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Development and Characterisation of Starch-Based Edible Films Incorporated with Hydroethanolic Spent Coffee Ground (SCG) Extract and Their Application as Functional Sachets for Instant Coffee Powder

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Research Article

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Development and Characterisation of Starch-Based Edible Films Incorporated with Hydroethanolic Spent Coffee Ground (SCG) Extract and Their Application as Functional Sachets for Instant Coffee Powder

Abstract

Purpose: Valorising agro-industrial by-products into functional biopolymer packaging is a key strategy for moving the food industry towards a circular economy. This study developed corn starch–glycerol edible films enriched with hydroethanolic spent coffee ground (SCG) extract and evaluated them as sachets for instant coffee powder.

Methods: Films were prepared at four extract levels (F0, control; F1, 5 mL; F2, 10 mL; F3, 15 mL per 100 mL film-forming solution). The extract was screened for phytochemicals and antioxidant activity, and films were characterised for thickness, moisture content, water solubility, tensile properties and microstructure (scanning electron microscopy). Heat-sealed F0 and F3 sachets were stored for 30 days under ambient conditions.

Results: The extract contained phenols, flavonoids, tannins and saponins (total phenolic content 23.4 ± 1.2 mg GAE/g; total flavonoid content 17.1 ± 0.9 mg QE/g; DPPH radical scavenging activity 98.34 ± 0.62 μmol TE/g). Tensile properties improved with extract concentration ($p < 0.001$); F3 showed the highest tensile stress at break (14.00 ± 0.38 MPa), elongation at break (25.00 ± 1.12%) and modulus of elasticity (0.685 ± 0.021 GPa). Moisture content (34.12% to 23.68%) and water solubility (91.07% to 81.03%) decreased significantly ($p < 0.05$), and micrographs showed a shift from porous to compact, homogeneous matrices. After 30 days, F3 sachets absorbed 76% less moisture than F0 (0.021 vs. 0.089 g; $p < 0.001$) and fully preserved powder flowability.

Conclusion: SCG-enriched starch films are a scientifically sound and eco-friendly alternative to conventional synthetic sachets.

Keywords: Spent coffee grounds; Edible film; Starch-based packaging; Active packaging; Antioxidant; Waste valorisation

1. Introduction

The global food packaging industry is faced with a critical task—both to reduce dependence on petroleum-based plastics and continue to meet the strict food preservation standards required by today's global food chain. The global production of plastic products has reached 460 million metric tonnes per year [1], and the food packaging sector is known to be the biggest source of post-consumer plastic waste. Around 79% of all plastic is in landfills, diffused within the natural environment and mechanically degraded and UV light results in the formation of micro- and nanoplastic particles that act as high surface area vectors for persistent organic pollutants (POPs) and endocrine-disrupting compounds [2, 3].

In recent years, the circular economy paradigm has brought together scientists towards the search for bio-based and biodegradable packaging materials from renewable agro-industrial raw materials [4]. Polysaccharide-based films, especially corn starch, have become prominent among potential biopolymer materials because of their biodegradability, film-forming capability and low cost [5]. However, the inherent hydrophilicity of this type of films based on starch and glycerol restricts their mechanical strength and moisture resistance. The incorporation of plant-based extracts containing phenolic compounds with polymers further reinforces the polymer network by hydrogen bonding, thus enhancing the mechanical and barrier properties, and also enables antioxidant activity [6, 7].

Spent Coffee Grounds (SCG) is a promising, yet under-exploited substrate for bioactive fortification. The coffee industry produces about six million tonnes of SCG worldwide every year [8]. The hydroethanolic extraction (50–60% v/v ethanol) is an efficient and scalable extraction protocol that has been used for the extraction of polyphenolic antioxidants from SCG, which is an amphiphilic solvent that helps in extraction of secondary metabolites from the cell wall matrix of SCG [9]. The application of SCG-based edible films as sachets for instant coffee powder is particularly synergistic—waste from coffee production directly packages the coffee product, embodying a zero-waste, closed-loop valorisation model [10]. This study addresses critical gaps by: (i) characterising the phytochemical and antioxidant profile of hydroethanolic SCG extract; (ii) developing corn starch-glycerol films enriched with SCG extract at four concentration levels (F0–F3); (iii) comprehensively characterising films using rigorous statistical analysis; and (iv) evaluating functional performance of the optimised film as an edible sachet in a 30-day ambient shelf-life study.

In the literature, there is still a critical gap about the dose–response relationship between hydroethanolic extract concentration of SCG and simultaneous improvement of the mechanical, moisture barrier and antioxidant properties of corn starch-glycerol films and the functional performance of the film when used as an edible film packaging material in heat-sealed edible sachets under ambient storage conditions has never been demonstrated.

2 Materials and Methods

2.1 Raw Materials and Reagents

Spent coffee grounds (SCG) were collected from local commercial coffee establishments in Coimbatore, Tamil Nadu, India. Commercial corn starch and analytical-grade glycerol were purchased from the local suppliers. All reagents for phytochemical analysis (Folin-Ciocalteu reagent, aluminium chloride, gallic acid, quercetin, and DPPH) were of analytical grade (Sigma-Aldrich, ≥98% purity). Solutions were prepared with double-distilled water unless stated otherwise.

2.2 Preparation and Hydroethanolic Extraction of SCG

Fresh SCG were air-dried at 25 ± 2°C for 24 h, then oven-dried at 60°C for 4 h to achieve a moisture content below 8%. The dried material was ground and sieved through a 250 µm mesh to obtain a uniform particle size. Hydroethanolic extraction was performed with 50-60% (v/v) aqueous ethanol (1:10, g: mL) by shaking at room temp intermittently for 45 min in a sealed conical flask. The slurry was centrifuged at 4000 rpm for 10 min, filtered using Whatman No.1 filter paper and ethanol was removed by water-bath evaporation at 40°C. The concentrated aqueous SCG extract was stored at 4°C in amber glass vials, as seen in Fig. 1a.

2.3 Phytochemical Characterisation of SCG Extract

2.3.1 Qualitative Phytochemical Screening

Standard qualitative assays were performed: Ferric Chloride test (phenols), Shinoda test (flavonoids), Gelatin precipitation test (tannins), and Froth test (saponins). All tests were performed in triplicate.

2.3.2 Total Phenolic Content (TPC)

TPC was determined by the Folin-Ciocalteu colorimetric method [11]. An aliquot of 0.5 mL SCG extract was mixed with 2.5 mL of 1:10 diluted Folin-Ciocalteu reagent, followed by 2.0 mL of 7.5% (w/v) sodium carbonate. After 30 min incubation at 25°C in darkness, absorbance was measured at 765 nm. Results are expressed as mg gallic acid equivalents per gram of extract (mg GAE/g; calibration curve $R^2 = 0.9986$, n = 3).

2.3.3 Total Flavonoid Content (TFC)

TFC was quantified by the aluminium chloride colorimetric method [12]. Aliquots (0.5 mL) were mixed with $AlCl_3$ (10%, w/v), potassium acetate (1 M), and methanol and the absorbance was measured at 415 nm after 30 min. Results were expressed as mg of Quercetin Equivalents per gram of extract (mg QE/g) ($R^2 = 0.9971$, n = 3).

2.3.4 DPPH Radical Scavenging Activity

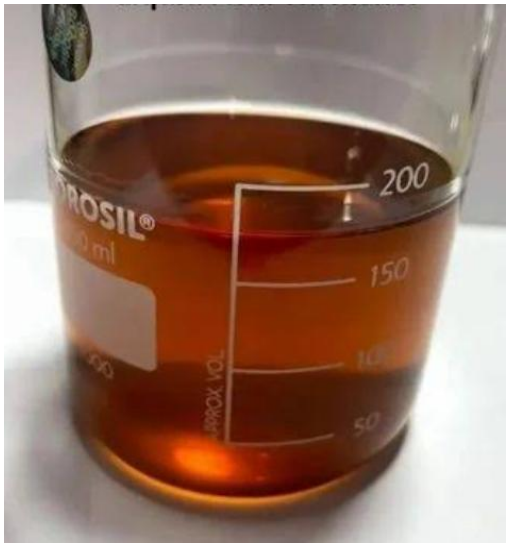
Antioxidant activity was evaluated by the DPPH assay [13]. Extract aliquots (0.1 mL) at varying concentrations were mixed with 3.9 mL of 0.1 mM methanolic DPPH and incubated for 30 min in darkness. Absorbance was measured at 517 nm, and inhibition was calculated as follows:

$$\text{Inhibition (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

where A_{control} and A_{sample} are the absorbances of the control and sample, respectively. Results are expressed as µmol Trolox equivalents per gram (µmol TE/g). IC_{50} was derived from a sigmoidal dose–response curve (n = 3).

2.4 Edible Film Preparation

Corn starch (4.0 g) was slurried in distilled water (100 mL), heated for 20 min at 85-90°C under constant stirring until complete gelatinisation to prepare film forming solutions. Glycerol (1.0 g) was added as plasticiser. After cooling to ~50°C, SCG extract was incorporated at designated volumes (Table 1). Solutions were homogenised, degassed for 15 min, and 30 mL cast onto level borosilicate glass plates. Films were dried for 48 h at 25 ± 2°C/50–55% RH and then conditioned in the same manner for 48 h before characterisation. The casting of film-forming solution and film drying under controlled conditions were depicted in Fig. 1b, c.



(a)



(b)



(c)

Fig. 1 Preparation of SCG extract and edible films: (a) hydroethanolic SCG extract after concentration, whose amber colour reflects its high polyphenolic content; (b) casting of film-forming solution onto a borosilicate glass plate; (c) cast films drying under controlled conditions (25°C, 50–55% RH)

Table 1 Formulation of corn starch–glycerol–SCG extract edible films

Film Code	Corn Starch (g)	Glycerol (g)	SCG Extract (mL)	Distilled Water (mL)
F0	4.0	1.0	0	100
F1	4.0	1.0	5.00	95.00
F2	4.0	1.0	10.00	90.00
F3	4.0	1.0	15.00	85.00

2.5 Characterisation of Edible Films

2.5.1 Film Thickness

Film thickness was measured by means of a digital Vernier calliper (±0.01 mm) at five random points per specimen (n = 3/film formulation). Mean ± SD are reported.

2.5.2 Moisture Content (MC)

Film specimens (2 cm × 2 cm, n = 3) were weighed (W_1) and dried at 105°C to constant mass (W_2). Moisture content was calculated as follows:

$$\text{MC}\ (\%)\ = \frac{W_1\ -\ W_2}{W_1} \times\ 100$$

2.5.3 Water Solubility (WS)

Pre-dried films of known dry mass (W_0) were immersed in 50 mL distilled water at 25°C for 24 h with agitation. Residual film was dried to constant mass (W_1), and water solubility was calculated as follows (n = 3):

$$\text{WS}\ (\%)\ = \frac{W_0\ -\ W_1}{W_0} \times\ 100$$

2.5.4 Mechanical Properties

The tensile properties were tested as per ASTM D882-12, using a universal testing machine (Instron 5565) at a crosshead speed of 5 mm/min at 25°C with dumbbell-shaped specimens (n = 5 per formulation) conditioned at 25°C/50% RH for 48 h before testing. Tensile stress at break (MPa), elongation at break (%), and modulus of elasticity (GPa) were derived from stress-strain curves.

2.5.5 Scanning Electron Microscopy (SEM)

Morphological characterization of the F0 and F3 films on the surface and cross section was conducted by SEM at an accelerating potential of 10-15 kV after gold sputter coating at magnification 500 and 1000 times corresponding to 20 µm and 10 µm scale, respectively.

2.6 Sachet Fabrication and Shelf-Life Evaluation

Based on optimal performance, F3 films were cut to 5 cm × 10 cm, folded, and the three sides heat-sealed using a direct impulse heat sealer. Each sachet was filled with 1.2 g instant coffee powder and the final edge

sealed. Sachets (n = 5 per formulation: F0 and F3) were stored at 25 ± 2°C/60 ± 5% RH for 30 days. Gravimetric moisture uptake was measured at 5-day intervals; powder was visually inspected for caking at each interval.

2.7 Statistical Analysis

All experiments were performed in triplicate (n = 3–5 as stated). Data are represented as mean ± SD. Inter-formulation comparisons were performed using one-way ANOVA and Tukey's HSD test with a significance set at $p < 0.05$. Pearson correlation coefficients were computed for SCG extract concentration vs. key film properties. IBM SPSS Statistics v29.0 was used for all analyses.

3 Results and Discussion

3.1 Phytochemical Profile of SCG Extract

Qualitative phytochemical screening of the hydroethanolic extract of SCG showed positive results for all four selected secondary metabolite classes (Table 2). The Ferric Chloride assay produced a characteristic blue-black colouration, confirming phenols. The Shinoda test produced noticeable magenta, which signifies the presence of flavonoids. The presence of tannins was confirmed by the white precipitate formation and saponins was confirmed by the persistent foam. The results are illustrated in Fig. 2.

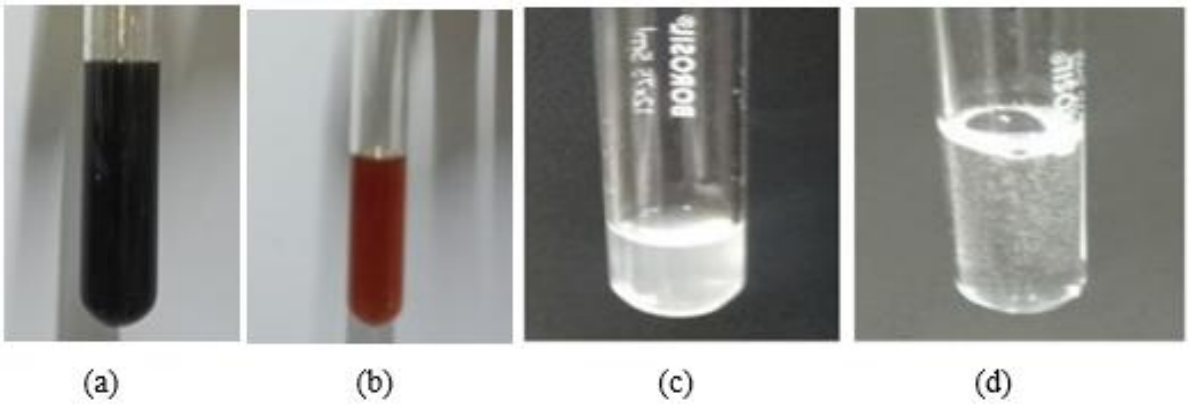


Fig. 2 Qualitative phytochemical screening of hydroethanolic SCG extract: (a) ferric chloride test, phenols (blue-black); (b) Shinoda test, flavonoids (magenta); (c) gelatin test, tannins (white precipitate); (d) froth test, saponins (persistent foam)

These results were supported by quantitative analysis. The TPC was 23.4 mg GAE/g ± 1.2 and the TFC was 17.1 mg QE/g ± 0.9 (Table 2), similar to optimised hydroethanolic SCG protocols [14]. The DPPH radical scavenging activity was 98.34 ± 0.62 µmol TE/g with an IC_{50} of 3.21 ± 0.18 mg/mL. These values indicate strong antioxidant activity, probably because of the combined effect of phenol and flavonoids fractions.

Table 2 Phytochemical and antioxidant profile of hydroethanolic SCG extract (mean ± SD, n = 3)

Parameter	Result / Observation	Interpretation
Phenols (Ferric Chloride)	Blue-black coloration (+)	Confirmed
Flavonoids (Shinoda test)	Magenta coloration (+)	Confirmed
Tannins (Gelatin test)	White precipitate (+)	Confirmed
Saponins (Froth test)	Persistent foam (+)	Confirmed
TPC (mg GAE/g extract)	**23.4 ± 1.2**	High phenolic recovery
TFC (mg QE/g extract)	**17.1 ± 0.9**	Significant flavonoid content
DPPH Activity (µmol TE/g)	**98.34 ± 0.62**	Potent radical scavenging

IC_{50} (mg/mL)	**3.21 ± 0.18**	Strong antioxidant efficacy

TPC, total phenolic content; TFC, total flavonoid content; GAE, gallic acid equivalents; QE, quercetin equivalents; TE, Trolox equivalents; IC_{50}, half-maximal inhibitory concentration; (+), positive result

3.2 Physicochemical Properties of Films

3.2.1 Film Thickness

Film thickness ranged from 0.202 ± 0.008 mm (F1/F2) to 0.254 ± 0.009 mm (F3), with F0 measuring 0.232 ± 0.007 mm (Table 3). Data analysis revealed a significant main effect of SCG concentration on thickness (at $p = 0.001$ with $F(3,8) = 14.23$). Tukey's HSD revealed that F3 presented significantly higher thickness than the other formulations ($p < 0.05$), which may be explained by the densifying polymeric network resulting from polyphenol-starch interactions, and the inclusion of lignocellulosic components of the SCG.

3.2.2 Moisture Content (MC)

MC exhibited a significant progressive decrease: F0 (34.12 ± 0.84%), F1 (30.45 ± 0.76%), F2 (27.31 ± 0.69%), F3 (23.68 ± 0.71%) (Table 3; Fig. 3). A one-way ANOVA showed that the variation between the groups was highly significant ($F(3,8) = 187.2$, $p < 0.001$); differences among all pairs were significant (Tukey's HSD, $p < 0.05$). Pearson correlation indicated that there was a strong negative correlation ($r = -0.99$, $p < 0.001$). The competitive hydroxyl-binding properties of polyphenolic SCG compounds compete with the hydroxyl-binding properties of the starch-glycerol matrix to decrease the number of water adsorption binding sites, leading to a decrease in hygroscopicity [5].

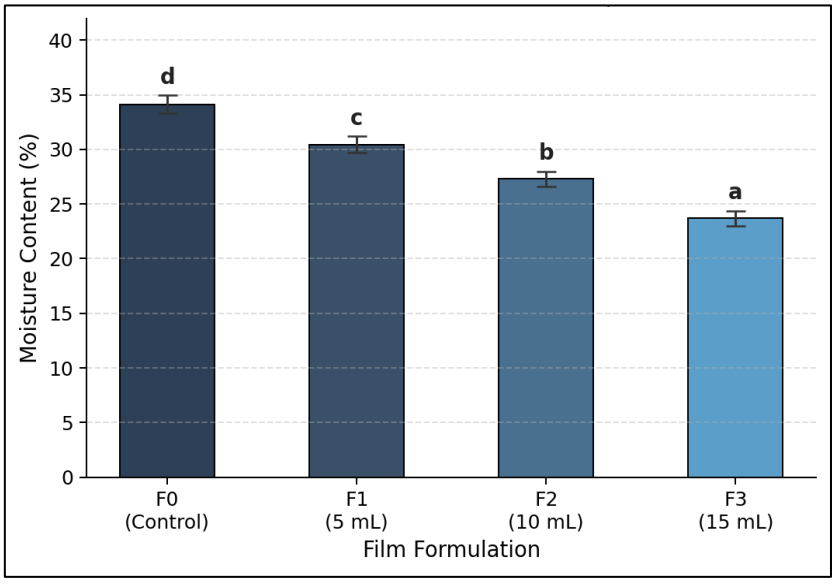


Fig. 3 Moisture content (%) of edible films F0–F3 (mean ± SD, n = 3). Different letters indicate significant differences (Tukey's HSD, $p < 0.05$)

3.2.3 Water Solubility (WS)

WS showed a non-monotonic pattern: F1 exhibited a slight increase over F0 (94.77 ± 1.41% vs. 91.07 ± 1.23%) before a progressive decline in F2 (87.18 ± 1.18%) and F3 (81.03 ± 1.08%) (Table 3; Fig. 4). The one-way ANOVA found a significant main effect ($F(3,8) = 89.4$, $p < 0.001$), and all post hoc comparisons were significant (Tukey's HSD, $p < 0.05$). Initially, a transient increase in F1 at low concentration of the extract is

supposed to indicate a partial disruption of starch crystalline regions before the cross linking of the network. The overall declining trend with higher concentration is attributed to the denser, more tortuous polymer network, as corroborated by SEM morphology [15]. High WS in F3 (81%) is desirable for edible sachet applications, ensuring complete dissolution in hot water without insoluble residue.

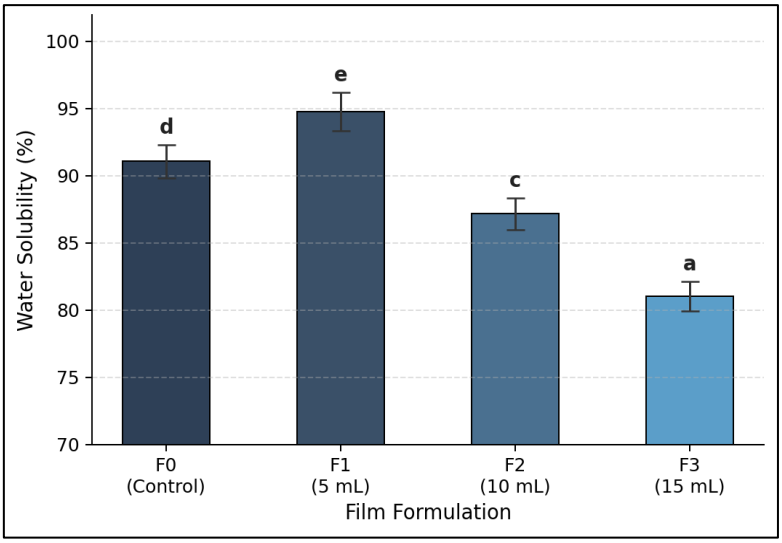


Fig. 4 Water solubility (%) of edible films F0–F3 (mean ± SD, n = 3). Different letters indicate significant differences (Tukey's HSD, $p < 0.05$)

Table 3 Physicochemical and mechanical properties of edible films F0–F3 (mean ± SD; n = 3 for thickness, moisture content and water solubility; n = 5 for mechanical properties)

Property	F0 (control)	F1 (5 mL)	F2 (10 mL)	F3 (15 mL)
Thickness (mm)	0.232 ± 0.007^{b}	0.202 ± 0.008^{a}	0.202 ± 0.009^{a}	0.254 ± 0.009^{b}
Moisture Content (%)	34.12 ± 0.84^{d}	30.45 ± 0.76^{c}	27.31 ± 0.69^{b}	23.68 ± 0.71^{a}
Water Solubility (%)	91.07 ± 1.23^{d}	94.77 ± 1.41^{e}	87.18 ± 1.18^{c}	81.03 ± 1.08^{a}
Tensile Stress at Max (MPa)	3.58 ± 0.21^{a}	1.63 ± 0.14^{a}	5.20 ± 0.19^{b}	13.98 ± 0.42^{c}
Tensile Stress at Break (MPa)	3.52 ± 0.18^{a}	1.58 ± 0.11^{a}	5.14 ± 0.22^{b}	14.00 ± 0.38^{c}
Elongation at Break (%)	8.21 ± 0.94^{a}	6.43 ± 0.72^{a}	11.30 ± 1.02^{b}	25.00 ± 1.12^{c}
Modulus of Elasticity (GPa)	0.324 ± 0.018^{a}	0.337 ± 0.022^{a}	0.481 ± 0.019^{b}	0.685 ± 0.021^{c}

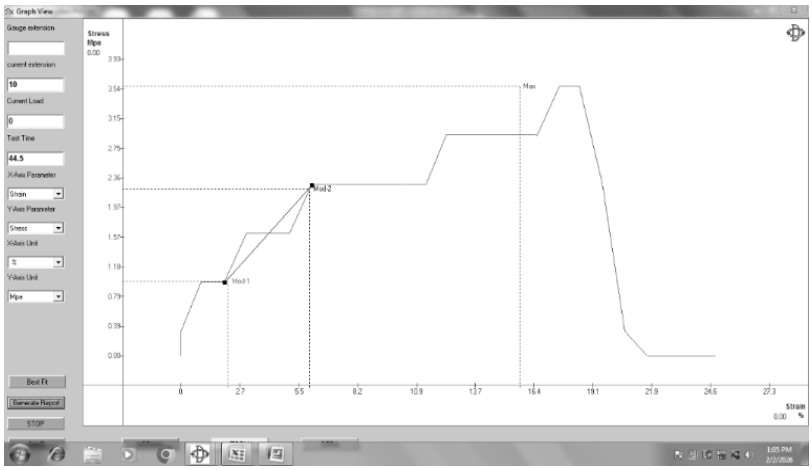
Values within a row followed by different superscript letters differ significantly (Tukey's HSD, $p < 0.05$)

3.3 Mechanical Properties

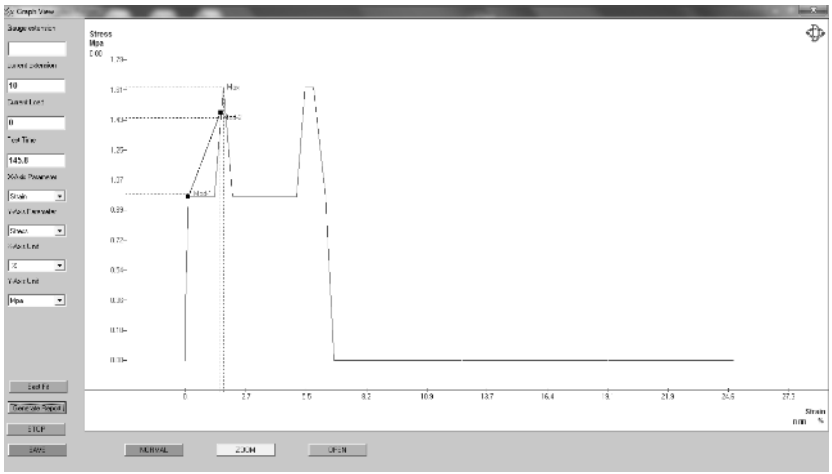
Mechanical characterisation showed that as the concentration of particles increase, there is a significant improvement in the tensile parameters (Table 3) which is evident. The F3 formulation achieved the highest tensile stress at break (14.00 ± 0.38 MPa), elongation at break (25.00 ± 1.12%), and modulus of elasticity (0.685 ± 0.021 GPa). One-way ANOVA confirmed highly significant differences among formulations for all mechanical parameters: tensile stress at break ($F(3,16) = 287.6$, $p < 0.001$), elongation at break ($F(3,16) = 198.4$, $p < 0.001$), and modulus of elasticity ($F(3,8) = 54.3$, $p < 0.001$). According to Tukey's HSD the formulation F3 was significantly better than all other formulations ($p < 0.05$). Pearson correlation showed that there was a strong

positive correlation between concentration of SCG extract and tensile stress ($r = 0.97$, $p < 0.01$) and modulus ($r = 0.95$, $p < 0.01$).

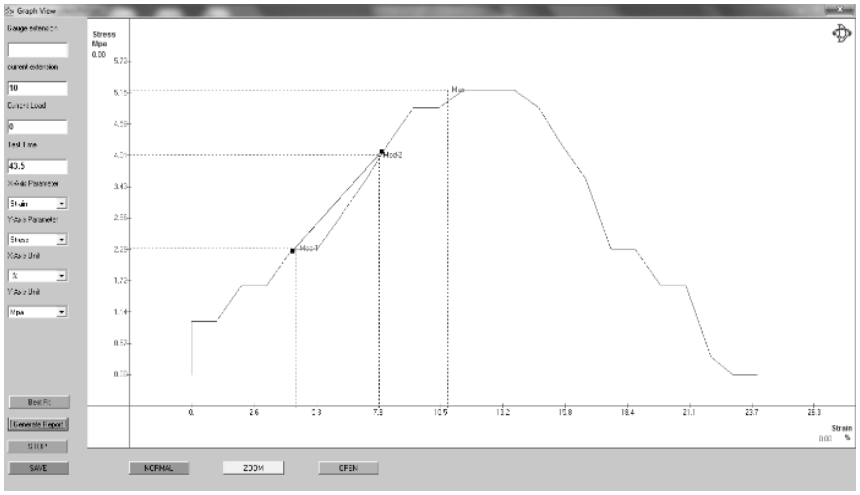
The mechanism involves presumably non-covalent intermolecular interactions between the hydroxyl groups of the polyphenolic compounds in the SCG derived phenolics and the hydroxyl-rich starch backbone, the main interaction being a hydrogen bond. These interactions enhance the density of the polymer network and reduce the mobility of the chains which significantly stiffen the material and promote failure stress. Besides that, the lignocellulosic fibre fraction of SCG can serve as a natural reinforcing filler [6, 16]. Stress-strain curves for individual formulations (F0–F3) are presented in Fig. 5.



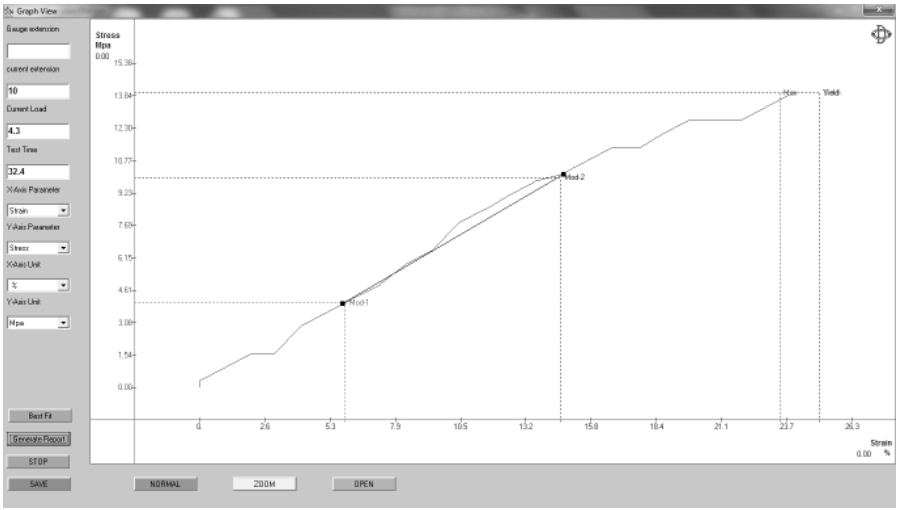
(a)



(b)



(c)



(d)

Fig. 5 Stress–strain curves of the film formulations obtained according to ASTM D882-12: (a) F0, maximum stress 3.58 MPa; (b) F1, 1.63 MPa; (c) F2, 5.20 MPa; (d) F3, 13.98 MPa. F3 shows markedly superior tensile performance, with the highest stress and elongation at failure, attributable to polyphenol–starch hydrogen bonding and lignocellulosic reinforcement from SCG

3.4 Microstructural Analysis (SEM)

The SEM micrographs highlighted two different fundamental microstructural architectures for films F0 and F3 (Fig. 6). At 20 µm magnification, the F0 control film had a structurally heterogeneous film surface with visible pores and microscale voids, which were caused by incomplete polymer chain entanglement. F0 cross-sectional image reveals that it has a porous and irregular cross-sectional structure with intercalated air pockets, which is consistent with the reduced mechanical strength and high moisture content of this product.

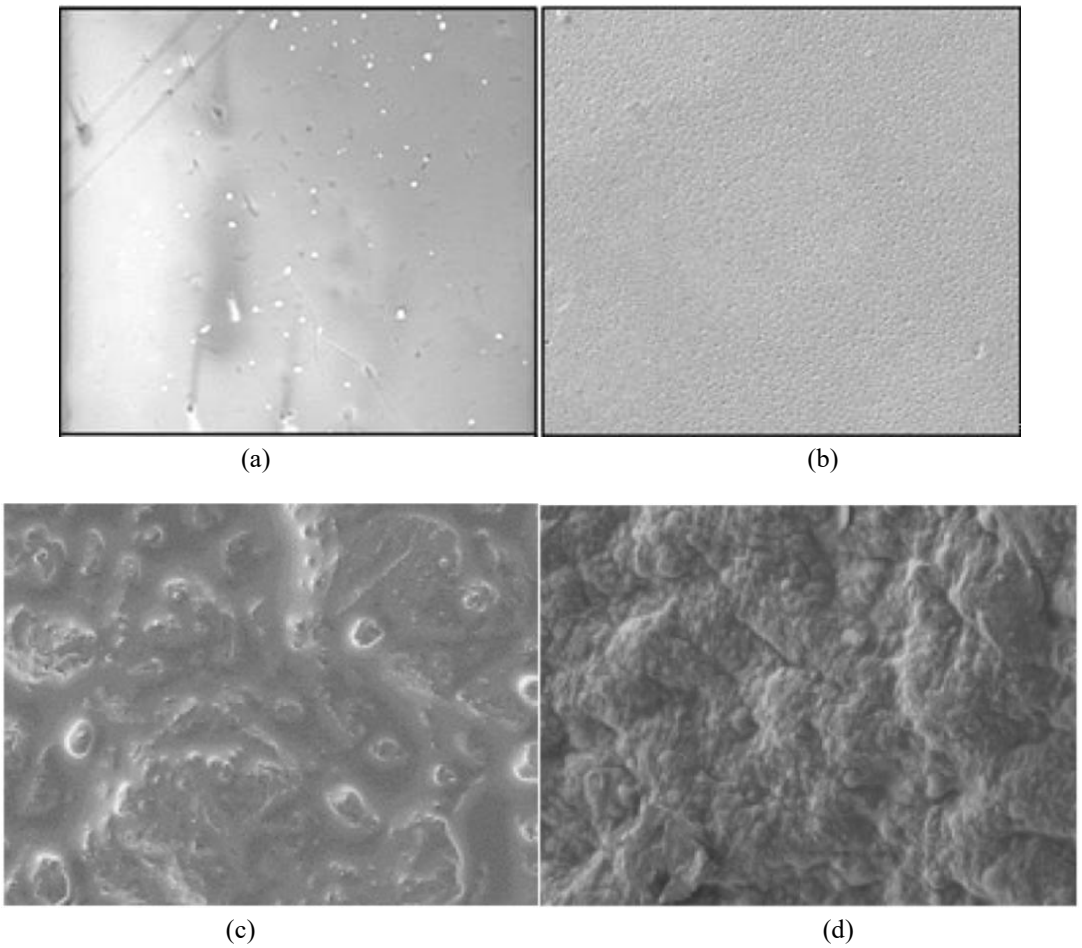


Fig. 6 Scanning electron micrographs of F0 (control) and F3 (optimised) films: (a) F0 and (b) F3 at the 20 µm scale; (c) F0 and (d) F3 at the 10 µm scale. The transition from a porous (F0) to a compact (F3) structure corroborates the mechanical and barrier improvements observed in physicochemical characterisation

By contrast the F3 film showed a very dense, uniform and homogeneous surface topology at 20 µm, with no sign of phase separation nor porosity. The dense and uniform cross-sectional architecture at 10 µm was also indicative of an extensively crosslinked polymer network, as a result of the hydrogen bonding between polyphenol-starch interactions and lignocellulosic microfibres from SCG reinforcement. These SEM observations unambiguously confirm the physicochemical data, as the lower porosity corresponds to higher moisture barrier properties, and as higher packing of the chains indicates a mechanistic basis for the better tensile properties of F3.

3.5 Shelf-Life Performance of Edible Sachets

The ambient shelf-life trial over a period of 30 days indicated a significant variation in moisture barrier effectiveness. After 30 days, the gravimetric moisture uptake was significantly lower in F3 sachets (0.021 ± 0.003 g) than in F0 sachets (0.089 ± 0.011 g), accounting for 76% decrease in moisture uptake (Table 4; Fig. 7) (Independent samples t-test at D30: $t(8) = 12.4$, $p < 0.001$).

Progressive softening of F0 sachets started from Day 10 and geometrical collapse was observed on Day 20 which suggested hygroscopic plasticisation of the starch-glycerol matrix. F3 sachets have demonstrated no significant change in dimensional stability, firmness of texture, or failure of heat seal during the times of observation. Visual inspection of enclosed coffee powder revealed that the F3 sachets maintained complete

flowability of the coffee powder without incidence of caking or inter-particle agglomeration while the F0 sachet had incipient caking from Day 15 onward (Fig. 8).

Table 4 Gravimetric moisture uptake (g) of F0 and F3 sachets during 30-day storage (mean ± SD, n = 5)

Sachet	Day 0	Day 5	Day 10	Day 20	Day 30
F0	0.000	0.018 ± 0.002	0.038 ± 0.004	0.064 ± 0.008	0.089 ± 0.011
F3	0.000	0.004 ± 0.001	0.009 ± 0.001	0.015 ± 0.002	0.021 ± 0.003
p-value	—	< 0.001	< 0.001	< 0.001	< 0.001

p-values from independent-samples t-test at each time point (n = 5 per group)

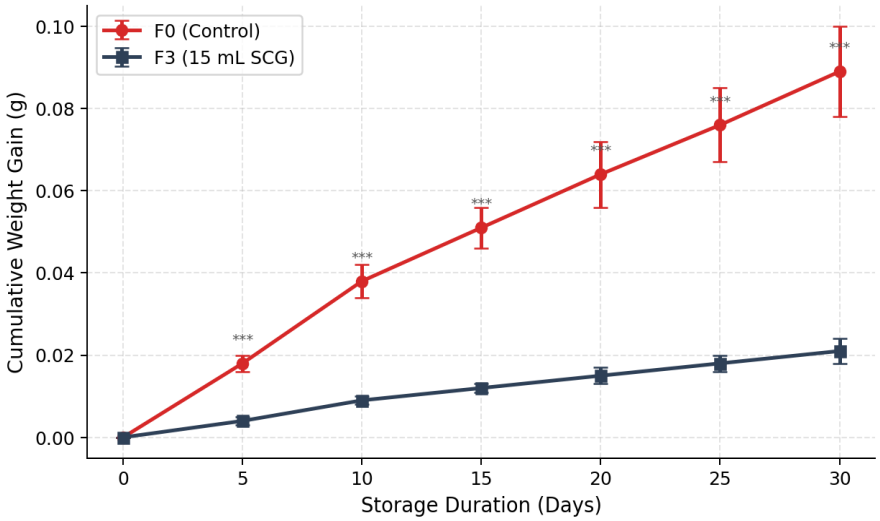


Fig. 7 Gravimetric moisture uptake of F0 and F3 sachets over 30 days of ambient storage (mean ± SD, n = 5); ***p < 0.001 at all measured time points (independent-samples t-test). F3 shows 76% lower total moisture uptake than the F0 control

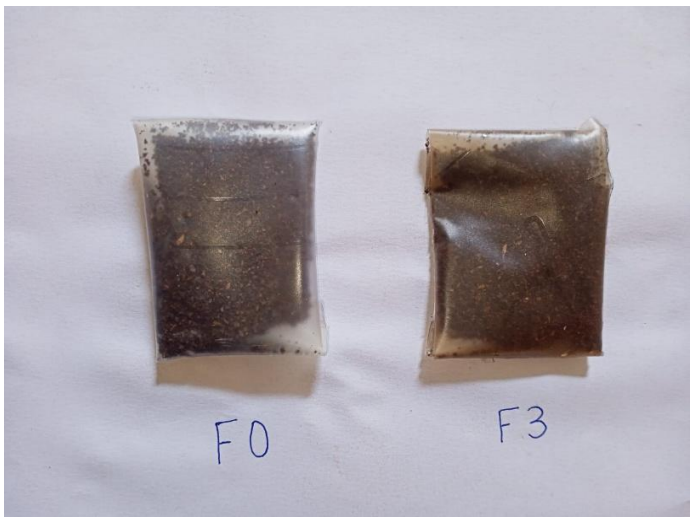


Fig. 8 Heat-sealed edible sachets filled with 1.2 g instant coffee powder: F0 (control, left) and F3 (15 mL SCG extract, right), showing visible differences in transparency and film integrity

The mechanical performance of F3 (tensile stress at break: 14.00 ± 0.38 MPa; elongation: 25.00 ± 1.12%) compares favourably with a broad range of plant extract-enriched starch films. Orhotohwo et al. [10] achieved tensile strength of 8.4–11.2 MPa for the coffee extract films with cassava starch; Qin et al. [17] obtained 10.6 MPa for curcumin-corn starch composites; Nogueira et al. [16] reported MC values of 20–28% for polyphenol films with corn starch, which were comparable to those obtained in the present study (23.68–34.12%). Optimisation of extraction parameters enhances DPPH antioxidant capacity of the hydroethanolic extract of SCG (98.34 ± 0.62 μmol TE/g), which is greater than many published values of hydroethanolic extract of SCG (70–95 μmol TE/g). Together, these comparisons place the current results at the higher end of performance of these types of sustainable packaging materials.

4. Conclusion

This study introduces statistically sound evidence supporting hydroethanolic extract of spent coffee grounds as an effective, multi-functional additive for starch-glycerol edible films that acts to positively improve mechanical strength, moisture barrier properties, and antioxidant activity, all in a concentration-dependent manner. The F3 formulation, containing 15 mL SCG extract per 100 mL film-forming solution, was selected as the optimum formulation because its tensile stress at break (14.00 ± 0.38 MPa), elongation at break (25.00 ± 1.12%), moisture content (23.68 ± 0.71%), and water solubility (81.03 ± 1.08%) were statistically superior to the control and lower concentration formulations (Tukey's HSD, $p < 0.05$). The SEM analysis confirmed the results of the physicochemical and mechanical improvements, showing a transition in the mechanism from a porous to a compact and homogeneous polymer matrix. The practical efficacy was assessed in a 30-day shelf-life study, where the F3 heat-sealed sachets exhibited 76% reduction in moisture absorption and maintained the flowability of coffee powder completely compared to the F0 (control), at $p < 0.001$.

This study exemplifies the circular economy by transforming a significant agro-industrial waste stream, SCG, into a useful packaging material and subsequently applying it to its own originators: agroindustry. Future research can involve FTIR spectroscopic fingerprinting of polyphenol-starch interactions, quantification of water vapour permeability (WVP) per ASTM E96, evaluation of antimicrobial activity and pilot scale fabrication feasibility studies.

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