Inclusive Society and Sustainability Studies, Vol. 6, No. 1 (2026) https://doi.org/10.31098/issues.v6i1.4125

Research Paper

Sensory, Phytochemical, and Antioxidant Evaluation of Dark Chocolate Fortified with Spent Coffee Grounds

Jona Anne Elaine Maningas, Karen A. Manaig, Alberto D. Yazon
Laguna State Polytechnic University – Los Baños Campus, Philippines

Received: October 14, 2025	Revised: June 2, 2026	Accepted: June 9, 2026	Online: June 18, 2026

Abstract

This study experimentally evaluated the sensory acceptability, total phenolic content, and antioxidant capacity of dark chocolate fortified with Spent Coffee Grounds (SCG) within a sustainability-oriented food innovation framework. Three formulations containing 15 g, 25 g, and 50 g SCG were assessed by 60 evaluators using a 9-point Hedonic Scale. One-way ANOVA and Tukey's HSD determined significant differences among samples ($p < 0.05$). Results revealed that the formulation containing 50 g SCG achieved significantly higher overall acceptability, indicating that increased SCG incorporation did not compromise sensory quality. The selected formulation exhibited higher total phenolic content and strong DPPH radical-scavenging activity, confirming functional improvement. This study's novelty lies in integrating sensory evaluation, phytochemical quantification, and antioxidant analysis across multiple formulations to identify an optimal balance between consumer acceptability and functional enhancement within a waste-valorization framework. Findings extend functional food theory by demonstrating that high-level incorporation of SCG can enhance bioactivity without reducing consumer acceptance when applied within a compatible cocoa-based matrix. The study contributes to sustainable food systems by providing an evidence-based model for transforming agro-industrial waste into value-added functional products.

Keywords: *Dark Chocolate, Spent Coffee Grounds, Phenolic Content, Antioxidant Capacity*

INTRODUCTION

The rapid growth of global coffee consumption has led to the large-scale generation of Spent Coffee Grounds (SCG), a by-product commonly discarded after brewing. Although often treated as waste, SCG contains substantial amounts of phenolic compounds, chlorogenic acids, flavonoids, and caffeine, which retain measurable antioxidant properties even after extraction. The disposal of SCG in landfills contributes to environmental burdens, including methane emissions and inefficient resource utilization. Consequently, transforming SCG into value-added food ingredients presents an opportunity to address both environmental sustainability and nutritional innovation.

Within the broader sustainability agenda, circular economy principles advocate reintegrating waste materials into productive systems. In food systems, circularity requires that agro-industrial by-products be repurposed into economically viable and socially acceptable products. However, the transition from waste material to functional food ingredient is not solely a technological challenge. It requires empirical validation across sensory, biochemical, and consumer acceptance dimensions to ensure feasibility beyond laboratory experimentation.

In developing economies such as the Philippines, the expansion of small-scale cafés and food enterprises has increased localized accumulation of SCG. Despite national sustainability initiatives that promote waste reduction and livelihood development, systematic research on incorporating SCG into commercially viable food products remains limited. Most valorization efforts focus on composting, biofuel production, or chemical extraction, with comparatively fewer studies investigating direct food applications that are cost-efficient and scalable for small producers. This creates both a sustainability challenge and an opportunity for inclusive innovation.

Corresponding author's email: jona.pinpin@lspu.edu.ph

Existing studies confirm that SCG possesses antioxidant potential and can enhance the nutritional profile of various food products. However, two primary gaps persist. First, a gap in the literature exists regarding the limited integration of sensory evaluation, phytochemical quantification, and antioxidant analysis across multiple formulation levels within a single experimental design. Many investigations emphasize chemical characterization while underrepresenting consumer acceptability, despite its critical role in market viability. Second, a practice gap persists in the absence of empirically validated, small-scale, consumer-acceptable product models that translate sustainability theory into applied food innovation.

From a theoretical perspective, functional food development operates at the intersection of health functionality and sensory satisfaction. Functional Food Theory suggests that foods enriched with bioactive compounds can contribute to disease prevention and health optimization. However, consumer research consistently demonstrates that perceived health benefits do not compensate for negative sensory experiences. Therefore, sustainable ingredient substitution must be evaluated within sensory thresholds to ensure practical adoption.

Dark chocolate represents a particularly relevant matrix for SCG incorporation due to its inherent polyphenol content and characteristic bitter flavor profile. The sensory compatibility between cocoa and SCG may mitigate the bitterness commonly associated with SCG fortification in lighter food matrices. This suggests that matrix compatibility may serve as a moderating factor in functional food acceptance. Empirical testing of this interaction is necessary to determine whether higher SCG concentrations can enhance functional properties without diminishing consumer satisfaction.

Accordingly, this study investigates whether dark chocolate formulations fortified with varying concentrations of SCG can achieve enhanced phytochemical and antioxidant properties while maintaining or improving sensory acceptability. By integrating sensory science with biochemical analysis within a sustainability framework, the study seeks to bridge the gap between environmental valorization and consumer-driven product development.

The following research questions guide the study:

1. Are there significant differences in sensory acceptability among dark chocolate formulations containing 15 g, 25 g, and 50 g of SCG?
2. Which formulation achieves the highest overall consumer acceptability?
3. Does the most acceptable formulation demonstrate enhanced total phenolic content and antioxidant capacity?

By addressing these questions, the study contributes to inclusive and sustainable food innovation by offering a model that integrates waste reduction, nutritional enhancement, and consumer acceptance. The findings aim to advance theoretical discourse in functional food development while providing practical guidance for small-scale producers and sustainability-oriented food enterprises.

Beyond its immediate implications for product development, the valorization of Spent Coffee Grounds intersects with broader global sustainability targets, including responsible consumption and production, climate mitigation, and resource efficiency. The food sector accounts for a significant proportion of global waste streams, and reducing post-consumption residues represents a critical intervention point. Coffee is one of the most traded commodities worldwide, and its by-products constitute a substantial yet underutilized biomass resource. Transforming SCG into functional food ingredients helps reduce landfill accumulation while creating nutritional and economic value.

Moreover, sustainable food innovation must reconcile environmental responsibility with consumer-driven market dynamics. Products that fail to meet sensory expectations are unlikely to gain adoption, regardless of their environmental benefits. Therefore, evaluating sustainability-

oriented ingredient substitution through both biochemical and sensory lenses strengthens translational impact. This study contributes to sustainability science by demonstrating a model in which environmental valorization is empirically validated within consumer acceptance frameworks rather than treated as a purely ecological initiative.

LITERATURE REVIEW

Sensory Acceptability of Spent Coffee Grounds (SCG)-Fortified Food Products

Consumer acceptability remains a critical determinant of the success of functional food products. While Spent Coffee Grounds (SCG) have gained attention as a sustainable source of bioactive compounds, their incorporation into food products often presents sensory challenges. SCG contains residual caffeine, chlorogenic acids, and phenolic compounds that contribute bitterness and roasted flavor characteristics, which may affect consumer preference when incorporated at high concentrations (Arya et al., 2022; Stylianou et al., 2018).

Previous studies evaluating SCG incorporation in bakery products, cereal-based foods, and snacks reported mixed sensory outcomes. Ballesteros et al. (2017) observed that increasing SCG concentration enhanced antioxidant activity but reduced consumer acceptability due to bitterness and coarse texture. Similarly, Narita and Inouye (2021) reported that excessive incorporation of SCG negatively affected flavor and mouthfeel in baked products. These findings suggest that sensory responses to SCG depend heavily on product formulation and ingredient compatibility.

Sensory Acceptability Theory emphasizes that food evaluation is multidimensional, involving appearance, aroma, texture, taste, and overall preference (Maina, 2018). Consumers generally prioritize sensory satisfaction over nutritional benefits, indicating that functional ingredients must be incorporated without compromising desirable sensory characteristics. Therefore, sensory evaluation remains essential in determining whether sustainability-oriented food innovations can achieve practical market acceptance.

Recent studies further emphasize that consumer acceptance of functional foods depends not only on nutritional value but also on the congruence between the sensory characteristics of the functional ingredient and the carrier food matrix (Granato et al., 2020). This suggests that products possessing naturally roasted or bitter flavor profiles may be more suitable carriers for SCG incorporation than neutral-flavored food systems.

Consumer Preference and Optimal SCG Formulation in Chocolate Products

Determining the optimal level of functional ingredient incorporation is a fundamental challenge in product development. Previous studies have demonstrated that increasing concentrations of bioactive ingredients may improve nutritional quality while simultaneously affecting consumer acceptance (Granato et al., 2020). Consequently, identifying formulation thresholds that maximize both functionality and acceptability is essential.

Dark chocolate is a particularly suitable carrier matrix for SCG because both ingredients share sensory characteristics such as bitterness, roasted notes, and complex aromatic compounds. Cocoa products naturally contain flavonoids and polyphenols that contribute characteristic sensory properties and health-promoting effects (Aprotosoaie et al., 2016). The compatibility between cocoa and SCG may reduce the negative sensory impacts commonly observed in other fortified foods.

Research on cocoa-based functional foods suggests that consumer acceptance is influenced by matrix compatibility, in which flavor alignment between the carrier matrix and the added ingredient enhances overall preference (Aprotosoaie et al., 2016). Products exhibiting congruent flavor profiles often demonstrate higher sensory acceptability despite increased concentrations of bioactive compounds. This concept is particularly relevant in dark chocolate, where moderate

bitterness is commonly perceived as a desirable quality attribute.

Although studies investigating SCG incorporation into chocolate products remain limited, available evidence suggests that cocoa-based matrices may accommodate higher levels of SCG than bakery or cereal systems (Martínez-Saez et al., 2017). Nevertheless, empirical evaluation is required to identify the concentration that optimizes consumer preference while maintaining desirable sensory quality.

Phytochemical Content and Antioxidant Capacity of SCG-Enriched Foods

Spent Coffee Grounds remain a rich source of bioactive compounds even after the brewing process. Several studies have confirmed the presence of chlorogenic acids, caffeic acid derivatives, flavonoids, and other phenolic compounds that contribute substantial antioxidant activity (Stylianou et al., 2018; Arya et al., 2022).

Phenolic compounds play a significant role in mitigating oxidative stress through free-radical scavenging mechanisms. These compounds have been associated with potential health benefits, including reduced risk of cardiovascular diseases, inflammation, and certain chronic conditions (Granato et al., 2020). Consequently, the recovery and utilization of phenolic-rich food by-products have become increasingly important within sustainable food systems.

Dark chocolate itself is recognized as a functional food due to its naturally occurring flavanols and antioxidant compounds. Previous investigations have shown that cocoa polyphenols contribute significantly to antioxidant capacity and may exert synergistic effects when combined with other plant-derived bioactive compounds (Aprotosoaie et al., 2016). This suggests that SCG and cocoa may function cooperatively to enhance antioxidant potential beyond the contributions of either ingredient alone.

The antioxidant capacity of SCG-fortified foods is commonly assessed using the DPPH radical scavenging assay, while total phenolic content is frequently measured using the Folin–Ciocalteu method (Ainsworth & Gillespie, 2007). These analytical procedures provide reliable indicators of functional enhancement and are widely used in food science research.

Despite growing evidence supporting the bioactive potential of SCG, existing studies often focus exclusively on chemical characterization while neglecting sensory evaluation. Furthermore, limited research integrates sensory acceptability, phytochemical quantification, and antioxidant assessment within a single experimental framework. This gap highlights the need for comprehensive investigations that simultaneously evaluate consumer acceptance and functional performance.

RESEARCH METHOD

Research Design

This study employed a quantitative experimental research design to examine the effects of varying concentrations of Spent Coffee Grounds (SCG) on the sensory acceptability, total phenolic content, and antioxidant capacity of dark chocolate formulations. An experimental approach was selected to allow controlled manipulation of SCG concentration (15 g, 25 g, and 50 g) while maintaining constant processing conditions across samples.

This design enabled direct comparison of formulation outcomes and alignment with the study's research questions concerning sensory differentiation and functional enhancement. The design integrates principles from functional food evaluation and sustainability-driven product development. By systematically assessing both consumer acceptability and biochemical properties, the study adopts a dual-validation framework that addresses the sensory–functionality balance identified in the literature.

Research Questions and Analytical Framework

To address Research Question 1, sensory acceptability scores for appearance, aroma, taste, texture, and general acceptability were analyzed using descriptive statistics and one-way Analysis of Variance (ANOVA) to determine whether significant differences existed among the three dark chocolate formulations. For Research Question 2, mean sensory scores and Tukey's Honestly Significant Difference (HSD) post hoc test were utilized to identify the formulation with the highest overall consumer acceptability.

To address Research Question 3, the formulation with the highest sensory acceptance score was subjected to total phenolic content determination using the Folin–Ciocalteu method and to antioxidant activity assessment using the DPPH free radical scavenging assay. These analyses provided empirical evidence of functional enhancement achieved by incorporating Spent Coffee Grounds while maintaining consumer acceptability.

Preparation of Spent Coffee Grounds and Chocolate Formulations

Spent Coffee Grounds were collected from freshly brewed Arabica coffee purchased from a local café to reflect real-world waste-generation conditions. The SCG were oven-dried at 60°C until moisture-free to prevent microbial growth and preserve phenolic stability. The dried grounds were then finely milled and sieved to achieve a uniform particle size distribution of less than 250 microns, ensuring smooth integration into the chocolate matrix and reducing potential textural coarseness.

This preparation protocol aligns with sustainable food valorization practices by using minimally processed waste materials without chemical extraction, thereby maintaining cost-efficiency and scalability for small-scale production. Three dark chocolate formulations were prepared by incorporating 15 g, 25 g, and 50 g of SCG into a standardized chocolate base. The base consisted of cocoa butter (50 g), cocoa powder, and powdered sugar, prepared using the double-boiler method to ensure controlled melting and homogenization.

All formulations were processed under identical conditions to minimize variability. The mixture was poured into silicone molds and cooled at a constant temperature to standardize crystallization. Controlling processing variables ensured that differences in sensory outcomes could be attributed primarily to SCG concentration rather than procedural variation.

Validity and Reliability of Instrument

Content validity of the sensory instrument was established through expert review by three faculty members in food science and product development. Reliability testing using Cronbach's alpha yielded a coefficient of 0.89, indicating high internal consistency across sensory attributes.

Sensory Evaluation

Sensory acceptability was evaluated using a 9-point Hedonic Scale, a standardized and widely accepted method in sensory science. Sixty (60) evaluators, composed of faculty members and students with backgrounds in food-related disciplines, assessed the samples. Evaluators rated each formulation in terms of appearance, taste, aroma, texture, and general acceptability, where 9 indicated "Like Extremely," and 1 indicated "Dislike Extremely."

Samples were coded and presented in randomized order to reduce bias. Drinking water was provided between tastings to cleanse the palate. Sensory evaluation procedures were conducted in accordance with established sensory testing protocols.

The use of 60 evaluators aligns with recommendations in sensory science literature, where consumer-type hedonic testing commonly employs 50–100 participants to achieve adequate statistical power and reliability (Sharif et al., 2017; Choi, 2021). Of the 60 evaluators, 65% were female and 35% male, with ages ranging from 18 to 45 years (mean age = 23.8 years). All

participants had prior exposure to sensory evaluation activities in academic settings, ensuring familiarity with hedonic scaling procedures.

The selection of 60 evaluators aligns with recommendations for consumer-type hedonic testing, where sample sizes of 50-100 participants are considered statistically adequate for detecting meaningful sensory differences. This sample size enhances reliability while remaining feasible within controlled academic testing environments.

To ensure instrument validity, the sensory questionnaire underwent expert content validation by three faculty members specializing in food science and sensory evaluation. Minor revisions were implemented to improve clarity and attribute specificity. Internal consistency reliability was assessed using Cronbach's alpha ($\alpha = .89$), indicating high reliability across sensory constructs.

While phytochemical and antioxidant analyses were conducted on the most acceptable formulation due to laboratory resource constraints, this design choice reflects a product-optimization framework rather than a purely comparative biochemical model. Nevertheless, future studies should conduct full comparative analyses to establish dose–response relationships across formulations.

Phytochemical Analysis

Phytochemical and antioxidant analyses were conducted on the formulation that obtained the highest overall sensory acceptability score during the evaluation phase. This approach follows a product-optimization framework commonly used in functional food development studies, in which biochemical validation is conducted on the formulation most likely to be accepted by consumers.

Because the primary objective of the study was to identify a formulation that balances sensory acceptability with functional enhancement, laboratory analysis was prioritized for the sample that demonstrated the strongest consumer preference. This decision was also influenced by laboratory resource constraints and the practical aim of validating the functional properties of the formulation with the greatest potential for real-world application.

However, focusing the phytochemical and antioxidant analyses on a single formulation limits direct biochemical comparison across all SCG concentration levels. As a result, the study does not provide empirical evidence of functional differences among the three formulations. Instead, the laboratory results confirm the presence of bioactive compounds and antioxidant activity in the most acceptable formulation.

The interpretation of potential functional differences among formulations is therefore discussed cautiously in relation to sensory outcomes and the existing literature on SCG phenolic content. Future studies are recommended to conduct comprehensive comparative phytochemical and antioxidant analyses across all formulations to establish dose–response relationships between SCG concentration and functional properties.

Antioxidant Capacity Analysis

Antioxidant activity was measured using the DPPH free radical scavenging assay, a widely recognized method for assessing antioxidant potential in food matrices. Percentage inhibition values were calculated to determine scavenging capacity. All biochemical analyses were performed in triplicate to ensure reproducibility and reduce experimental error.

Statistical Analysis

Descriptive statistics, including mean and standard deviation, were used to summarize sensory acceptability data. One-way Analysis of Variance (ANOVA) was applied to determine

significant differences among the three chocolate formulations across sensory attributes. When significant differences were observed, post hoc comparisons were conducted using Tukey's HSD test. Statistical significance was set at $p < 0.05$. All statistical analyses followed standard procedures commonly used in food science research.

Ethical Considerations

Participation in sensory evaluation was voluntary. Participants were informed of the study's purpose and provided verbal consent prior to evaluation. No personal identifying information was collected, ensuring confidentiality and minimal risk.

Research Process Flow

The overall research workflow included product formulation, sensory evaluation, statistical analysis, and laboratory testing for phytochemical content and antioxidant activity. These procedures were conducted sequentially to ensure consistency and reproducibility.

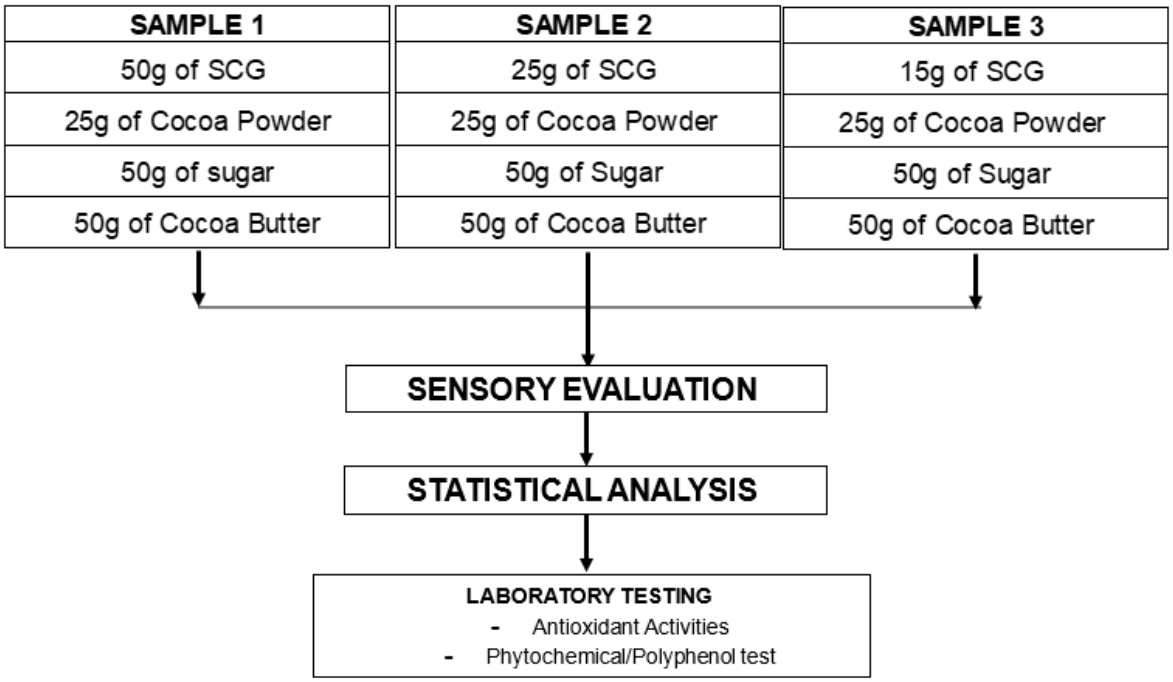

Figure 1. Research Process Flow for The Development and Evaluation of Dark Chocolate with Spent Coffee Grounds

FINDINGS AND DISCUSSION

This section presents and discusses the key findings of the study on the sensory acceptability, phytochemical content, and antioxidant capacity of dark chocolate incorporating Spent Coffee Grounds (SCG). The discussion synthesizes the results and highlights how the findings align with, extend, or differ from previous research.

Sensory Acceptability of Dark Chocolate with Spent Coffee Grounds

The sensory evaluation revealed that the level of SCG incorporation significantly influenced consumer acceptability across all evaluated attributes. Among the three formulations, the dark chocolate with the highest SCG content demonstrated superior overall sensory performance. These findings suggest that SCG can be successfully integrated into dark chocolate without diminishing, and in some aspects improving, sensory quality.

Influence of SCG Concentration on Sensory Attributes

Taste and Aroma

The results revealed that the formulation containing 50 g of Spent Coffee Grounds (SCG) achieved significantly higher scores for taste and aroma than the other formulations. This finding contrasts with previous studies on SCG-fortified bakery products, in which increasing SCG concentrations often reduced consumer acceptability due to excessive bitterness and undesirable aftertaste (Martínez-Saez et al., 2017).

One possible explanation for the present finding is the inherent flavor compatibility between dark chocolate and SCG. Both ingredients possess roasted, bitter, and complex aromatic characteristics, which may have produced a complementary sensory interaction rather than sensory conflict. Similar observations were reported by Aprotosoaie et al. (2016), who suggested that flavor congruence between functional ingredients and carrier matrices positively influences consumer acceptance.

Appearance

The formulation with the highest SCG concentration also achieved the highest appearance ratings. This result may be attributed to the visual compatibility between SCG and dark chocolate. Unlike lighter-colored food products, in which SCG incorporation may cause undesirable discoloration, dark chocolate naturally has a deep brown color that effectively masks the presence of SCG particles. Previous studies reported that consumer perception of product appearance is strongly influenced by expectations associated with the food category, particularly for cocoa-based products, where darker coloration is often interpreted as richness and higher cocoa content (Aprotosoaie et al., 2016). Consequently, increased SCG incorporation may have enhanced visual appeal rather than diminished it.

Texture

Contrary to studies reporting coarse texture and grittiness in SCG-enriched bakery products (Choi, 2021), the present study found improved texture acceptability at higher SCG incorporation levels. This outcome may be explained by the fine particle size of the SCG used in the formulation and the high cocoa butter content of the chocolate matrix. The sieving process performed prior to incorporation likely minimized particle perception, while cocoa butter contributed to smooth mouthfeel and favorable texture characteristics. These findings suggest that processing conditions play a critical role in determining sensory outcomes of SCG-fortified products.

General Acceptability

The 50 g SCG formulation demonstrated the highest overall acceptability, indicating that increased functional enrichment did not compromise consumer preference. This finding challenges the commonly reported sensory-functionality trade-off described in functional food literature (Granato et al., 2020). Instead, the results support the concept of matrix compatibility, in which sensory alignment between a bioactive ingredient and its carrier matrix enables higher incorporation levels without compromising acceptability. The findings further suggest that consumer acceptance of functional ingredients is highly context-dependent and may vary according to the sensory characteristics of the food vehicle.

Total Phenolic Content

The phytochemical analysis confirmed that the most preferred formulation contained substantial levels of phenolic compounds. This finding supports previous reports that Spent Coffee Grounds retain significant concentrations of chlorogenic acids and other antioxidant compounds

even after brewing (Arya et al., 2022; Stylianou et al., 2018). The elevated phenolic content observed in the present study may be attributed to the combined contribution of cocoa polyphenols and residual coffee-derived bioactive compounds. The interaction between these compounds may enhance the overall functional value of the product.

Antioxidant Capacity

The DPPH assay demonstrated strong antioxidant activity in the selected formulation, indicating considerable free-radical scavenging potential. Similar findings have been reported by Bevilacqua et al. (2023), who observed that food products enriched with coffee by-products exhibited enhanced antioxidant properties. Synergistic interactions between cocoa flavonoids and SCG-derived phenolic compounds may explain the observed antioxidant activity. Although only the most acceptable formulation underwent biochemical analysis, the results provide evidence that functional enhancement can be achieved without negatively affecting sensory quality.

Interpretation of Unexpected Findings

A noteworthy finding of the study is that higher SCG incorporation was associated with greater sensory acceptability, contrary to numerous previous studies on bakery- and cereal-based products (Martínez-Saez et al., 2017). This unexpected outcome may be explained by the matrix compatibility hypothesis, which posits that the sensory effects of functional ingredients depend on their compatibility with the carrier matrix's sensory characteristics. In the case of dark chocolate, bitterness and roasted flavors are generally perceived positively and associated with premium product quality. Therefore, the incorporation of SCG may have enhanced rather than diminished the sensory experience. Nevertheless, consumer preferences may vary according to cultural background, familiarity with dark chocolate, and individual taste sensitivity. Future studies should therefore include more diverse consumer populations to validate these findings across broader demographic groups.

Comparative Interpretation of SCG Formulations

The sensory evaluation results demonstrate that the level of SCG incorporation significantly influenced consumer acceptability across the three formulations. Among the tested samples, the formulation containing 50 g of SCG achieved the highest scores across taste, aroma, texture, appearance, and overall acceptability. The 25 g formulation received moderate ratings, while the 15 g formulation recorded slightly lower but still acceptable sensory scores. These findings indicate that increasing SCG concentration did not adversely affect consumer perception within the tested range and may have enhanced the chocolate matrix's flavor complexity.

One possible explanation for this outcome lies in the inherent flavor compatibility between dark chocolate and SCG. Dark chocolate naturally possesses bitter and roasted flavor characteristics derived from cocoa polyphenols and Maillard reaction products during processing. The roasted and slightly bitter notes of SCG may therefore complement the existing flavor profile of dark chocolate rather than create sensory contrast.

Previous studies on the incorporation of SCG into bakery products have reported reduced acceptability at higher inclusion levels due to bitterness and a coarse texture. However, the present findings suggest that matrix compatibility plays an important moderating role in sensory perception. When the functional ingredient shares similar flavor characteristics with the base product, higher levels of incorporation may remain acceptable or even desirable.

Although phytochemical and antioxidant analyses were conducted only on the most acceptable formulation, the sensory results across formulations provide indirect insights into how SCG concentration may influence the product's functional profile. SCG are widely reported to

contain phenolic compounds and antioxidant molecules that remain present after coffee brewing.

Therefore, it is theoretically plausible that formulations with higher SCG levels may contain greater concentrations of bioactive compounds. However, because biochemical testing was performed only on the selected formulation, this study does not provide empirical evidence of functional differences among all formulations. As such, conclusions about functional properties across different SCG levels must be interpreted with caution.

The phytochemical analysis confirmed that the most acceptable formulation contained measurable levels of phenolic compounds, while antioxidant testing demonstrated significant free radical scavenging activity. These results validate the functional potential of SCG as a bioactive ingredient when incorporated into a chocolate matrix. Importantly, the study demonstrates that functional enhancement can coexist with positive sensory perception, addressing a limitation frequently reported in previous SCG-based food applications, in which nutritional enrichment reduced consumer acceptability.

Nevertheless, because biochemical analysis was limited to the highest-rated formulation, the present study cannot establish a definitive dose–response relationship between SCG concentration and antioxidant capacity. Future investigations should conduct phytochemical and antioxidant testing across all formulation levels to determine how the quantitative increase in SCG incorporation affects functional properties. Such comparative profiling would provide stronger evidence for optimizing SCG-based functional foods.

Overall, the results suggest that dark chocolate represents a promising carrier matrix for SCG incorporation due to its sensory compatibility and inherent polyphenol content. By integrating sensory evaluation with biochemical validation of the most acceptable formulation, the study provides preliminary evidence that food waste valorization can yield consumer-acceptable functional products while advancing sustainability-oriented food innovation.

Comparison with Previous Studies and Research Implications

Overall, the findings of this study both confirm and extend the existing literature on the functional potential of Spent Coffee Grounds. While prior research has consistently highlighted the antioxidant properties of SCG, many studies reported sensory limitations at higher inclusion levels or focused solely on chemical characterization.

The present study differs in that it demonstrates that higher SCG incorporation can simultaneously improve sensory acceptability and functional properties when applied to a suitable food matrix, such as dark chocolate. These results provide empirical support for the use of dark chocolate as an effective and consumer-acceptable vehicle for SCG valorization. The findings also contribute to sustainable food innovation by offering a practical approach to waste reduction, functional food development, and small-scale, cost-efficient product formulation.

Scientific Contribution

This study contributes theoretically by:

1. Extending Functional Food Theory through empirical evidence that bioactive enrichment can coexist with high sensory acceptability at elevated incorporation levels.
2. Refining Sensory Acceptability Theory by identifying matrix compatibility as a moderating variable.
3. Bridging sustainability and food innovation literature through an integrated sensory–biochemical evaluation model.

Practically, the study offers a scalable formulation strategy for educational institutions, small enterprises, and sustainability-driven food developers seeking to valorize agro-industrial waste.

Theoretically, this study advances functional food development models by proposing the

matrix compatibility hypothesis, which posits that the sensory impact of bioactive enrichment depends on flavor congruence between the carrier matrix and the functional ingredient. This framework extends beyond the SCG application and may guide formulation strategies in other sustainability-driven food innovations.

Furthermore, the integrated sensory–biochemical approach addresses the methodological fragmentation observed in prior research, in which functional properties and consumer acceptability are often examined independently. By bridging these domains, the study contributes a more holistic evaluation model for sustainable product development.

Interpretation of Unexpected Patterns

Contrary to common findings in SCG-enriched bakery systems where higher inclusion levels reduced acceptability due to bitterness, the present study found increased acceptability at the highest SCG concentration. This divergence suggests that matrix compatibility plays a moderating role in sensory perception. The inherent bitterness of dark chocolate may mask or harmonize the roasted notes of SCG, thereby reducing negative sensory contrast.

However, it is important to acknowledge that sensory tolerance thresholds may differ among broader consumer populations beyond academically trained evaluators. Cultural familiarity with bitter flavor profiles, frequency of dark chocolate consumption, and individual taste sensitivity may influence acceptability outcomes. Thus, while the findings are promising, generalization should be approached cautiously.

From a sustainability perspective, the study demonstrates that agro-industrial waste streams can be transformed into consumer-validated food products without requiring complex extraction technologies. This approach lowers barriers to entry for small enterprises and educational institutions seeking to integrate circular economy principles into food production.

In inclusive development contexts, particularly within emerging economies, food-based livelihood initiatives benefit from product models that combine low raw material cost with added nutritional value. SCG, often available at minimal or no cost, represents a resource accessible to community-based producers. The validation of sensory acceptability ensures that such initiatives are not merely environmentally motivated but commercially viable. Thus, the study's implications extend beyond laboratory formulation to community-level sustainability strategies, supporting the alignment of environmental responsibility with economic participation.

CONCLUSIONS

This study demonstrates that sustainable ingredient substitution does not inherently compromise consumer satisfaction. By identifying 50 g SCG incorporation as both sensory-preferred and functionally enhanced, the findings illustrate that strategic matrix compatibility enables the successful transformation of food waste into value-added functional products.

Rather than merely comparing formulation differences, the study provides empirical support for the matrix compatibility hypothesis, which posits that flavor congruence between a carrier matrix and a bioactive ingredient moderates consumer acceptability. This conceptual contribution extends functional food development models by demonstrating that sensory and functional optimization can be achieved concurrently when the formulation strategy is theoretically informed.

First, the study demonstrated that dark chocolate formulations with varying SCG levels differed significantly in sensory acceptability. Among the three formulations, the dark chocolate with the highest SCG content exhibited the greatest acceptability for taste, appearance, aroma, texture, and overall preference. This finding challenges assumptions from previous SCG-based food applications, in which higher inclusion levels were associated with decreased palatability, suggesting that the product matrix plays a decisive role in sensory perception.

Second, significant differences were observed among the formulations, leading to the rejection of the null hypothesis. These results reinforce the importance of systematic formulation testing in sustainability-driven food innovation, where incremental changes in ingredient concentration can produce measurable sensory shifts. The findings highlight that functional enrichment must be evaluated within a structured experimental framework rather than assumed to automatically enhance product value.

Third, the most acceptable formulation exhibited a high total phenolic content and strong antioxidant capacity, confirming SCG's functional contribution to the product. The combination of cocoa- and SCG-derived bioactive compounds enhanced antioxidant potential, supporting the role of dark chocolate as an effective carrier of functional ingredients. This dual enhancement—sensory and biochemical—demonstrates that waste valorization strategies can align with consumer-driven quality standards.

Importantly, the study bridges a methodological gap in prior research by integrating sensory evaluation and biochemical analysis within a single experimental design. This holistic approach strengthens the translational relevance of the findings, as consumer acceptance and functional efficacy were evaluated simultaneously rather than independently.

Overall, the findings contribute to the fields of functional food development and sustainable food systems by offering a practical, consumer-acceptable approach to waste valorization. The study advances theoretical discourse by illustrating how sustainability principles, sensory science, and functional nutrition can converge within a unified product development framework. In doing so, it provides a scalable model for transforming agro-industrial by-products into market-viable functional foods.

Future product developers should conduct pilot-scale production trials, optimize the particle size distribution to keep it below 250 microns to maintain a smooth texture, and perform shelf-life testing under controlled humidity conditions (≤50% RH) to preserve antioxidant stability. Additionally, expanded demographic validation and comprehensive comparative phytochemical profiling across all formulation levels are recommended further to refine theoretical models of sensory–functional interaction and enhance commercial scalability.

LIMITATION & FURTHER RESEARCH

This study has several limitations related to its design and methodology that should be considered when interpreting the findings. First, the sensory evaluation was conducted with a limited sample size, primarily comprising students and faculty members with food-related academic backgrounds. While this ensured informed evaluation, the results may not fully represent the preferences of the general consumer population.

Second, the study focused on three predetermined levels of incorporation of Spent Coffee Grounds (SCG). Although these concentrations were sufficient to identify significant differences in acceptability and functionality, intermediate or higher levels of SCG inclusion were not explored, which may limit conclusions regarding the full range of optimal formulation thresholds.

Third, phytochemical and antioxidant analyses were conducted only on the most acceptable formulation. As a result, comparative functional profiles across all formulations were not established, limiting a more comprehensive understanding of how SCG concentration influences bioactive properties.

Finally, the study was limited to short-term sensory evaluation and laboratory analysis. Factors such as shelf life, storage stability, microbial safety, and long-term sensory changes were not assessed and may influence product quality under commercial conditions.

Based on these limitations, several areas for further research are recommended. Future studies should include a broader and more diverse consumer population to improve the

generalizability of sensory acceptability findings. Expanding the range of SCG concentrations and particle sizes may also help determine precise formulation limits and optimize both sensory and functional outcomes.

Further research should conduct comprehensive nutritional profiling, including proximate composition, vitamin and mineral content, and dietary fiber analysis, to strengthen health-related claims. Comparative phytochemical and antioxidant analyses across all formulations are also recommended to establish clearer dose–response relationships.

In addition, shelf-life studies and packaging evaluations should be performed to assess product stability and commercial feasibility. Finally, future investigations may explore the application of Spent Coffee Grounds in other cocoa-based or non-cocoa food matrices to validate the broader potential of SCG valorization in sustainable and functional food development.

Future studies should test the proposed matrix-compatibility hypothesis across alternative food carriers (e.g., milk chocolate, cereal bars, beverages) to further refine theoretical models of sensory–functional interaction. Comparative biochemical analysis across all formulation levels is also necessary to establish dose–response relationships in functional food enrichment.

Future research should empirically test the proposed matrix compatibility hypothesis across alternative food systems, including milk chocolate, cereal-based products, and beverage applications. Additionally, expanded demographic sampling will enable examination of moderating variables such as age, gender, and flavor familiarity.

Establishing dose–response relationships between SCG concentration and phenolic content through full biochemical profiling will further strengthen theoretical modeling of functional enrichment. Such investigations will refine sustainable food innovation frameworks and contribute to the development of predictive formulation guidelines.

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