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Utilisation of spent coffee grounds in biocomposite cup production: Influence of filler source and biopolymer type

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In this study, two types of spent coffee grounds (SCG, Machine and Turkish) were tested in the production of SCG-biopolymer composite cups. The objective was to develop a simple and sustainable preparation approach for SCG-based biocomposites, ensuring sufficient mechanical and thermal stability for practical applications. Biocomposite cups, containing 55 to 72% of SCG were produced using sodium alginate as the primary polymer binder. To enhance mechanical performance, a secondary binder (additional polymer), either cellulose ether (carboxymethyl cellulose (CMC) or hydroxypropyl cellulose (HPC)) or natural polysaccharides (dextran or pectin), was incorporated. Comprehensive characterisation was performed using fluorescence and FTIR spectroscopy, tensile testing, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). Fluorescence spectroscopy/microscopy revealed a higher content of naturally fluorescent organic compounds in Machine SCG compared to Turkish SCG. FTIR spectroscopy confirmed the successful SCG incorporation into the biopolymer matrix. Tensile testing showed that Machine SCG-based biocomposites were slightly more flexible than those prepared with Turkish SCG. Glass transition temperature (T_g) of SCG biocomposites depends on their composition and varied from around 75 to 100°C. The TGA results demonstrated that SCG exhibit a greater thermal stability than both SCG–alginate biocomposites and SCG biocomposites containing additional polymers.

Keywords: spent coffee grounds (SCG), biocomposite, polysaccharides, DSC, mechanical properties

INTRODUCTION

Millions of tons of spent coffee grounds (SCG) are generated annually as a by-product of coffee consumption. Since only about 30% of coffee bean mass is extracted into the beverage we drink, the majority ends up as waste. Traditionally discarded, SCG has recently gained an increasing attention for its potential reuse, especially over the past decade [1]. SCG can be either recycled in a biorefinery-based process to produce biofuels and value-added products [2–4], or used as bio-fillers in the production of biopolymer composites (bioplastic) [5, 6], as well as in many other applications [1, 7]. Thus, the environmental issues, hazardous emissions, and costs associated with SCG disposal are avoided.

Biobased and biodegradable plastic (biopolymers) is a type of plastic capable of breaking down into organic compounds, CO_2, water, and other biomass under the influence of microorganisms in natural conditions or under biological treatment. Bioplastics offer numerous benefits compared to traditional plastics, including being biodegradable, having a reduced carbon footprint, being energy-efficient, and possessing versatility. They also exhibit distinct mechanical and thermal properties

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and enjoy societal acceptance [8]. Among the various materials explored for biocomposite production, spent coffee grounds have emerged as a valuable renewable resource. Instead of allowing SCG, a valuable organic material, to contribute to pollution, it can be repurposed into biodegradable plastic cups or packaging suitable for serving coffee, tea, juice, and other beverages, as well as food [9]. There are several commercially available biocomposite products associated to SCG, such as cups, cutlery sets or lunch boxes, cups, plates, etc. [10].

The properties of the biocomposite derived from spent coffee grounds (SCG), as well as the characteristics of the products formed from them, are highly dependent on the chemical composition of SCG. In polymer science, the lignocellulosic composition of SCG, which is abundant in cellulose, hemicellulose, lignin, proteins and lipids, presents a valuable opportunity for improving the performance and sustainability of biopolymer composites. Cellulose and hemicellulose serve as reinforcing fibers, contributing to the increased stiffness and mechanical strength, while lignin enhances thermal stability due to its aromatic nature. Proteins can enhance interfacial adhesion with the polymer matrix, thereby boosting mechanical integrity. Lipids and sugars can affect flexibility and impact resistance, as well as influence the material's hydrophobic properties [5, 11]. The chemical composition of SCG and the comparison with some other coffee waste types is shown in Table 1.

Previous studies have shown that SCG can be incorporated into a range of biopolymers, including polylactic acid (PLA) [6], blends of PLA and polyhydroxybutyrate (PHA) [16], polybutylene succinate (PBS) [5, 17], starch/alginate system [18], and polybutylene adipate terephthalate (PBAT) [5, 19] resulting in diverse impacts on the physical, mechanical and thermal characteristics of composites.

For example, de Bomfim et al. demonstrated that the incorporation of 20 wt.% spent coffee grounds (SCG) into polylactic acid (PLA) resulted in properties that were comparable to or superior to those of pure PLA, while also being more cost-effective. By altering the crystallinity, the glass transition temperature was decreased, and the toughness of the biocomposite was enhanced [6]. Vy H. T. Nguyen and colleagues have employed SCG as a reinforcing biowaste filler in thermoplastic starch/alginate films for food packaging. Their findings indicated that incorporating 5 to 20 wt% of SCG into the composition slightly enhanced the thermal stability of the biocomposite films. However, the tensile strength of the biocomposites decreased by 15 and 28% with the addition of SCG up to 10% and higher, respectively [18]. SCG exhibit a significant potential as a biobased resource for the production of sustainable biocomposites for cup applications, supporting circular economy principles. However, significant advancements in biocomposite formulation with SCG are still necessary to improve its properties.

The purpose of the present study was to investigate how various local types of spent coffee grounds (SCG) can be repurposed to create biodegradable plastic (biocomposite) cups as an alternative to conventional disposable cups, thereby addressing both synthetic plastic pollution and coffee waste management in an innovative and environmentally friendly manner. The incorporation of larger amounts of spent coffee grounds (SCG) remains technically challenging; however, in the present study, a particular emphasis was placed on maximising the SCG

Table 1. **SCGs' typical chemical composition range in comparison to the chemical composition range of other coffee waste types (wt/wt% dry basis) [12–15]**

Chemical component	Spent coffee grounds (SCG)	Coffee husk	Coffee silverskin
Cellulose	8.6–12.4	39.0–61.0	16.0–23.8
Hemicellulose	32.0–43.0	4.0–12.6	4.0–22.0
Lignin	19.8–33.6	9.0–26.2	28.6–39.0
Proteins	11.5–18.0	3.0–13.0	15.0–23.0
Lipids	2.3–17	0.5–6.0	0.3–4.0
Caffeine	0.02–0.4	0.5–2.0	0–1.4
Chlorogenic acids	1.8–11.5	2.0–12.6	3.0–15.8
Ash	1.1–2.2	6.0–9.5	4.7–9.5

loading as much as possible. The study examined two types of SCG in conjunction with several polysaccharides, such as pectin, dextran, hydroxypropyl cellulose (HPC), and carboxymethylcellulose (CMC), together with the main natural sodium alginate biopolymer, to assess their potential in forming biodegradable plastic cups. Sodium alginate was chosen because it is biodegradable, inexpensive, biorenewable, and widely used in a variety of applications. The analysis included FTIR and fluorescence spectroscopies, as well as an evaluation of the thermal and mechanical properties of both the SCG and the resulting biocomposites. The principal schema of SCG biocomposite cup preparation is given in Fig. 1.

EXPERIMENTAL

Materials

Two different types of spent coffee grounds (SCG) were obtained from local sites. Machine Coffee Grounds (coffee bean blend 'Espresso Italiano' (composed of 80% Arabica and 20% Robusta)) collected from the school's coffee machine at Meridiano Licejus and Turkish Coffee Grounds obtained from 'Kurukahveci Mehmet efendi' Turkish coffee. Both SCG samples were obtained from Arabica coffee beans. Glycerol (≥99%, Enola SIA), cedarwood and tea tree essence oils (100%, Kaigert), sodium alginate (food grade, GF 150, Luis Francois), aqueous 2% calcium chloride ($CaCl_2$), carboxymethyl cellulose sodium salt (CMC, purum, viscosity ~500 mPa·s, Fluka), hydroxypropyl cellulose (HPC, >99%, viscosity 400 mPa·s, Keune Fabrik E. Wasserfuhr GMBH), pectin (purum, ash content <2%, molecular weight 25000–50000, from citrus, Fluka), dextran (molecular weight ~6000, ≥98.0%, from Leuconostoc ssp, Fluka), and isopropyl alcohol (tech., 99.8%, distributor UAB Mavis) were used as received.

SCG preparation

Before being incorporated into the biocomposite formulation, SCG was pre-treated to remove pigments, oils, and other unwanted compounds that could affect food safety and bioplastic composition. That procedure enabled the removal of residual low-molecular-weight organic compounds from spent coffee grounds that are soluble in water and isopropanol. The treatment involved hot water extraction – SCG was washed with hot water to eliminate water-soluble residues (samples Machine-2 and Turkish-2). Then washing with isopropyl alcohol was performed to remove lipids and organic compounds (samples Machine-1 and Turkish-1). Finally, SCG was air-dried before use. The comparison of washing methods and the mass change after washing steps is given in Table 2.

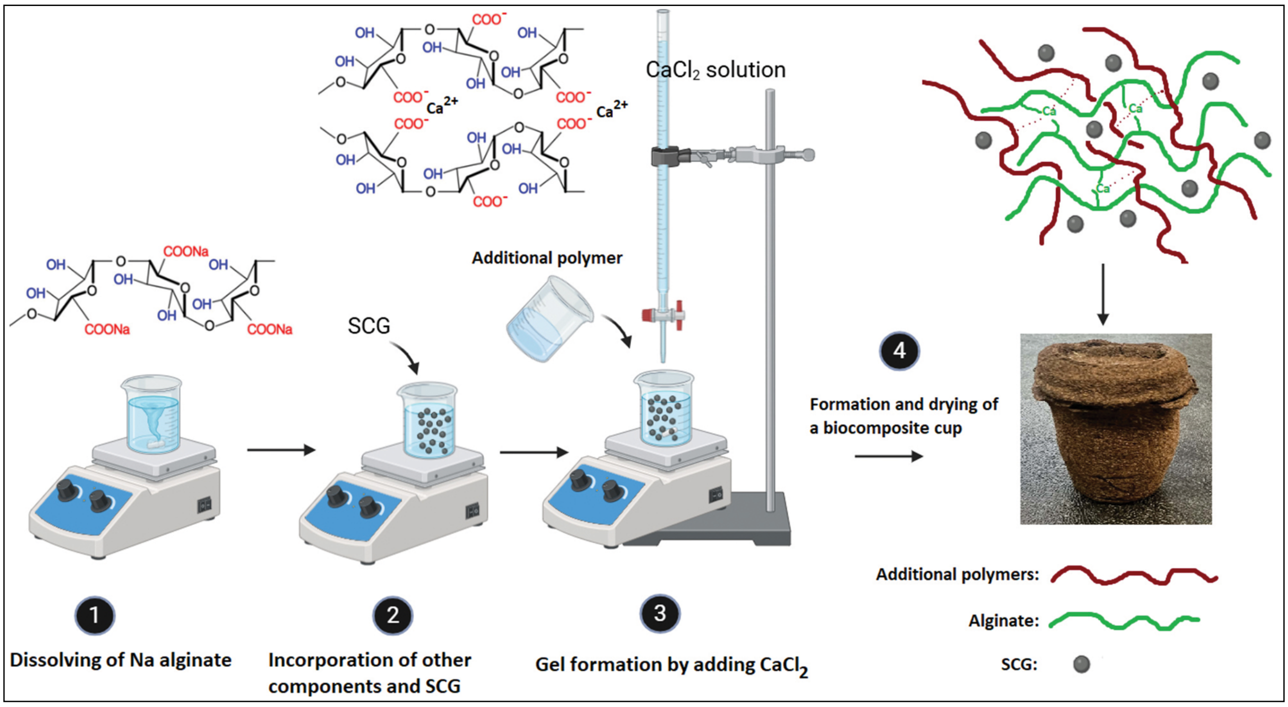


Fig. 1. Schematic representation of SCG biocomposite cup formation

Table 2. **The mass change of SCG before and after being treated with hot water, and with hot water and isopropyl alcohol (IPA)**

Coffee ground type	Initial dry mass, g	Dry m (after treating with hot H_2O), g	Dry m (after treating with hot H_2O and IPA), g	Δm, %
Machine-1	100	–	76.1	23.9
Machine-2	50	41.1	–	17.8
Turkish-1	100	–	78.6	21.4
Turkish-2	50	37.7	–	24.6

SCG biocomposite preparation

Sodium alginate (5 g) was dissolved at room temperature in water (150 ml) using a magnetic stirrer for continuous mixing, ensuring even dispersion. Glycerol (10 ml) was added to the solution, pretreated, dried SCG (50 g) was gradually added to the biopolymer solution while stirring continuously to achieve a homogeneous mixture. After that, 2 ml of essence oil (cedarwood oil) was added for antibacterial and antifungal properties. Then, 5 g of calcium chloride ($CaCl_2$) was added dropwise while the mixture was still being stirred. This step initiated gel formation, which provided the necessary structure for the biocomposite cup. The additional biopolymer (2 g of pectin, dextran, HPC, or CMC) was dissolved in 30 mL of warm water and added shortly after the incorporation of sodium alginate. The main recipe of biocomposite preparation is given in Table 3. After 5–8 min, the reaction mixture was poured into coffee cup-shaped silicone molds. The molded cups were placed in a food dehydrator at 60°C for 48 h to allow complete drying and solidification.

The names of the analysed samples and their exact compositions in the final SCG biocomposite are presented in Table 4. When an additional biopolymer was added to the SCG biocomposite, the same

Table 3. **The composition of SCG and polymer biocomposites**

Substance	Mass, g	Mass % (with water)	Mass, g (after drying) (in product)*	Mass % in product	Water needed for dissolution, g
Sodium alginate	10	3.0	10	22.0	150
Additional polymer	5	1.5	5	11.0	60
Glycerol	3	0.9	3	6.6	–
Spent coffee grounds (SCG)	25	7.6	25	54.9	–
$CaCl_2$	1.5	0.5	1.5	3.3	75 (to achieve 2% solution)
Cedarwood oil	1	0.3	1	2.2	–
Water	285	86.2	–	–	–
Overall:	330.5	100	45.5	100	285

* Assuming all the water has evaporated.

Table 4. **The samples of SCG biocomposites and their composition after drying**

Sample No.	Sample name	SCG content, wt%	Alginate content, wt%	Additional polymer and content, wt%
1	Machine-alginate-1	72	7.4	–
2	Machine-alginate-2	72	7.4	–
3	Turkish-alginate-1	72	7.4	–
4	Turkish-alginate-2	72	7.4	–
5	Alginate-CMC	55	22	Carboxymethyl cellulose, 11
6	Alginate-HPC	55	22	Hydroxypropyl cellulose, 11
7	Alginate-dextran	55	22	Dextran, 11
8	Alginate-pectin	55	22	Pectin, 11

SCG (machine-type, washed with hot water and IPA) were used in all formulations.

Instrumental methods

Fluorescence spectroscopy was done by using a Nikon eclipse 80i fluorescent microscope. The normalised fluorescence intensity was measured across with and under different filters (green, blue, UV and no filter) using the magnification x40. The wavelength range was 560–800 nm.

The FT-IR spectroscopy of SCG and SCG biocomposites was implemented using a Perkin Elmer Frontier spectrometer in a range of 500–4000 cm^{-1}.

We applied a pulling (tensile) load, measured the force and the cross-sectional area, then calculated the tensile strength and elongation at break of SCG biocomposites. The tensile strength tests were performed at school under room temperature conditions (≈23°C). A tensile load was applied at a constant, slow rate using the school laboratory equipment until fracture occurred. Due to equipment limitations, the exact crosshead speed could not be precisely controlled. However, all samples were tested under identical conditions to ensure a reliable comparison.

The softening and melting points of biocomposites were determined. The samples were placed in water baths at different controlled temperatures, and visible changes in shape, flexibility, and surface integrity were observed. This allowed an approximate determination of the softening temperature under school laboratory conditions.

A calorimeter Perkin Elmer DSC8500 was used to study the thermal properties of Turkish and machine coffee grounds and their biocomposites. DSC test was performed under nitrogen atmosphere (rate 40 mL/min). A sealed empty aluminum pan was used as a reference. Samples of 3–7 mg were heated from –30 to 150°C at the rate of 10°C/min. For the SCG–alginate samples, the heating cycle was repeated a second time. As the thermograms obtained from the first and second heating cycles were similar, only a single heating cycle was performed for the SCG–additional polymer biocomposites. The endothermic peaks in graphs are shown down.

The thermal stability of the SCG biocomposites was determined using a Perkin Elmer STA 6000 Simultaneous Thermal Analyzer. The samples of about 10 mg were heated from room temperature to 800°C at a heating rate of 10°C/min. The nitrogen gas flow rate was 40 ml/min.

RESULTS AND DISCUSSION

Fluorescence spectroscopy and microscopy

First, microscopic fluorescence analysis of SCG was performed to detect the presence of organic compounds that fluoresce under visible or UV light. The microscopic fluorescence analysis indicated that the stronger fluorescence observed in Machine SCG under blue and green filters is likely attributable to high concentrations of naturally fluorescent chlorogenic acids [20] and Maillard reaction-derived melanoidins [21], which are formed during coffee bean roasting. Whereas the lower fluorescence intensity in Turkish SCG suggests reduced levels of these compounds, as supported by fluorescence profiling studies of coffee constituents (Table 5).

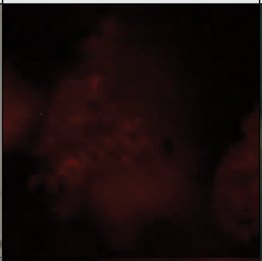
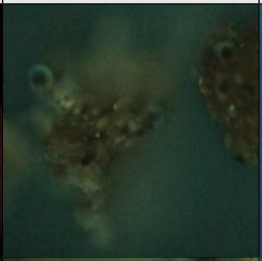
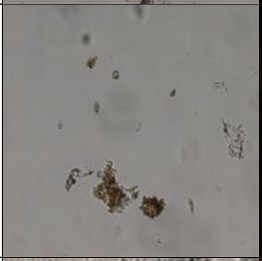
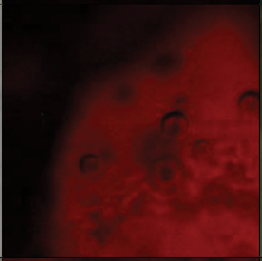
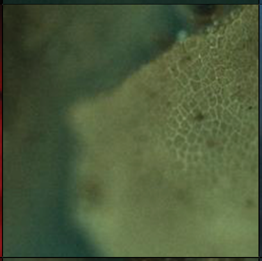
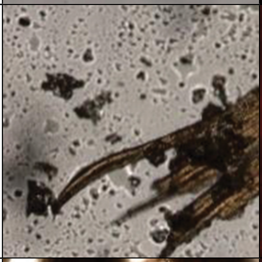
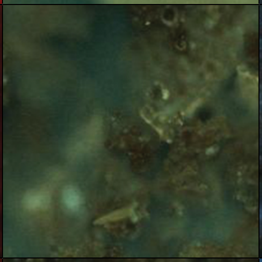
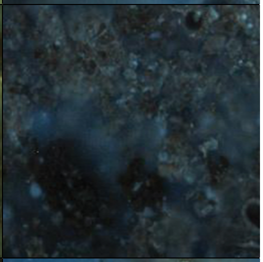
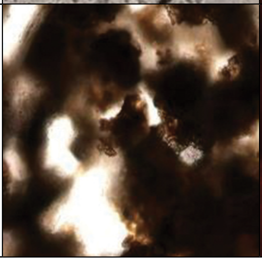
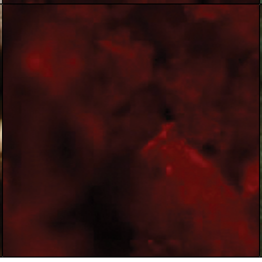
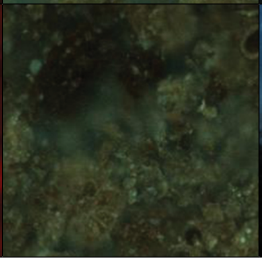
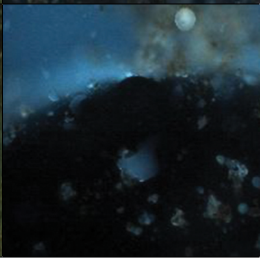
The samples of SCG and sodium alginate biocomposites with a different type of SCG were prepared (Table 4, Samples No. 1–4). Figure 2 shows the fluorescence spectroscopy results of Turkish and Machine SCG alginate biocomposites. The fluorescence spectroscopy analysis confirms that the fluorescent properties of the SCG biocomposites originate from the coffee grounds themselves, with no additional fluorescent compounds introduced during processing. The Machine SCG biocomposite exhibited a higher fluorescence intensity, particularly around 670 nm, suggesting a greater presence of chlorophyll derivatives [20, 22, 23] compared to the Turkish SCG biocomposite.

FTIR spectroscopy of SCG and biocomposites

To obtain more information about the composition of spent coffee grounds (SCG) and SCG biocomposites, FTIR analysis was implemented. The results are given in Fig. 3.

The broad peak observed at 3333 cm^{-1} in dried SCG is attributed to –OH stretching vibrations, primarily associated with polysaccharides such as cellulose and hemicellulose, as well as phenolic hydroxyl groups in lignin [5]. This peak may also correspond to the vibration of water present [23]. A weak band at 3009 cm^{-1} is linked to the C–H stretching in double bonds (C=C), found in unsaturated fatty acids such as linoleic and oleic acids present in SCG [5]. The presence of methyl ($-CH_3$) and methylene ($-CH_2$) groups is confirmed by

Table 5. **Micrographs of observing SCG samples under fluorescence microscope**

SCG sample	No filter	Green filter	Blue filter	UV filter
Machine-1				
Machine-2				
Turkish-1				
Turkish-2				

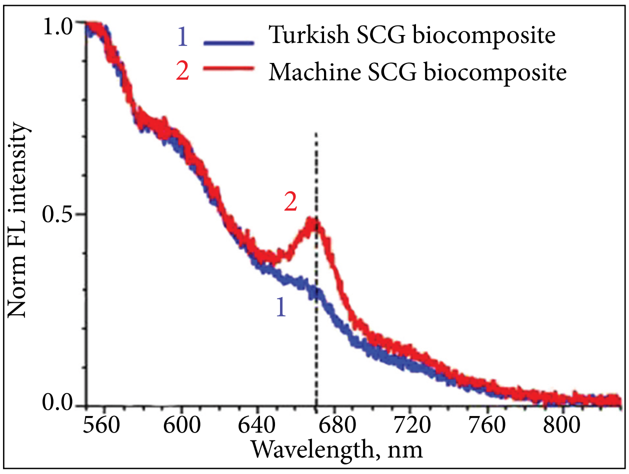


Fig. 2. Fluorescence spectra of different SCG alginate biocomposite samples

the peaks at 2924 and 2855 cm^{-1}, attributed to the asymmetric and symmetric stretching of C–H bonds in aliphatic chains. These peaks have been previously identified in roasted coffee and attributed to the presence of caffeine [25, 26], and fatty acid structures [5, 25]. The sharp band at 1743 cm^{-1} is associated with the carbonyl vibration (C=O) in aliphatic esters or in triglycerides. Therefore, this band can be also attributed to lipids [5, 24]. The absorption at 1649 cm^{-1} is linked to the C=C stretching vibration of cis-olefins and may also correspond to the C=O stretching vibration of amide I, characteristic of protein structures [5].

The absorption at 1457 cm^{-1} is associated with the C–H bending vibrations in aliphatic $-CH_2$ and $-CH_3$ groups, whereas the band at 1376 cm^{-1} corresponds to the symmetric C–H bending in $-CH_2$ groups, typically attributed to coffee oil components [5]. The low intensity band at 1518 cm^{-1} is due to the C=C vibration of aromatic rings from lignin moieties [25]. The absorption band at 1237 cm^{-1} is linked to the C–O–C linkages in cellulose and

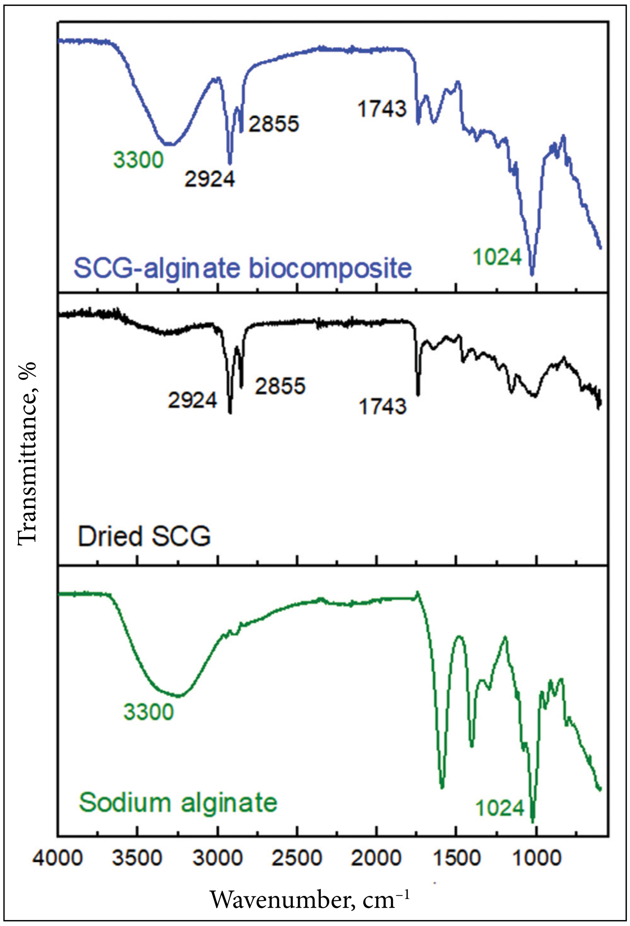


Fig. 3. FTIR spectra of sodium alginate, dried SCG, and SCG alginate biocomposite Machine-alginate-1

may also include the C–O stretching vibrations from the O=C–O functional group in hemicelluloses [5]. The wavenumber range of 1400–900 cm^{-1} is characterised by vibrations of several types of bonds, including C–H, C–O, C–N and P–O characteristic of polysaccharides [25, 26]. The bands at 1376, 1237, 1159 and 1008 cm^{-1} can also be attributed to the chlorogenic acids, because the vibrations of this class of esters are present in a region of 1450–1000 cm^{-1} [25, 26]. The signal at 717 cm^{-1} results from the overlapping aliphatic $-CH_2$ rocking vibrations and out-of-plane deformations of cis-disubstituted olefins, commonly found in coffee oil components [5].

In sodium alginate FTIR spectra, several characteristic bands are observed. The broad intensive band at around 3300 cm^{-1} corresponded to the stretching of –OH groups. The absorption peaks at 1593 and 1407 cm^{-1} are assigned to the asymmetric and symmetric stretching vibrations of the carboxylate (–COO–) groups of alginate salts, respectively. The sharp peak at 1024 cm^{-1} is attributed to the stretching vibration of C–O–C group (glycosidic bond) and C–O stretching in the pyranose ring. The absorption band at 1297 cm^{-1} was noticed for the C–O stretch. In addition, a band at about 947 cm^{-1}, corresponding to a C–H deformation mode coupled with the glycosidic C–O–C vibration of the 1,4-β-glycosidic bond, typical of polysaccharides, is also visible in spectra [18].

The FTIR spectra of the SCG–sodium alginate biocomposite exhibit the characteristic peaks of both SCG and sodium alginate, confirming the successful incorporation of SCG into the biopolymer matrix. Notably, the sharp absorption bands at 1593 and 1407 cm^{-1}, corresponding to the asymmetric and symmetric stretching vibrations of the carboxylate ($-COO^-$) groups, are absent in the biocomposite spectra. This disappearance is attributed to the crosslinking of sodium alginate with $CaCl_2$, which forms ionic interactions between the carboxylate groups and calcium ions.

The FTIR spectra of SCG biocomposites containing the additional polymer (CMC, HPC, dextran or pectine) showed minimal differences compared to the SCG-alginate biocomposites, as the FTIR spectra of polysaccharides are generally similar and their characteristic peaks largely overlap. For this reason, their spectra are not shown.

Mechanical and thermal properties

The results of mechanical and thermal resistance testing of SCG composites are listed in Table 6.

The elasticity testing revealed that the Machine SCG-based biocomposites exhibited an elongation at break of approximately 25–28%, indicating a slightly greater stretchability and flexibility. In contrast, the biocomposites based on Turkish coffee grounds were stiffer and more mechanically robust, with an elongation at break of around 20%. Correspondingly, the tensile strength of Machine SCG-based biocomposites was lower than that of Turkish SCG-based biocomposites, reaching approximately 3 MPa compared to values of up to 4 MPa, respectively. Still, the biocomposites containing only alginate as the biopolymer were brittle, and their mechanical properties were insufficient, indicating the need for further improvement. Therefore, an additional biopolymer was incorporated into the SCG biocomposite formulation, thereby increasing the overall binder content in the biocomposite up to 33 wt%. The formulation of SCG biocomposites was also significantly

Table 6. Results of mechanical and thermal resistance testing of SCG biocomposite samples

SCG biocomposite	Tensile strength, MPa	Elongation at break, %	Softening point, °C	Melting point, °C	Structural integrity maintained until, °C
Machine-alginate-1	2.75	27.5	88	90	86
Machine-alginate-2	3.21	24.5	75	77	74
Turkish-alginate-1	3.42	22.5	68	70	67
Turkish-alginate-2	3.98	19.5	71	75	69

improved, making it easier to mold the cups and reducing shrinkage during drying.

The thermal resistance testing demonstrated that the Machine SCG-based biocomposites remained stable at higher temperatures, withstanding heating up to 80–90°C. This thermal behaviour suggests their suitability for applications involving hot beverages. By comparison, Turkish SCG-based biocomposites exhibited a reduced thermal stability, showing softening and melting at lower temperatures of approximately 70°C.

The DSC results of SCG and SCG biocomposites are given in Fig. 4. When sodium alginate is crosslinked with $CaCl_2$, a network structure is formed, in which spent coffee grounds (SCG) can be incorporated as a functional filler. SCG contains polar functional groups, particularly polysaccharides (cellulose, hemicellulose), which can establish intermolecular interactions – especially hydrogen bonds – with alginate and other biopolymers (CMC, HPC, Dextran or pectin). Due to the rigid fibrous structure of SCG, the polymer matrix, which is already crosslinked and of a low mobility, becomes even stronger and stiffer, with a further restricted polymer chain mobility upon SCG incorporation [5]. As a result, thermal transitions are hardly detectable and poorly expressed in DSC curves.

Although it is reported that SCG exhibits a crystalline structure and melts at approximately 76°C [12], this peak is also associated with the evaporation of water. Water is always present in the SCG structure, and in this case, during biocomposite formation in the water system, not all of it evaporates. Consequently, thermal transitions in SCG–alginate biocomposites are minor. Nonetheless, noticeable differences in thermal behaviour can be observed when comparing different SCG types. In the DSC curve of the Turkish SCG–alginate biocomposite (Fig. 4, left, blue curve), a small peak corresponding to a transition appears at around 75–80°C, whereas in the Machine SCG–alginate biocomposite (Fig. 4, left, black curve) the peak maximum shifts to a higher temperature range of approximately 100–110°C. In conjunction with the softening temperature measurements, these results indicate that the thermal transitions of Machine-SCG biocomposites occur in a higher temperature range than those of Turkish-SCG biocomposites.

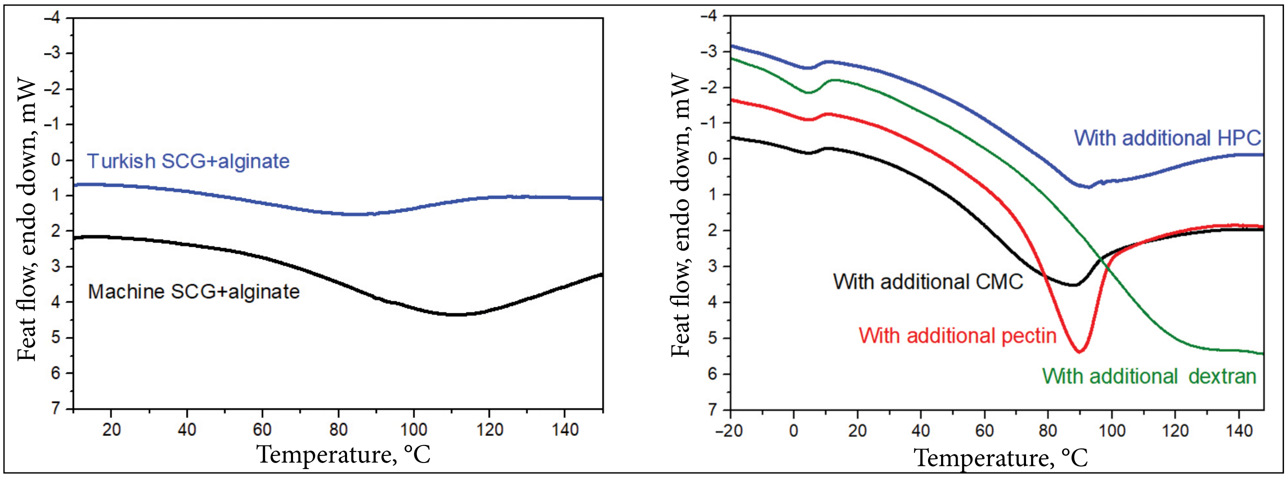


Fig. 4. DSC results of SCG–alginate biocomposites (left) and SCG–alginate biocompasites with an additional biopolymer (right)

When additional biopolymers such as pectin or CMC are incorporated into the Turkish and machine coffee ground biocomposites, then the overall SCG content is lower (55 vs 72 wt%), and more pronounced peaks due to the higher biopolymer content (better-defined transitions) appear in the DSC curves. The glass transition temperature (T_g) of the CMC-containing biocomposite is approximately 75°C (Fig. 4, right, black curve), while that of the pectin-containing biocomposite is higher, reaching about 81°C (Fig. 4, right, red curve). The reported T_g values for pure CMC are in a range of 78–83°C [27, 28], while those for pectin are around 90°C [29]. Our determined values are close to those reported previously. They are somewhat lower, which can be explained by the complexity of the SCG-based biocomposite system and net structure, where not only additional polymer but also other components influence the thermal properties (T_g). In addition, the molecular weight of the added biopolymer plays an important role in the observed differences in glass transition temperature. The thermogram of the SCG–HPC biocomposite shows an endothermic peak at around 90°C. In contrast, the SCG–dextran biocomposite does not exhibit a clear thermal transition within the examined temperature range.

Additionally, the minor transition observed around 0°C (Fig. 4, right) corresponds to the melting of water in the samples.

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability of SCG, SCG–alginate and SCG–alginate biocomposites containing additional biopolymers. The corresponding thermograms are presented in Fig. 5.

The thermal destruction of all samples can be divided into 3 stages. The first stage, occurring below 150°C, represents the evaporation of residual moisture and physically adsorbed water. The second stage, observed between 250–350°C in the SCG thermograms (Fig. 5, black and red curves) is associated to the thermal degradation of cellulose, hemicellulose, and partially lignin [5]. The third stage occurs at high temperature – from 350 to 450°C. This phase is related to the further degradation of lignin. For SCG-biocomposites, the second stage initial degradation temperature is lower – the destruction region is at about 200–250°C (Fig. 5, green and blue curves). The third degradation stage also begins earlier, at around 300°C, and these results suggest that SCG exhibit a greater thermal stability than both SCG–alginate biocomposites and SCG biocomposites containing additional polymers (Fig. 5, right). This observation correlates well with literature data showing that pure biopolymers such as CMC, HPC, dextran and pectins undergo thermal degradation in similar temperature ranges (typically ~200–300°C for the main chain decomposition [330–31], whereas the multicomponent structure of SCG, containing lignin and other high-temperature degrading compounds, contributes to a wider and higher temperature thermal resistance.

CONCLUSIONS

This study demonstrates that spent coffee grounds (SCG) can be effectively repurposed as a functional and sustainable filler for bioplastic cup production. The valorisation of SCG not only contributes

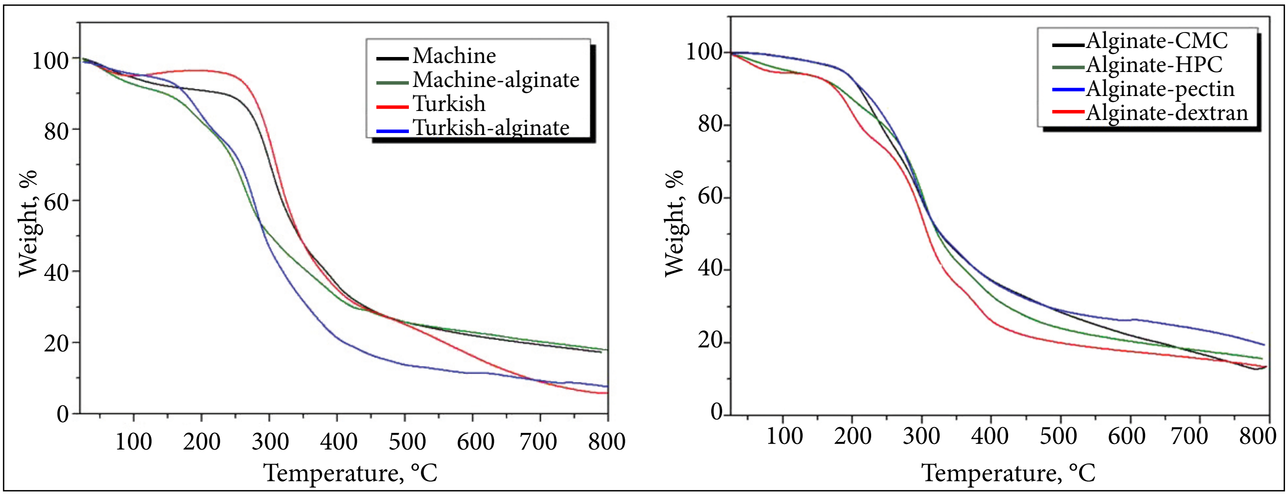


Fig. 5. TGA results of SCG, SCG-alginate and SCG biocomposites with an additional biopolymer

to the reduction of organic waste but also enables the development of environmentally friendly products, thereby supporting circular economy strategies.

A comparative evaluation of two SCG sources – Machine and Turkish coffee grounds – revealed distinct differences in their chemical composition, processing behaviour, and influence on the resulting biocomposite properties, including glass transition temperature, and thermal and mechanical stability. Biocomposite cups containing 55–72 wt% SCG were successfully fabricated using a sodium alginate–$CaCl_2$ system as the primary polymer binder. Mechanical and thermal analyses indicated that the Machine SCG-based biocomposites exhibited a higher elasticity and retained structural integrity at elevated temperatures, making them more suitable for hot-beverage cup applications. In contrast, the Turkish SCG-based biocomposites showed a greater stiffness and tensile strength but a reduced elongation at break. To further enhance the mechanical performance of the biocomposite cups, 11 wt% of a secondary polysaccharide-type binder was incorporated during the preparation process. Thus, not only were the mechanical properties improved, but the formulation of SCG biocomposites was also significantly enhanced, facilitating cup molding and reducing shrinkage during drying.

The glass transition temperature (T_g) of SCG biocomposites depends on their composition and varied from around 75 to 100°C. TGA results demonstrated that SCG exhibit a greater thermal stability than both SCG–alginate biocomposites and SCG biocomposites containing additional polymers.

Overall, the findings confirm that SCG is a viable and sustainable filler for bioplastic applications, with material properties that can be tailored by selecting the SCG source and optimising the amount of an additional biopolymer. Biocomposites containing pectin were found to be relatively soft, while the use of HPC presented challenges due to its limited water solubility. In contrast, composites prepared with dextran and CMC exhibited the best overall properties; therefore, further optimisation of these formulations is highly justified. Future research should focus on biodegradation behaviour, durability under thermal exposure, and further optimisation of the mechanical performance of SCG-based biocomposite cups.

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PANAUDOTOS KAVOS TIRŠČIŲ TAIKYMAS BIOKOMPOZITINIŲ PUODELIŲ GAMYBOJE: UŽPILDO KILMĖS IR BIOPOLIMERO TIPO ĮTAKOS TYRIMAS

Santrauka

Šis tyrimas parodė, kad panaudotos kavos tirščiai (PKT) gali būti sėkmingai įterpiami į biopolimerinius kompozitus kaip tvarus ir funkcionalus užpildas puodelių gamybai. Toks PKT pritaikymas ne tik mažina atliekų kiekį, bet ir skatina tvarių produktų kūrimą, atsižvelgiant į žiedinės ekonomikos principus. Tyrime buvo analizuoti du PKT tipai: kavos aparatuose susidarantys tirščiai (*Machine* tipas), surinkti Meridiano licėjuje, ir maltos turkiškos „Kurukahveci Mehmet Efendi“ kavos tirščiai (*Turkish* tipas). Biopolimeriniai puodelių kompozitai buvo gaminami, esant 55–72 % masės PKT, o polimerinę matricą sudarė natrio alginatas, tinklintas $CaCl_2$.

Nustatyta, kad biopolimerų su PKT savybės skiriasi priklausomai nuo PKT kilmės: biokompozitinių puodelių su *Machine* PKT elastingumas buvo didesnis, o pagaminti puodeliai pasižymėjo terminiu atsparumu ir struktūriniu tvirtumu nei puodeliai, pagaminti naudojant *Turkish* PKT. Siekiant dar labiau pagerinti mechanines biokompozitinių puodelių savybes, gamybos metu papildomai įterpta 11 % masės pasirinkto polisacharido. Tai ne tik pagerino galutinio produkto mechanines savybes, bet ir palengvino puodelių formavimo procesą bei sumažino jų susitraukimą džiūvimo metu. Geriausi rezultatai pasiekti kaip papildomus biopolimerus naudojant celiuliozės darinius (CMC) ir dekstraną.

Apibendrinant galima teigti, kad PKT yra perspektyvus užpildas biokompozitinių puodelių gamybai. Tinkamai pasirinkus PKT tipą ir jo kiekį, galima gauti norimų savybių produktą. Ateities tyrimai turėtų būti nukreipti į tokių biokompozitinių puodelių bioskaidumo ir patvarumo esant aukštai temperatūrai tyrimus bei tolesnį mechaninių savybių optimizavimą.