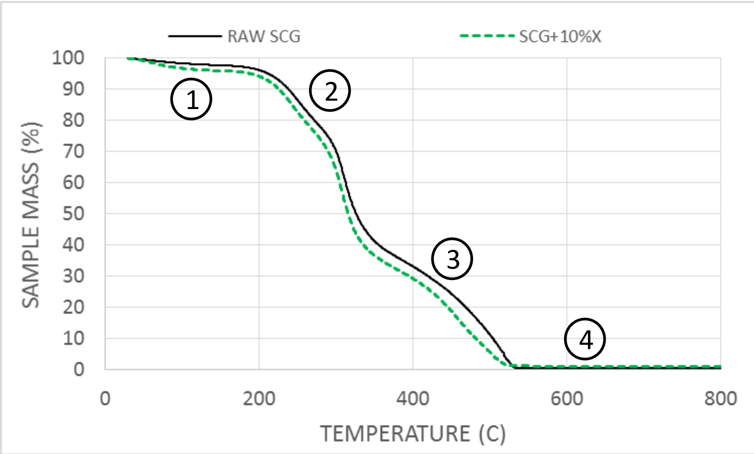
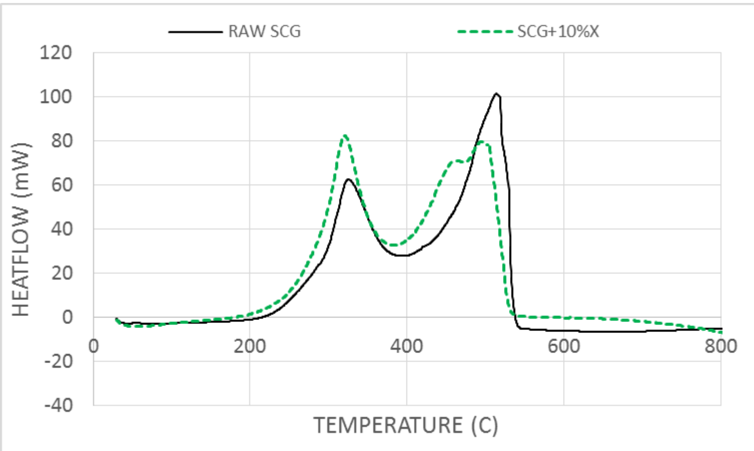



f)

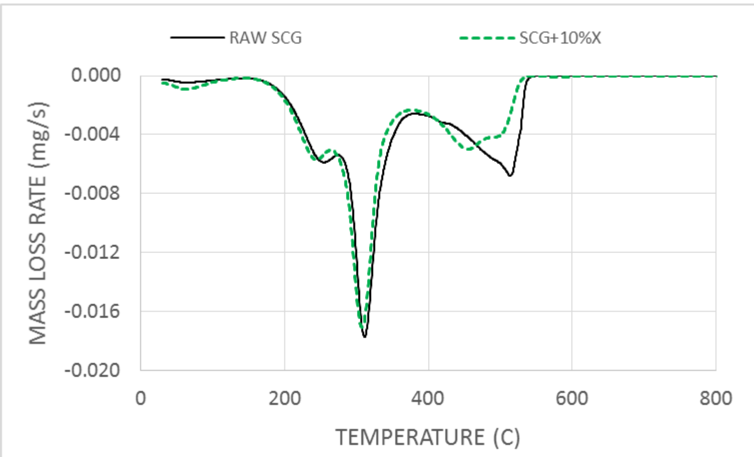
FIGURE 5. Thermogravimetric analysis. a) TG, b) DTG and c) DTA.




a)




b)




c)