



Perspectives on the use of coffee silverskin in food formulations

Gianni Zoccatelli, Marco Ciulu *

Department of Biotechnology, University of Verona, Strada le Grazie 15, 37134, Verona, Italy

A B S T R A C T

In recent years, there has been a growing interest in circular food economy approaches by which wastes from food production processes are reconverted into raw materials for a new cycle. The coffee industry, one of the world's most consumed beverages and the second most traded commodity after petroleum, produces millions of tons of waste each year, including defective beans, husk, pulp, spent coffee grounds, and silverskin. The latter in particular, consists of the skin that coats the coffee bean and is produced during the roasting process. Various studies have highlighted the great potential of silverskin in the formulation of functional foods and prebiotics. In fact, the chemical composition of silverskin turns out to be rich in dietary fibre such as cellulose, hemicellulose and lignin, antioxidants, and phenolic compounds. Among these, chlorogenic acids are of particular importance and make this material interesting from a nutraceutical point of view. Recent studies have shown that the geographical origin has a strong influence on the chemical composition of silverskin, and therefore, the choice of the starting material to be repurposed for food formulations will have, in the future, to take into account its origin. The purpose of this perspective article is to suggest the direction that scientific research should take in order to assess the effective use of coffee silverskin in food formulations, also taking into account safety and traceability aspects.

1. Introduction

Coffee is one of the most popular beverages worldwide, produced by brewing ground roasted coffee beans. In the 2023–2024 period, global production of green coffee exceeded 10 million tons [1], with Brazil being by far the largest producer (39 %), followed by Vietnam (16 %) and Colombia (8 %). Coffee production is primarily based on two species: *Coffea arabica* and *Coffea canephora*, commonly known as arabica and robusta, which accounted for 56 % and 44 % of the total 2022/2023 production, respectively [2]. Many other species and varieties are known, but they represent less than 1 % of total global production.

Apart from some fluctuations, the growing global coffee production raises a serious question about the sustainability of the supply chain, as 39 million tons of biomass are generated annually from the fruit, commonly known as the “cherry” [3]. This normally undergoes a depulping step, followed by two possible procedures aimed at purifying the bean: a “dry” method and a “wet” method [4]. The dry method is a simple process that involves the natural or mechanical drying of whole coffee cherries, followed by hulling to remove the outer layers. In the wet method, the fruits are depulped upon maceration and subjected to a fermentation step. After washing and drying, the beans are hulled. Green coffee obtained through this method is considered to be of higher quality. During these processes, the fruit skin, pulp, pectic layer and parchment are removed, while a thin layer attached to the bean, known as coffee silverskin (CS), remains. Since the dry method, associated with

a higher CS retention, is more commonly applied to robusta coffee, this species represents a quantitatively more significant source of CS compared to Arabica. Once the coffee is roasted, the CS is finally removed due to the high temperature, making it the only by-product generated during this process.

From a botanical point of view, CS is an integument that covers the bean, accounting for 2–3 % of its weight. It has a high dietary fibre content (55–60 %, [5]), 13–15 % of which is soluble fibre [6] and 30 % lignin. Additionally, its chemical composition also includes proteins (16–20 %), minerals (7 %) along with phenolics and Maillard reaction compounds formed during the roasting process [7]. Fats make up 1–3 %, while caffeine averages around 1 %, with significant variability depending on species, variety, and geographical origin [8] (See Fig. 1).

Due to its elevated content of nutritional and functional compounds, CS has been the subject of several studies focused on its characterization and evaluation as a potential functional food ingredient. Although these studies show the great potential of CS within the food industry, many research gaps need to be filled in order to have a clear idea of how CS can be used efficiently and in a way that ensures consumer protection and, at the same time, an economic benefit for producers. In the following paragraphs, the results of some of the most relevant studies concerning the characterisation of the chemical composition of CS, its functional and nutraceutical properties and its use as an ingredient will be briefly outlined.

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* Corresponding author.

E-mail address: marco.ciulu@univr.it (M. Ciulu).

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2. Functional properties of CS

Available data on the functional properties of CS are limited. In an attempt to evaluate the suitability of CS as a functional ingredient, Ballesteros et al. [6] and Martuscelli et al. [9] characterized its water-holding capacity (WHC) and oil-holding capacity (OHC), by mixing 1 g sample with water or oil, and measuring the volume of the supernatant after vortexing and centrifuging WHC refers to the ability of a material, such as a food ingredient, to retain water within its structure under specific conditions, even when external forces, such as gravity or pressure, are applied. This property is crucial for maintaining the texture, juiciness, and weight of certain foods, such as meat, dairy products, and baked goods. Similarly, oil-holding capacity refers to the ability of an ingredient to retain oil, which positively impacts food creaminess and richness, and prevents oil separation. Both studies reported that CS possesses high WHC and OHC, with values ranging from 4.9 to 5.1 g water/g CS and 3.0–4.7 g oil/g CS, respectively. Few data are available regarding the emulsifying properties of CS, which primarily depend on its fibre and protein content. Ballesteros et al. [6] demonstrated that the emulsifying activity (i.e., the ratio between the emulsified layer and the total volume used) and stability of CS in relation to heat treatment at 80 °C for 30 min, surpass those of other food ingredients, such as lima beans. However, further analysis is needed to fully characterize the emulsifying properties of CS. No data about the foaming and the gelling properties of CS are available.

3. CS as a source of bioactive compounds

Another reason that makes CS most interesting as a potential ingredient in the formulation of food products is, without any doubt, its documented biological activity. In fact, several studies show that CS possesses a strong antioxidant capacity that, combined with its prebiotic properties, allows this matrix to be used as a functional component of various types of food products such as cookies, gummy candies, yogurt, bread, and beverages [10].

As for the antioxidant capacities of CS, these have been evaluated in several studies using traditional spectrophotometric approaches such as DPPH, ABTS, and FRAP assays. The values found were, in some cases, comparable to those of black chocolate or certain spices, including oregano, rosemary, and black pepper [11].

There are many compounds to which the antioxidant capacity of CS

can be ascribed, but polyphenols are certainly the ones that interest researchers the most by virtue of their relevance in the nutraceutical sphere. Although the evaluation of the total polyphenol content (TPC) is in most cases carried out by means of the well-established Folin-Ciocalteu's procedure, a comparison of the data from the different studies is made difficult by the expression of the results with different units of measurement (e.g., gallic acid or catechin equivalents). In addition, the origin of the CS together with the different combinations of

Table 1

Extraction conditions and TPC of CS obtained in selected studies.

Solvent	Solid/solvent ratio	Conditions	TPC content	Reference
Subcritical water	1:50	210 °C	36 ± 3 mg GAE/g CS	[12]
Acidified water (1 % formic acid)	1:10	Step 1. UAE bath (30 min) Step 2. heating at 70 °C (60 min)	16.1 ± 1.2 mg CE/g CS	[11]
Ethanol:water (60:40)	1:35	a SLE (45 min, 80 °C, 80 µm) b MAE (32 min, 51.5 °C, 80 µm) c UAE (bath, 29.5 min, 80 °C, 250 µm)	10.01 ± 0.21 mg GAE/g CS (dw) 7.34 ± 0.23 mg GAE/g CS (dw) 9.91 ± 0.24 mg GAE/g CS (dw)	[13]
Ethanol:water (50:50)	1:50	SLE (60 min, 40 °C)	20.3 ± 0.3 mg GAE/g CS	[5]
Methanol:water (80:20)	1:50	Step 1. UAE (probe, 38 W/cm ² , 10 min) Step 2. SLE (50 °C, 24 h)	8.94 ± 0.01 mg GAE/g CS	[14]
Ethanol:water (70:30)	1:5	UAE (bath, 40 kHz, 120 min, 20 °C)	73.4 ± 6.6 mg GAE/g of dw of extract	[15]
Water	1:20	Hydrothermal extraction (125 °C, 25 min)	55.59 (≈9.46 mg) ± 0.12 µmol GAE/g C	[16]

TPC, total phenolic content; SLE, solid-liquid extraction; UAE, ultrasound-assisted extraction; CE, catechin equivalents; GAE, gallic acid equivalents; MAE, microwave-assisted extraction; dw, dry weight.

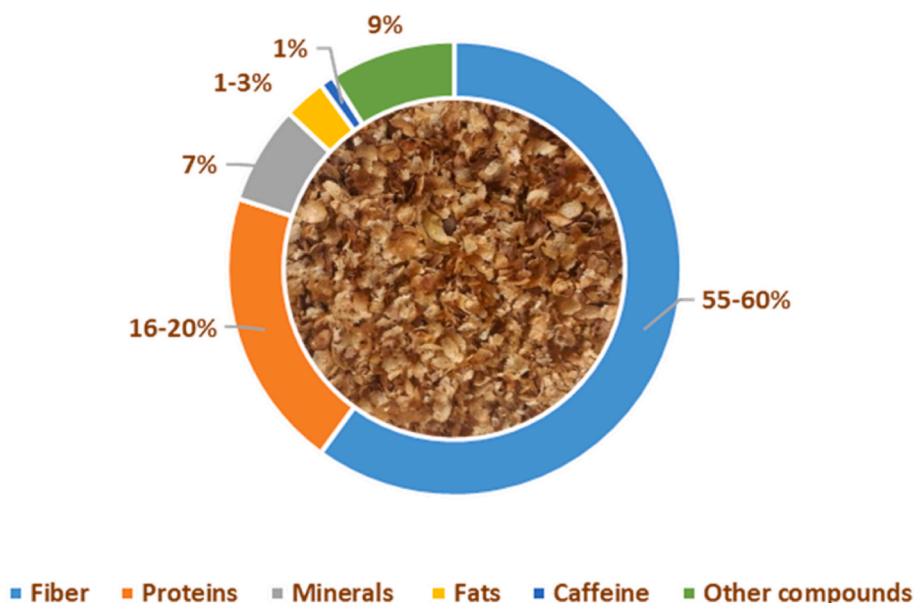


Fig. 1. Graphical representation of the proximate composition of CS.

technological parameters can also have a considerable influence. Table 1 shows the results of selected studies concerning the determination of TPC in CS, in order to also have an overview of the extraction methods used so far and to understand how these may influence the final data.

Some studies conducted *in vitro* suggest how the antioxidant activity attributable to polyphenols increases following gastro-intestinal digestion, hypothesizing an enhancement of the bioaccessibility of these compounds by the human colonic microflora [17]. The bioaccessibility experiment was conducted by means of the harmonized protocol INFOGEST [18], that included a simulation of microbiota hydrolytic activity, applied to a phenolic extract obtained by suspending CS in water at 80 °C, adopting a 1/10 solid-liquid ratio, and performing the extraction twice.

In the quali-quantitative profile of polyphenols, both phenolic acids and flavonoids were identified. Within the first of the two classes, chlorogenic acids (CGAs, esters of cinnamic acids and quinic acid) are the most characterized and primarily define CS as a source of bioactive compounds. In addition to its antioxidant activity, chlorogenic acid exhibits numerous pharmacological properties, including anti-inflammatory, antibacterial, antiviral, anti-glycaemic, lipid-lowering, cardiovascular-protective, and anti-mutagenic effects [19]. Furthermore, the ability of CGA to adhere to the structure formed by dietary fibre gives the latter antioxidant properties, allowing it to be classified in all respects as an antioxidant dietary fibre [20,8]. Regarding the profile of CGAs, esters of caffeic acid, ferulic acid, and *p*-coumaric acid, in the form of different structural isomers, were identified in CS, along with dicaffeoylquinic and caffeoyl-feruloylquinic acids. Other phenolic acids detected in CS include, among the others, vanillic, gallic, shikimic and, obviously, caffeic acid [17,21]. The studies conducted on the characterisation of chlorogenic acids highlight how advanced analytical techniques, such as those based on mass spectrometry, are essential in this context. For example, the aforementioned studies by Angeloni et al. [21] and Castaldo et al. [17] were respectively carried out using HPLC-MS/MS triple quadrupole and UHPLC-Q-Orbitrap HR-MS, in order to correctly elucidate the structures of these analytes, whose profiles could be of difficult interpretation due to the presence of various isomers. Although to the best of our knowledge there are no studies on how technological and storage parameters influence the composition of the profile of these important bioactive compounds in CS, it is known that in general the coffee bean roasting process leads to the degradation of CGAs to quinic acid and its epimer as well as to the formation of several corresponding lactones [22]. It is also known that the initial moisture value of the coffee bean is decisive for the kinetics of these reactions and the definition of the final profile, and therefore, the careful choice of the starting product variety could also be important in the future for outlining the profile of the bioactives in the by-products to be reused, such as CS.

Alkaloids also belong to the group of biologically active substances traceable in CS. Of these, caffeine is clearly the predominant compound, although other substances have been identified and may, therefore, contribute to the nutraceutical action of CS. These include quinine, theophylline, theobromine, and trigonelline [17,15].

Among the substances that help define the antioxidant capacity of CS are the melanoidins that are formed in the last phase of the Maillard reaction during the roasting process. The presence of melanoidins is to be considered an added value, not only for the aforementioned antioxidant capacity but also for the proven prebiotic effects. This can be expressed as the ability of bacteria to utilize CS as carbon source which is evaluated assessing the growth of different bacterial strains (i.e., *Lactobacillum* spp., *Bifidobacterium* spp., *Bacterioides* spp. and *Clostridium* spp.) by qRTi-PCR after *in vitro* gastrointestinal digestion [23]. This property appears to be unaffected by the antimicrobial capacity of CGAs and makes CS interesting for the formulation of food products with a prebiotic action. The melanoidins that are formed in the coffee bean and thus form part of the chemical composition of its by-products, including CS, belong mainly to the melanosaccharide family, with the

core of these polymers being saccharidic in nature [24]. However, this core also contains phenolic compounds, including caffeic acid and ferulic acid, constituting 77 % and 20 % of the total-bound phenolics, respectively. Although not much is known about CS melanoidins, it has been shown that melanoidins generally remain more or less intact in the upper digestive tract and can be degraded by microflora once they reach the colon, thus exerting their prebiotic action [24].

Also the lipophilic fraction of CS offers interesting insights in the search of compounds with potential biological activity. For instance, the content of vitamin E, one of the most renowned naturally occurring antioxidants, has recently been quantified for the first time in CS. In addition, seven different vitamers have been identified. The analysis of the profile of tocopherols was performed extracting the lipid fraction of CS by Soxhlet during 2.5 h with hexane and analysing the extract by NP-HPLC using both DAD and FD as detection systems [25]. Although the fatty acid profile shows a predominance of saturated fatty acids, the high content of linoleic acid (C18:2 n6) has been indicated as a possible added value for this matrix, given its ability to reduce cardiovascular risk [21,26].

Finally, the characterisation by LC-MS/MS of CS protein hydrolysates obtained with various enzymes made it possible to identify several peptides with diverse types of biological activity, such as ACE and dipeptidyl peptidase IV inhibition, for which the absence of possible toxicological effects was also proven [16].

4. Use of CS in food formulations

Given its excellent functional, nutritional, and health-promoting traits, the valorization of CS represents a virtuous activity within a circular economy framework. In the last decade, many studies have highlighted several potential food applications of CS aiming at improving the nutritional quality and/or specific technological features of a given food. For example, due to its high fibre content, CS has been suggested as a natural phosphate replacer in Irish breakfast sausages [27]. An excess of phosphate in the diet is, in fact, not recommended for people suffering from chronic kidney disease. By partially substituting synthetic phosphate with CS, the authors were able to enhance the water-holding capacity of the sausages by more than 80 % and reduce the cooking loss to less than 10 %. In addition to the evident technological advantages in limiting cooking loss, CS also proved to be effective in limiting lipid oxidation in chicken burgers [28]. In this case, the authors showed that hexanal, a typical marker of oxidation, was completely eliminated in cooked burgers. CS addition to burgers did not drastically alter the sensory profile, and could actually help mitigate early signs of deterioration (warmed-over flavour) during storage. However, increased bitterness and astringency at higher inclusion levels (3 %) should be taken into account. Thanks to the high fibre content, CS has also been described as a fat substitute in cake [29]: water-treated CS could substitute up to 30 % of the fat in cake formulations, improving fibre content without significantly altering some perceived cake textural characteristics, e.g. fibrousness and oiliness, but impacting crumb porosity, colour and cohesiveness, and slightly hardness. When used to partially replace fat in chicken patties, CS was shown to influence all sensory characteristics, with the formulation containing 2 % CS and a 2 % reduction in fat yielding sensory evaluation scores closest to the control [30]. Also the phenolic and melanoidin content of CS can be exploited: by partially substituting wheat flour with CS, Gocmen et al. [20] could increase the color appearance and antioxidant properties of model cookies. Sensory analysis revealed a slight bitter taste and a softer texture in the cookies, with an overall profile considered more than acceptable by the panelists. By a similar approach, cow milk yogurt was fortified with different percentages of CS, showing an increase in bioactive compounds such as dietary fibre, phenolic compounds, chlorogenic acids, and caffeine [31]. In this case, the textural analysis showed an increase in firmness of fortified products during cold storage in comparison to the control.

From a biorefinery perspective, CS can also be valorized through the recovery of specific components, which can subsequently be used as high-value extracts. While this approach is more complex and expensive compared to the use of whole CS, it can, in some cases, yield better results. For instance, Dauber et al. [32] demonstrated that the use of a green CS extract improved the nutritional quality of model cookies, achieving better sensory properties compared to the use of whole CS. In addition, extracting specific fractions of molecules enables more accurate titration and characterization, while also being easier to use and having a lower impact on the sensory characteristics of foods.

5. CS as a source of wall materials for the encapsulation of bioactive molecules

The nutraceutical industry can greatly benefit from the upcycling of CS, not only through the recovery of the antioxidant and bioactive molecules mentioned above, but also by valorizing its fibre, protein, and lipid fractions. Indeed, to develop supplements and functional foods enriched with nutraceutical molecules such as polyphenols, carotenoids, and omega-3, it is essential to encapsulate them using specific wall materials. These materials protect the molecules and enhance their delivery, addressing their typical low stability and bioavailability [33]. Many approaches have been developed using a variety of materials, including proteins, lipids, and polysaccharides such as whey proteins, starches, alginate, synthetic lipids, maltodextrin, and Arabic gum. However, the search for novel, cost-effective, and more sustainable materials is considered strategic. From this perspective, CS may represent a promising source. Fibre, and in particular hemicellulose, could be tested as wall materials for spray-drying applications. In fact, recently, wood-derived hemicellulose, namely galactoglucomannans and glucuronoxylans, have been described as efficient wall materials to encapsulate berry juice and flaxseed oil, the latter extremely rich in omega-3 fatty acids [34,35]. In particular, in the case of flaxseed oil, the encapsulation efficiency of galactoglucomannans was 88–96 %, and that of glucuronoxylans was 63–98 %, definitely higher if compared to gum arabic (49–92 %). The amphiphilic nature of proteins is highly valued for emulsifying and encapsulating target molecules. In this context, CS represents an interesting source of vegan-friendly and sustainable proteins that could partially replace commonly employed whey and soybean proteins both of which are derived from allergenic sources. In contrast, coffee is rarely reported as an allergenic food, even if green coffee powder can be responsible for respiratory allergic symptoms in coffee workers [36]. Notably, coffee is not included in the list of mandatory allergens in food labeling regulations in regions such as the European Union and the United States. While CS contains limited amounts of fats, their characteristics are unique, with saturated fatty acids making up as much as 80 % of the total [5]. This composition of high-melting-point fatty acids is quite unusual for a plant source and could be utilized for the development of special lipid-based encapsulates [37], such as solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC), for which synthetic lipids are often used. These carriers are considered among the most efficient in the delivery of lipophilic bioactive compounds such as carotenoids, curcumin, omega-3-rich oils, and some flavonoids like quercetin. Nevertheless, to explore these possibilities, further research focused on characterizing the functional properties of CS and its fractions is necessary.

6. Perspectives for the use of CS in food formulations

Although still a poorly characterised matrix, the data at our disposal hint at the great potential of CS in food formulation and also in the nutraceutical industry. However, studies aimed at elucidating the chemical composition of CS, both in terms of major and minor components, are limited and often do not consider the variability of this composition based on its origin. In fact, only a few examples in the literature address this important aspect. For instance, in the recent study

by Aroufai et al. [38], it is suggested how the content of total polyphenols along with the different types of antioxidant activity differs not only for distinct botanical varieties (i.e., arabica vs. robusta) but how geographical origin also seems to play a role. Similarly, in the work of Castaldo et al. [17], it is reported that samples from different sources show a different profile of phenolics and alkaloids, both qualitatively and quantitatively. In addition, also lipids and vitamin content can be strongly influenced by geographical origin [5]. As an example, a diagram illustrating the different total phenolic content of CS coming from different geographical origins is proposed in Fig. 2. When it comes to the functional properties of CS, the relationship between these characteristics and the geographic origin, or more simply, the coffee variety, is entirely unexplored. It is clear that climatic characteristics and the different harvesting methods, which in turn are combined with different processing procedures, contribute to the variability in CS composition. However, we are currently far from understanding how the origin of the CS can influence its composition. For this reason, scientific research will have to

intensify its efforts to understand the advantages of choosing a raw material from one region over another. Such an investigation will have to make use of reliable analytical approaches, such as high-resolution mass spectrometry, in order to clearly elucidate the macro- and micro-composition of CS in relation to botanical variety, provenance, technological aspects, etc. Only with this type of data will the coffee industry be able to adopt circular economy strategies based on a targeted and informed selection of the starting product, tailored to the intended reuse of CS.

It is also worth mentioning that the use of CS as a functional food or, more generally, in the formulation of food products, cannot disregard safety assessment and associated risk estimation. In addition, CS is considered as a novel food in the European Union, due to the lack of significant consumption within the EU prior 1997 (Regulation EU 2015/2283). This means that before CS can be marketed as a food ingredient or supplement in the European territory, it must undergo the necessary authorization procedures to ensure its safety and compliance with regulatory standards.

To the best of our knowledge, there are still few scientific contributions addressing this aspect. In this context, it is worth mentioning the recent study by Nolasco et al. [39], in which an extensive characterization regarding the possible presence of various classes of contaminants shows the absence of pesticides, rare earth elements, process contaminants (i.e., acrylamide and furanic compounds), ochratoxin and polycyclic aromatic hydrocarbons in the robusta variety and traces of chrysene, phenanthrene, and fluoranthene in Arabica. Among the toxic metals, arsenic was the most representative with concentrations ranging from 0.21 to 0.29 mg/kg. It is clear that even in this context, the study of the influence of the origin of the raw material is fundamental due to, for example, the close correlation between elemental profile and botanical/geographical variety as well as the possible presence of pesticide residues whose use is regulated differently in different countries around the world.

CRediT authorship contribution statement

Gianni Zoccatelli: Writing – review & editing, Writing – original draft, Conceptualization. **Marco Ciulu:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

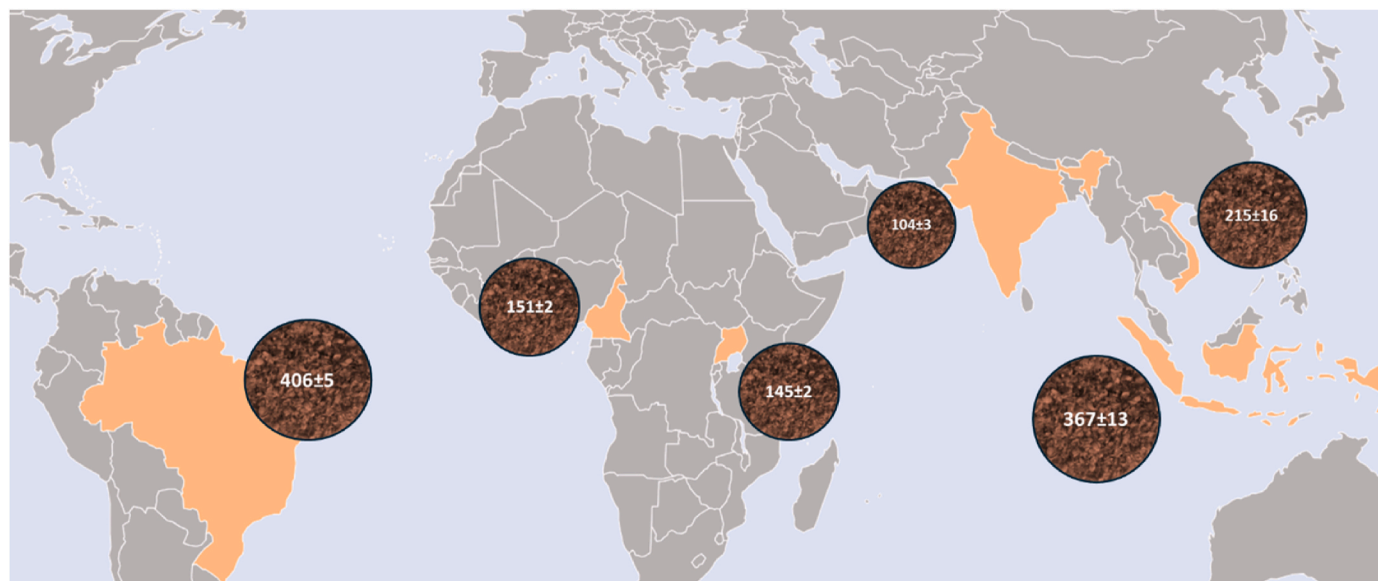


Fig. 2. Total phenolic compounds (expressed as mg of gallic acid equivalents/L) of CS coming from Brazil, Cameroon, Uganda, Indonesia and Vietnam, according to Bessada et al. [5].

Data availability

No data was used for the research described in the article.

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