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INCORPORATION OF COFFEE SILVER SKIN FOR DEVELOPMENT OF A SMOOTHIE AND A NUTRACEUTICAL PRODUCT

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Abstract: Coffee silver skin (CSS), a by-product of the coffee industry, is derived from the seed coat during the roasting of green coffee beans. Owing to its high content of phenolic compounds, antioxidants, dietary fibre, and prebiotic properties, CSS has gained interest as a functional food ingredient. This study aimed to evaluate the potential of CSS as a major component in a smoothie formulation, focusing on its antioxidant capacity (DPPH assay), cytotoxicity, effects on human dermal fibroblasts (HDF), microbial stability, and shelf-life. CSS extract was obtained using the cold maceration technique and assessed for antioxidant and cytotoxic activities. It was subsequently incorporated into smoothies at varying concentrations (1g, 2.5g, 3g, 3.5g, and 5g), followed by sensory evaluation, and monitoring of microbial activity and shelf-life at seven-day intervals. Nutritional analysis revealed that CSS is rich in dietary fibre (50%-60%), protein (16%-19%), and fats (1.56%-3.28%), underscoring its value as a functional food. The extract exhibited no cytotoxic effects up to a concentration of 1 g/ml. Incorporation of CSS into smoothies not only enhanced their nutritional and functional properties but also maintained product stability, supporting its application as a health-promoting beverage ingredient.

Keywords: Antioxidant, Coffee silver skin, Cytotoxicity, Health, Microbial activity, Smoothie.

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INTRODUCTION

Health and maintaining a healthy lifestyle are critically important due to their profound impact on overall human well-being. A healthy lifestyle is typically associated with a fit body and an active, refreshed mind (Jannissen and Huynh, 2018). One of the fundamental components of such a lifestyle is a balanced and nutritious diet. Eating well contributes significantly to both physical and emotional health, offering protection against various health conditions such as heart disease, obesity, cardiovascular diseases, and type 2 diabetes (Klingel *et al.*, 2020).

A healthy diet emphasizes the reduction of salt, sugar, and processed food intake. As such, the concept of 'eating smart' should be prioritized to maintain optimal health. In modern times, the

consumption of unhealthy foods has become increasingly prevalent, often leading to poor dietary habits, chronic diseases, infections, and decreased physical performance. A balanced daily diet should consist of essential nutrients, including vitamins, minerals, proteins, carbohydrates, and dietary fibre. Choosing lean and wholesome food is the main key to supporting long-term health.

Healthy meals may include solid foods as well as liquids or semi-liquid foods, such as beverages (Martinez-Saez *et al*., 2014). Beverages play a vital role in nutrition, contributing to hydration and providing essential nutrients. Options such as shakes, smoothies, and various types of teas and coffees not only offer refreshment but also serve as sources of energy and nutrition. These beverages are becoming an increasingly important component of daily diets, helping individuals meet their energy requirements and maintain overall health (Maria *et al*., 2021).

Among these, smoothies are semi-thick, creamy beverages typically made by blending fresh fruits and vegetables with milk, yogurt, cream, or ice cream, and sometimes incorporating dry fruits for added flavor. Smoothies are recognized for their ability to enhance protein intake, support immune function, and boost dietary fibre, which contributes to the regulation of blood pressure and overall health. As a result, they have gained significant popularity across all age groups. While fruits and vegetables are commonly used as the base ingredients in smoothies, this study explores a novel approach-developing a nutritious smoothie using coffee silver skin (CSS) as the primary ingredient (figure 1). Unlike conventional ingredients, CSS provides a sustainable and functional alternative, contributing to the growing trend of innovative, health-promoting beverages (Bertolino *et al*., 2019).

Fig. 1: Coffee Silver Skin (CSS).

Coffee silver skin (CSS) is the thin, translucent layer that covers the outer surface of green coffee beans (Maria *et al*., 2021). Although it is a major by-product of the coffee industry, CSS is often discarded during processing, despite its considerable health-promoting properties (Alves *et al.,* 2009). CSS is notably rich in dietary fibre (50%-60%), protein (16%-19%), and fats (1.56%-3.28%) (Saenger *et al*., 2001). These attributes surely contribute to its beneficial effects on gastrointestinal and skin health. Additionally, chlorogenic acid (CGA), present in CSS, has been shown to lower blood glucose levels, regulate vascular function in hypertensive individuals, support weight loss, inhibit DNA damage, and provide protection against carcinogenesis (Ates and Elmaci, 2018).

Given its nutritional profile and bioactive compounds, CSS holds great potential as a food supplement (Gocmen *et al*., 2019). As a readily available by-product of the coffee roasting process, the CSS is both sustainable and economically feasible for large-scale application.

During the roasting of green coffee beans, CSS is formed as a result of the Maillard reaction, which is triggered by the presence of specific organic compounds (Sacchetti, 2009). Multiple studies have demonstrated the functional and nutritional value of CSS, supporting its use in a variety of food applications (Toschi *et al*., 2014).

CSS is particularly rich in phenolic compounds, which contribute to the sensory qualities of fresh and processed plant-based foods. These phenolics play a key role in protecting tissues from oxidative stress, due to their powerful antioxidant capacity. The antioxidants help to neutralize free radicals, whose accumulation in the body leads to oxidative stress and cellular damage (Apak *et al*., 2008). In addition, the high dietary fibre content of CSS supports digestive health and exerts a prebiotic effect, fostering the growth of beneficial gut microbiota and enhancing immune function (Krahulcova *et al*., 2021).

Incorporating CSS into food products, such as smoothies as illustrated in figure 2 offers a

promising approach to improving human health. Given its antioxidant richness and functional health benefits, CSS can serve as a valuable primary ingredient in smoothie formulations

Fig. 2: CSS Smoothie.

MATERIALS AND METHODS

Sample preparation of CSS extract

A sample of 100 g of coffee silver skin (CSS) was macerated in 500 mL of distilled water overnight. After maceration, the mixture was boiled for 5-10 minutes to reduce the volume by half. During boiling, an additional 500 mL of distilled water was added. After cooling, the extract was filtered using Whatman Filter Paper No. 1, and the filtrate was collected. The filtrate was then concentrated using a rotary evaporator. The final extract was stored at 4°C until further chemical analysis.

Determination of Antioxidant Activity of CSS Extract

The cytotoxicity assay was conducted at V.G. Vaze College of Arts, Science and Commerce, Mulund (East), Mumbai. The CSS extract solutions were prepared in culture medium at the following concentrations: 1, 0.5, 0.25, 0.125, 0.0625, and 0.0312 mg/ml. Human dermal fibroblast (HDF) cells were procured from HiMedia Laboratories and cultured in Dulbecco's Modified Eagle's Medium (DMEM), which is supplemented with 10% fetal bovine serum (FBS) and 1% antibiotic solution in a humidified incubator at 37°C.

Determination of Cytotoxicity of CSS Extract

The cytotoxicity assay was conducted at V.G. Vaze College of Arts, Science and Commerce, Mulund (East), Mumbai. The CSS extract solutions were prepared in culture medium at the following concentrations: 1, 0.5, 0.25, 0.125, 0.0625, and 0.0312 mg/ml. Human dermal fibroblast (HDF) cells were procured from HiMedia Laboratories and cultured in Dulbecco's Modified Eagle's Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 1% antibiotic solution in a humidified incubator at 37°C.

Cytotoxicity was assessed using the Sulforhodamine B (SRB) assay. Cells were seeded in a 96-well plate at a density of 0.5×10^4 cells per well and incubated for 24 hours at 37°C. The next day, the culture medium was replaced with CSS extract solutions at different concentrations, followed by second 24-hour incubation. Post-incubation, the cells were fixed using 10% trichloroacetic acid (TCA) and stained with SRB dye for 30 minutes. Excess dye was removed by washing with 10% glacial acetic acid. The bound dye was solubilized using 10 mM Tris buffer, and optical density (OD) was measured at 530 nm using a spectrophotometer. Cells cultured without CSS extract served as the control.

The percentage of cytotoxicity was calculated using the following formula:

$$\% \text{ Cytotoxicity} = (\text{Absorbance of Control} - \text{Absorbance of Test}/\text{Absorbance of Control}) \times 100$$

Smoothie formulations were prepared following standard procedures. The CSS was ground into a fine powder using a mixer. CSS powder was incorporated in varying concentrations (1g, 2.5g, 3g, 3.5g, 4g, 4.5g, and 5g) into 30 mL of different base liquids, including water, milk, almond milk, and fresh cream. After preparation, the smoothies were stored in a deep freezer to assess their shelf life.

Among all variations tested, the formulation containing 5g of CSS powder was found to be the most acceptable based on sensory evaluation. Therefore, 5g of CSS powder was used for all

subsequent formulations. A comprehensive nutritional and proximate analysis was conducted, including the determination of protein, fat, carbohydrate content, energy value, total sugars, ash content, moisture, pH, and total solids. Microbial analysis was also performed to evaluate the shelf life of the CSS-based smoothie. In addition, sensory evaluation was carried out to assess taste, texture, aroma, and overall acceptability.

RESULTS AND DISCUSSION

This research aimed to develop a novel health beverage by incorporating coffee silver skin (CSS) as a functional ingredient. For extract preparation, an extraction time of one hour was selected, as extending the extraction period did not yield additional benefits. The extraction temperature was optimized based on economic feasibility, as higher temperatures did not significantly improve extraction efficiency (Costa *et al.,* 2014).

DPPH Radical scavenging activity

The antioxidant activity of CSS was assessed using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, which is one of the most widely used methods for evaluating antioxidant potential. As the DPPH radicals are reduced by antioxidants, their characteristic absorbance at 517 nm decreases (Marxen *et al.,* 2007). The DPPH radical exhibits a deep purple color due to its unpaired electron, and upon reaction with an antioxidant, it is reduced to a yellow-colored compound, diphenylpicrylhydrazine. The degree of color change is directly proportional to the hydrogen-donating capacity of the antioxidant (Ronald *et al.,* 2005). This reduction in absorbance is used to quantify antioxidant activity (Bresciani *et al.*, 2019).

In this study, the DPPH scavenging activity of the water-based CSS extract was found to be 90.76%, which was slightly lower than the values reported by Rodrigues *et al.* (2015) , where the DPPH values ranged from 95.95 μmol to 216.40 μmol depending on the extraction solvent (water or ethanol), as shown in figure 3. Ethanol-based CSS extracts demonstrated higher antioxidant activity compared to water-based extracts.

Additionally, the antioxidant activity varied depending on the coffee variety. Robusta CSS exhibited a DPPH value of 54.80%, whereas Arabica CSS showed 26.30%. This difference is attributed to the higher total phenolic content in Robusta CSS, as antioxidant activity tends to increase with phenolic content (Tan *et al.,* 2017). Narita and Inouye (2014) further reported that CSS extract obtained using subcritical water treatment at 25-270°C demonstrated significantly higher antioxidant activity, with DPPH values reaching 379±3 μmol. The mean R^2 value for the DPPH assay calibration curve in this study was 0.97, indicating a strong linear correlation, as represented in figure 3.

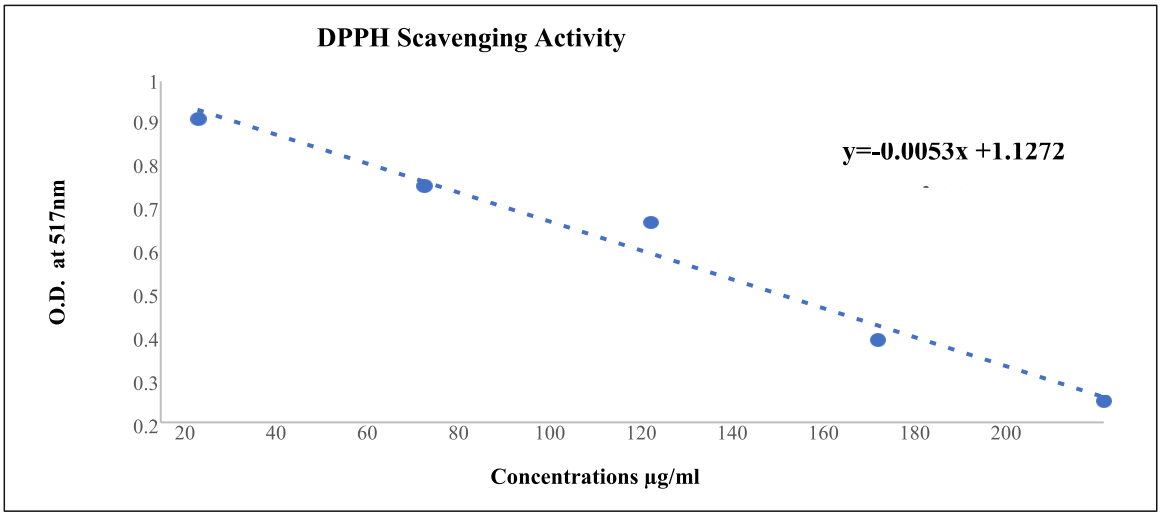

Fig. 3: Standardgraph of DPPH assay (Ascorbic acid as standard) representing OD at 517 nm on X axis and concentration in g/ml on Y axis.

The antioxidant activity of the CSS extract was found to be 90.76%, indicating a strong free radical scavenging potential. The primary aim of this research was to develop a nutritional beverage with health-promoting benefits. Due to the high antioxidant content of CSS, it holds significant potential as a functional ingredient across various sectors, particularly in the food industry (Rodrigues *et al.,* 2015).

Cytotoxicity of CSS extract

Cytotoxicity studies were conducted to evaluate the effect of the CSS extract on the proliferation of human dermal fibroblasts (HDF) in vitro. The assay was performed using HDF cell lines obtained from HiMedia Laboratories, which are widely considered appropriate in vitro models for assessing the toxicological safety of substances intended for dermatological applications.

According to the results, the CSS extract exhibited no cytotoxic effects on HDF cells at concentrations of 1, 0.5, 0.25, 0.125, 0.0625, and 0.03125 μg/mL, as shown in table 1. These findings clearly suggest that CSS extract is biocompatible and safe for potential use in functional foods and nutraceuticals.

Table 1: Cytotoxicity assay: Results represent the mean (Data expressed as mean of triplicates ± SD).

Conc. (μg/Ml)	Set 1	Set 2	Set 3	SD	Avg	% Cytotoxicity
1	0.135	0.129	0.137	0.00416	0.134±0.004	3.83693
0.5	0.162	0.155	0.181	0.01345	0.166±0.013	-19.425
0.25	0.173	0.183	0.167	0.00808	0.174±0.008	-25.42
0.125	0.185	0.198	0.177	0.0106	0.187±0.010	-34.293
0.0625	0.187	0.191	0.216	0.01572	0.198±0.015	-42.446
0.03125	0.198	0.207	0.192	0.00755	0.199±0.007	-43.166

The results obtained showed that the CSS extracts can be a useful source of bioactive agents. CSS extract showed skin cell proliferation capacity when tested *in vitro*. The evidence of possible absence of cytotoxicity of this extract at six different concentrations, namely 1, 0.5, 0.25, 0.125, 0.0625 and 0.03125 μg/ml, implies that these extracts show no toxicity to these cells.

The cytotoxicity results indicate that the extract of CSS have no adverse effect on the human dermal fibroblast cell viability *in vitro*. Therefore, the CSS extract showed skin cell proliferation capacity when tested *in vitro*. The results obtained were like the result suggested that CSS extracts at concentrations <1000μg/ml, has no adverse effect on the viability of fibroblast cells in vitro (Rodrigues *et al.,* 2015).

Cem (2002) reported the effect of coffee on Caco-2 cells and no cytotoxicity was observed. McCarthy *et al.* (2013) studied effect of Brewer's spent grain against U937 and Jurkat T cells and concluded that cytotoxicity is low. Khonkarn *et al.* (2010) studied the fruit peel extract from rambutan, mangosteen and coconut against KB and Caco-2 cells and reported that coconut showed high cytotoxicity towards KB cells. All these reports mean that most of the by-product extract has some amount of cytotoxicity but CSS showed no toxicity for concentrations above 1000μg/ml.

There was no significant decrease ($p>0.05$) when the three trial sets were measured, which suggested that CSS at the concentrations tested have no adverse effect on theviability of HDF cells. These similar results were obtained where there was no significant decrease ($p>0.05$) in absorbance after incubation of the compound when cell viability was measured and have no adverse effect on the viability of HaCaT cells (Iriondo-DeHond *et al.,* 2016).

In order to explore the HaCaT cell response to oxidative treatment, the cells were treated with different concentrations of t-BOOH (tert- butyl

hydroperoxide), used previously by Kucera *et al.* (2014) and the viability was estimated after 1, 6 and 24 hours. The result showed no significant cell viability reduction ($p>0.05$) when the estimation was carried out after 1 hour. But there was decrease in the cell viability treated with t-BOOH for 6 and 24 hours. Higher concentrations of t-BOOH were cytotoxic to HaCaT cells and cell viability was significantly reduced ($p>0.05$) as shown in figure 4.

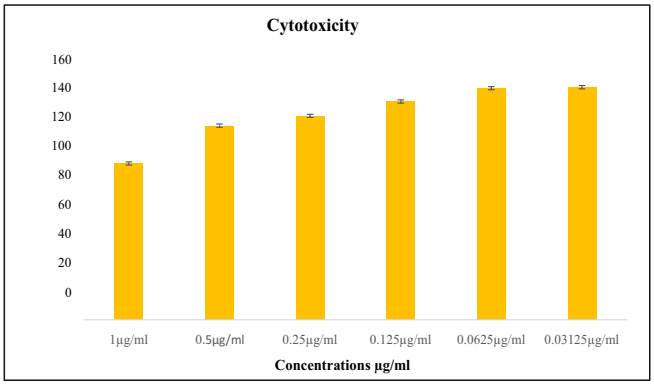

Fig. 4: % Viability cell cytotoxicity of Human Dermal Fibroblast Cells at various concentrations. Data are expressed as mean of triplicates ±SD. ($p>0.05$).

However, higher concentrations of t-BOOH at 6 hours caused a significant decrease ($p< 0.05$) in cell viability, reducing it by nearly 60%, thereby inducing oxidative stress (Iriondo-DeHond *et al.*, 2016). Therefore, a significant decrease in cell viability ($p< 0.05$) might also be observed if higher concentrations of CSS extract are used, particularly when assessed after 6 or 24 hours of exposure.

Analysis of multicomponent of CSS Smoothie

Sensory analysis based on One-factor optimization

One-factor optimization of the CSS smoothie was performed using 10 mL of water with varying concentrations of CSS powder. Additionally, 5 g of CSS powder was used in formulations with varying amounts of Rajgira powder.

Sensory Evaluation at every seven-day intervals:

Sensory evaluation plays a crucial role in product development. It aids research and development by measuring, analyzing, and interpreting results based on various sensory parameters such as color, flavor, taste, sweetness, aroma, texture, mouth feel, and overall acceptability of a food product. To assess the freshness of the prepared CSS smoothie, sensory evaluations were conducted at regular intervals.

During the evaluation period of 21 days, slight changes were observed in the sensory parameters as the storage duration increased. Notably, the CSS smoothie showed decreased acceptability on day 21 compared to freshly prepared samples, as illustrated in figure 5.

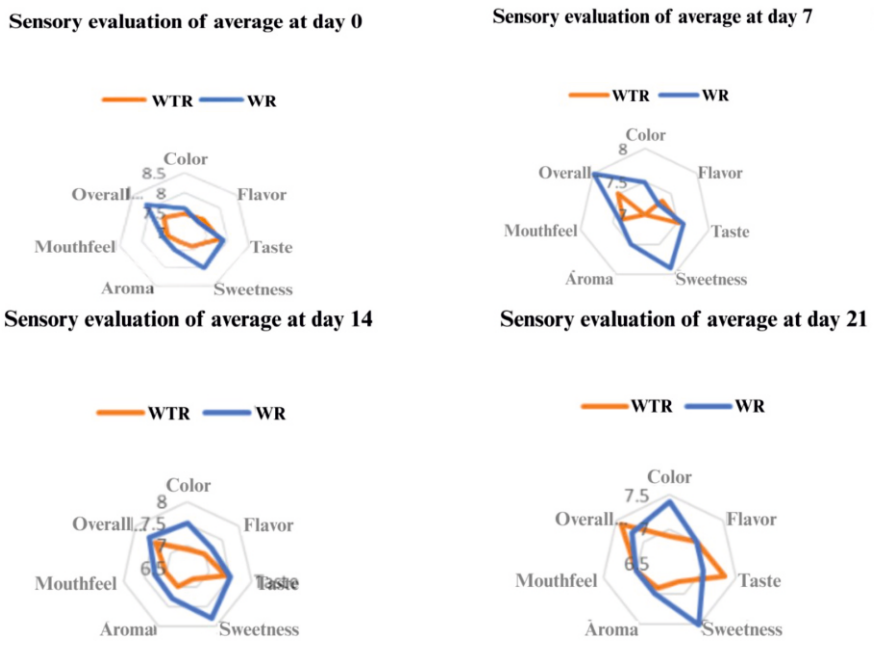

Fig. 5: Radar chart for Sensory analysis at different time interval.

Effect of Storage Period on Sensory Attributes:
The effect of the storage period on various sensory characteristics is discussed below. All attributes were affected as the storage duration increased, although changes in most parameters were negligible compared to fresh products.

Appearance is a major factor influencing consumer perception and quality evaluation of food products, and it is primarily judged by color. Flavor contributes to the overall taste of the product; the smoothie contains natural flavors with no artificial additives. The storage duration affected the taste of the CSS smoothie, with a decrease in taste scores recorded over the storage period.

Sweetness is important in human nutrition as it provides energy and essential nutrients. Consequently, the sweetness of the CSS smoothie was also impacted by the storage period. Aroma plays a central role in sensory evaluation, enhancing flavor and influencing mood. It is distinct from taste and is perceived when food interacts with saliva during consumption. Mouth feel data are presented in the table. Overall acceptability depends on the combined evaluation of color, flavor, and taste. Fresh products received slightly higher overall acceptability scores compared to those stored for 21 days. The sensory scores for overall acceptability are presented in figure 6.

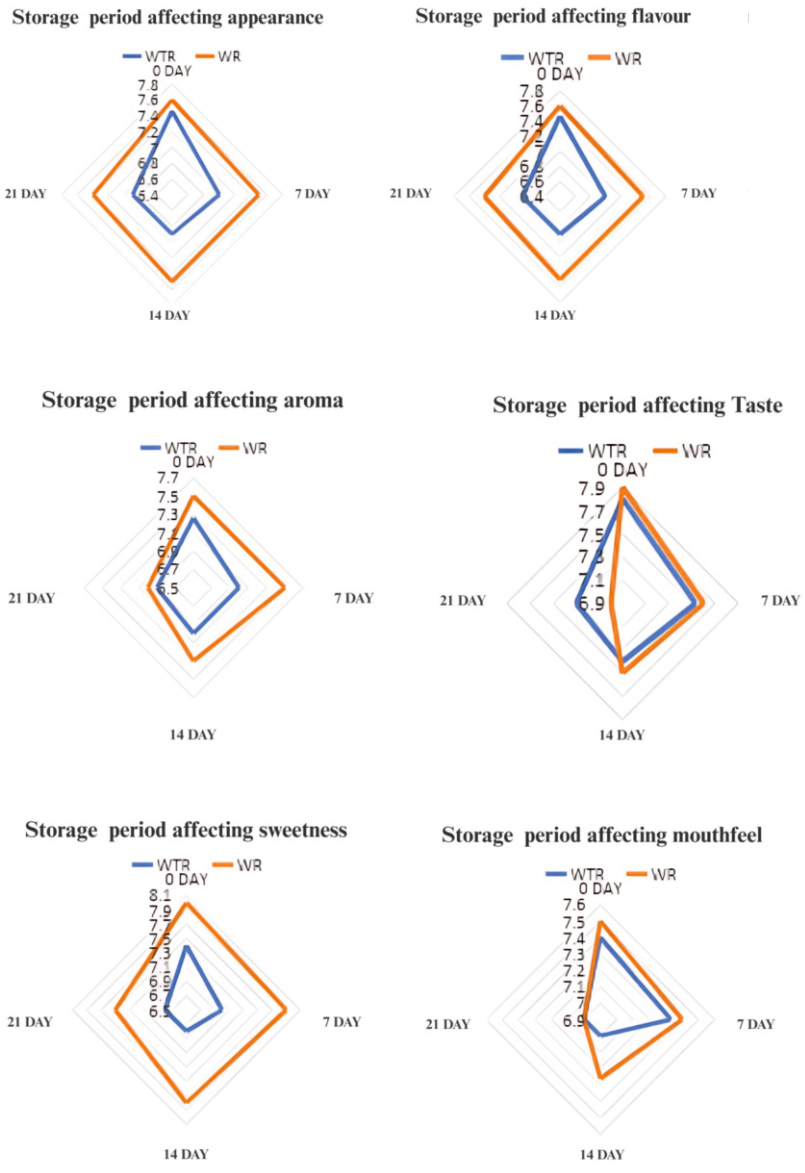

Fig. 6: Radar chart for Storage period of CSS smoothie.

Proximate Analysis of CSS Smoothie:
The CSS smoothie was analyzed for its proximate composition following the standard procedures outlined by the AOAC. The nutritional composition of both smoothie variants with Rajgira (WR) and without Rajgira (WTR), is presented in table 2 and figure 7. All values are expressed per 100 g of sample.

Moisture content refers to the amount of water present in the food product. The moisture content was slightly higher in the CSS smoothie with Rajgira (WR), at 80.4% g/g, compared to 79.2% g/g in the smoothie without Rajgira (WTR). Ash content, representing the total mineral content in the sample, was found to be 0.31% g/g in the WR smoothie and 0.43% g/g in the WTR smoothie.

Additional nutritional parameters—including energy, protein, fat, carbohydrates, total sugar, and dietary fiber were also evaluated using standard analytical methods. The smoothie with Rajgira showed significantly higher protein content (14.54 g) compared to the smoothie without Rajgira (3.72 g). This increase in protein is attributed to the inclusion of Rajgira and almond, both of which are high in protein and relatively low in fat.

Table 2: Proximate analysis of CSS Smoothies.

Sr. No.	Parameters	Results		Unit	Method Reference
		WR	WTR		
1.	Moisture	80.4	79.2	%g/g	FSSAI-5
2.	Ash	0.31	0.43	%g/g	FSSAI-5
3.	Protein	14.54	3.72	%g/g	IS7219:1973
4.	Fat	6.54	6.14	%g/g	IS12711:1989
5.	Carbohydrate	25.05	17.25	%g/g	IS1656:2007
6.	Energy	217.22	139.14	%g/g	IS13285:1992
7.	Total sugar	10.39	11.65	%g/g	IS6287:1985
8.	Dietary fibre	6.25	2.94	%g/g	DACPL/NMUWCHEM/SOPNOIS

Therefore, a slight difference was observed between both smoothie samples, with the WR sample containing 6.54 g of fat and the WTR sample containing 6.14 g, respectively. The carbohydrate content in the WR smoothie was 25.05 g, which was higher compared to 17.25 g in the WTR smoothie. This increase is attributed to the addition of dates and Rajgira, both of which are rich sources of carbohydrates. Notably, dates contain approximately 75% carbohydrates.

The sugar content was slightly higher in the WTR smoothie (11.65 g) compared to the WR smoothie (10.39 g). This may be due to Rajgira's low fat content and its ability to support metabolism without significantly contributing to weight gain.

Dietary fiber plays a critical role in maintaining gut health and reducing the risk of chronic diseases. The dietary fiber content was higher in the WR smoothie (6.25 g) compared to the WTR smoothie (2.94 g), due to the presence of fiber-rich ingredients such as dates, Rajgira, and almonds.

Energy content was significantly greater in the WR smoothie (217.22 Kcal) compared to the WTR smoothie (139.14 Kcal). This is primarily due to the inclusion of Rajgira, which enhances the energy, protein, dietary fiber, and carbohydrate content, making the WR smoothie suitable for individuals on high-protein diets or those seeking healthy weight management (Clifford, 1999).

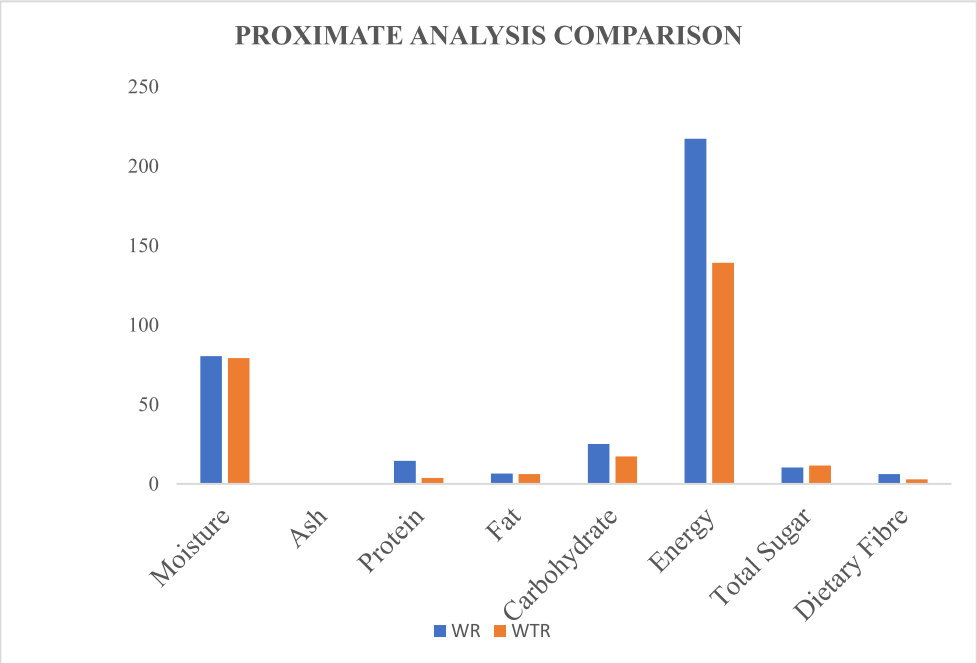

Fig. 7: Nutritional information of Smoothies containing CSS with and without Rajgira.

The nutritional composition of the CSS smoothie, both with Rajgira (WR) and without Rajgira (WTR), was found to be superior when compared to standard fruit and green smoothies as reported in the USDA Food and Nutrient Database and by Julika *et al.* (2022). The fruit smoothie contains 136 kcal, whereas the CSS smoothies provide 217.22 kcal (WR) and 139.14 kcal (WTR), respectively. In comparison, the green smoothie provides 146 kcal.

In terms of protein content, the CSS smoothie WR contains 14.54g, which is significantly higher than the 5.2g found in a fruit smoothie and the 6.9g in a green smoothie. The dietary fiber content is also improved in the CSS smoothie WR (6.23g) compared to the fruit smoothie (2.6g) and is slightly higher than the green smoothie (5.3g). The WTR variant contains 2.94g of dietary fiber.

Although the carbohydrate content in the CSS smoothie WR (25.05g) is comparable to that of the fruit smoothie (25g), it is significantly higher than the WTR version (17.25g). These enhanced nutritional values in the CSS smoothie WR are primarily due to the inclusion of Rajgira, dates, and almonds ingredients known for their high energy, protein, and carbohydrate content.

Regarding shelf life, the CSS smoothie remained stable under refrigerated conditions for up to 21 days. Minimal microbial growth was observed after the 21st day. Throughout the storage period, there were no significant changes in pH, color, or aroma. The smoothie maintained a pleasant aroma and acceptable sensory characteristics, indicating a good shelf life without the need for added preservatives, as illustrated in figure 8.

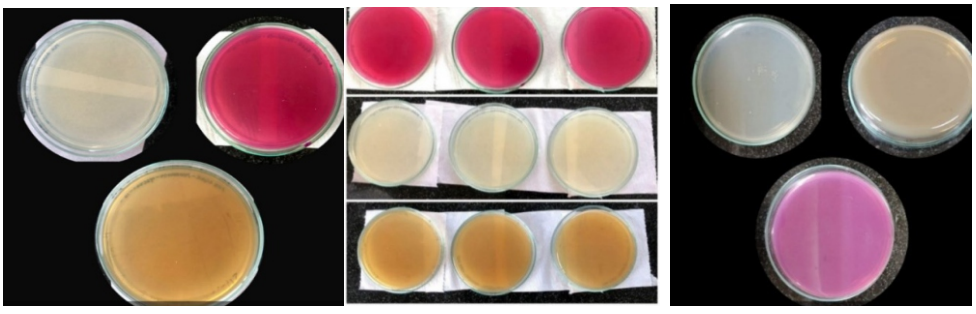

Fig. (a) Day 0 Fig. (b) Day 14 Fig. (c) Day 21

Fig. 8: Microbial Analysis of CSS Smoothie to check shelf life on different media plates.

Microbiological and Physicochemical Stability of CSS Smoothie

Fungal Growth (PDA):

Potato Dextrose Agar (PDA) was used to assess fungal or mold growth during storage. On the 21st day, slight fungal growth was observed on the PDA plate. However, throughout the 21-day storage period, no significant changes in pH or color were detected, indicating good product stability. Notably, the smoothie exhibited a satisfactory shelf life without the use of any preservatives.

Coliform Count (Endo Agar):

Endo Agar was employed to detect coliform presence. No coliform growth was observed during the 21-day storage period, indicating that the smoothie was prepared under safe and hygienic conditions. The absence of coliforms serves as a strong indicator of microbiological quality and sanitary processing.

pH Determination:

pH is a critical factor for determining food safety and shelf life. The pH of the CSS smoothie was measured using a pH meter and was found to be 5.92 ± 0.72. This pH level is within the acceptable range for beverages and suggests a low risk of microbial spoilage.

Color Measurement:

Color analysis was conducted to establish a control standard for the final product and to monitor any changes during processing and storage. The color of the smoothie was measured at 420 nm absorbance using a colorimeter, and the recorded value was 0.8730 ± 0.22.

Microbiological Stability and Aerobic Plate Count (PCA):

The total plate count (TPC) was used to assess microbial growth over time. On Plate Count Agar (PCA), the CSS smoothie remained microbiologically stable under refrigerated conditions up to day 21. A slight increase in aerobic microbial growth was observed at day 21, but it was not significant.

Throughout the study period, there were no major changes in pH or color, and the smoothie retained a pleasant aroma, supporting its stability and shelf life at refrigeration temperature. These results confirm that the CSS smoothie is microbiologically safe and organoleptically acceptable for up to 21 days without the addition of preservatives.

CONCLUSION

The CSS can be considered as a new sustainable food ingredient, which can increase the protein and dietary content as well as a functional food ingredient with antioxidant, nutritional, and sensory-enhancing properties. Its incorporation in smoothies can improve both nutritional content and consumer acceptability, especially when combined with Rajgira. Additionally, in our study CSS showed no cytotoxicity and exhibited favourable shelf-life stability.

It can be concluded from this study that CSS can be used up to 5% in the formulation of smoothies without effect on overall quality. Given its bioactive profile and functional benefits, CSS could also be explored as a natural colorant and antioxidant additive in other food and cosmetic applications. However, further research is needed to explore its long-term effects, optimize its use in diverse food systems, and assess the economic and environmental feasibility of integrating CSS into the food production chain, contributing to a circular and sustainable food industry model.

CONFLICT OF INTEREST

The authors declare that there are no known conflicts of interest associated with this publication. Furthermore, no financial support was received that could have influenced the outcome of this work.

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