COFFEE GROUNDS AND ITS BY-PRODUCTS AS SOURCES OF ANTIOXIDANT COMPOUNDS FOR THE OXIDATIVE STABILIZATION OF MEAT PRODUCTS - REVIEW

A.-M. Ioniță[1*], M.-M. Lăpădat[1], A.-M. Pîndaru[1,2], D.-C. Popa[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest, Faculty of Animal Productions Engineering and Management, Department of Production and Processing Technologies, Romania, e-mail: igpa@usamv.ro
[2]University of Bucharest, Faculty of Biology, Department of Botany and Microbiology, Romania, e-mail: secretariat@bio.unibuc.ro

Abstract

Coffee processing generates large volumes of by-products - spent grounds, green beans, silverskin and husk - rich in chlorogenic acids, caffeine and flavonoids with radical-scavenging capacity. This review synthesizes 22 experimental studies (2015-2026) testing these by-products as natural antioxidants in meat matrices (beef, pork, chicken, mutton), selected from a verified bibliographic matrix after excluding duplicate and non-meat records. Coffee-derived treatments consistently reduced lipid-oxidation markers (TBARS, volatile aldehydes), often matching or exceeding BHA, BHT, ascorbic acid and rosemary, at doses from 0.025% to 10% w/w. Protein oxidation was less consistently controlled, and higher doses of green-coffee products altered colour via chlorogenic acid-myoglobin interactions; silverskin and husk showed favourable profiles. These findings support coffee by-products as viable circular-economy meat antioxidants, if dose selection balances efficacy against sensory constraints.

Keywords*: spent coffee grounds; coffee by-products; natural antioxidants; lipid oxidation; meat products*

INTRODUCTION

Coffee is among the most widely consumed beverages worldwide, and its processing generates considerable volumes of organic residues at every stage of the value chain, from the husk and pulp removed during the processing of the ripe fruit, through the silverskin released during roasting, to the spent coffee grounds (SCG) discarded after brewing [1]. It is estimated that for every tonne of green coffee processed, a large share of the raw material ends up as by-product rather than as the final beverage, and SCG alone represents one of the most abundant food-industry residues at the global level [1, 2]. Because these residues are rich in organic matter and are typically disposed of in landfills or incinerated, their accumulation raises environmental concerns, while at the same time their chemical composition suggests they are far from inert waste [2, 3].

Chemical characterization studies have repeatedly shown that coffee by-products retain a substantial fraction of the bioactive compounds originally present in the green or roasted bean. Chlorogenic acids and their isomers (3-, 4- and 5-caffeoylquinic acid), caffeine, melanoidins formed during roasting, flavonoids, tannins and, in the case of silverskin and pulp, dietary fibre and proteins, have all been identified and quantified across different by-product fractions [3, 4, 5, 6, 7, 8]. These compounds confer coffee by-products with a measurable radical-scavenging and metal-chelating capacity,

*Corresponding author: alexandra.maria2311@yahoo.ro
The manuscript was received: 18.10.2026
Accepted for publication: 18.11.2026

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

which is the chemical basis for their proposed use as natural antioxidants [4, 5, 9].

Because the bioactive potential of these residues depends strongly on how they are recovered and stabilized, a parallel line of research has focused on optimizing extraction, fermentation and encapsulation strategies. Solid-state fermentation with Bacillus clausii has been shown to increase both the phenolic content and the antioxidant and antimicrobial bioactivity of spent coffee grounds extracts [10], while early work on green and roasted Arabica and Robusta beans established that controlled thermal and pressure extraction conditions can maximize antioxidant yield [11]. Spent coffee grounds obtained specifically from espresso preparation have also been shown to contain previously under-characterized bioactive molecules, such as tyrosol and tocopherols, at concentrations relevant for pharmaceutical or nutraceutical use [12]. To overcome the inherent instability of free phenolic compounds during processing and storage, encapsulation technologies - including spray-drying and freeze-drying with different wall materials [13], microwave-assisted extraction coupled with spray-dried microencapsulation [14], and encapsulation of cold-brew spent-coffee-grounds extracts validated under simulated gastrointestinal conditions [15] - have been developed specifically to protect these compounds, which is directly relevant to their eventual incorporation into food matrices such as meat products.

Beyond their technological use as antioxidants, coffee by-products have also attracted interest for their broader nutritional and health-related properties, which further illustrates the diversity of this residue stream. Antioxidant dietary fibre isolated from spent coffee grounds has been reported to reduce the formation of advanced glycation end-products during baking by up to six-fold compared with an untreated control, together with a potential reduction of the glycaemic index through α-glucosidase inhibition [16], and to promote a distinct colonic microbiome signature with potential benefits for subjects affected by chronodisruption [17]. Coffee silverskin, tested in both flake and powder form, has similarly been characterized as a source of phenolic compounds, flavonoids and dietary fibre with favourable water- and oil-holding properties, although lacking emulsifying or gelling capacity in its raw form [18]. Together, this body of evidence indicates that coffee by-products are not a homogeneous waste stream but a diverse set of substrates whose composition and functional properties vary with botanical origin, processing step and extraction method - a heterogene-ity that, as shown below, is also reflected in their performance when applied directly to meat matrices.

Oxidative degradation of lipids and proteins is one of the main causes of quality loss in meat and meat products during processing and storage, leading to rancid off-flavours, discoloration, nutrient loss and, in some cases, to the formation of secondary compounds of toxicological concern. For decades, the meat industry has relied on synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT) and synthetic ascorbates to delay this process; however, consumer demand for "clean-label" products and the increasing scrutiny of synthetic food additives have driven research toward natural alternatives capable of providing an equivalent protective effect. Within this context, coffee by-products have attracted growing interest as a renewable, inexpensive and locally available source of natural antioxidant compounds for meat applications, in line with circular-economy and food-waste-valorization principles [1, 2].

A growing but still fragmented body of experimental literature has tested spent coffee grounds, green (unroasted) coffee beans, coffee silverskin and coffee husk, applied as crude powders, aqueous or ethanolic extracts, or encapsulated preparations, in a range of fresh and processed meat matrices — beef, pork, chicken and mutton —

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

eval-uating their effect on lipid and protein oxi-dation markers, instrumental and sensory quality, and, in several cases, antimicrobial activity. This literature, however, is hetero-geneous with respect to the by-product form tested, the dose range applied, the storage conditions and duration, and the oxidative or sensory endpoints measured, which makes direct comparison across studies dif-ficult and, to date, no single review has brought all of these experimental meat-ma-trix studies together in a structured and standardized manner [3].

The aim of the present review is therefore to critically identify, extract and synthesize the available experimental evidence on the antioxidant efficacy of spent coffee grounds and the other main coffee by-products (green coffee, silverskin and husk) when incorporated into meat and meat products, with specific attention to the type of meat matrix, the form and dose of the by-product applied, the storage conditions and oxidative indicators used, and the main quantitative outcomes reported. By organizing this evidence by type of by-product, the review seeks to highlight both the consistent antioxidant benefits already documented and the remaining methodological gaps - particularly regarding protein oxidation, sensory validation and dose standardization that should guide future research on the valorization of coffee residues as functional ingredients for the meat industry.

MATERIAL AND METHOD

As this contribution is a literature review rather than an original experimental study, the present section describes the methodology used to identify, select and extract the data synthesized in the Results and Discussion section, rather than an experimental protocol.

Candidate publications were identified through academic bibliographic databases and search engines (including PubMed, PMC, ScienceDirect, SpringerLink, SciELO and Google Scholar), using combinations of the terms "spent coffee grounds", "coffee silverskin", "coffee husk", "coffee pulp", "green coffee", "coffee by-product", cross-referenced with "meat", "lipid oxidation", "protein oxidation", "antioxidant" and "TBARS". Bibliographic metadata (authors, title, journal, year, DOI) for every candidate record were independently cross-checked against the Crossref database and, where necessary, against the publisher's own page, to avoid relying on secondary or potentially inaccurate citation data.

All candidate records were organized in a structured bibliographic matrix and classified into two non-exclusive categories: Category A, comprising primary experimental studies that tested a coffee-derived by-product as an antioxidant directly in a real meat or meat-product matrix; and Category C, comprising contextual and supporting references describing the chemical composition, extraction, or non-meat valorization of coffee by-products, used to document background information in the Introduction. Screening of the initial pool of Category A records (24 candidate studies) yielded 22 unique, non-overlapping experimental studies: one master's thesis [19] was excluded from the quantitative synthesis after verification because its dataset had already been incorporated, by the same research group, into a subsequently published peer-reviewed journal article also retained in the matrix [20] (avoiding duplicate counting of the same dataset), and one further record [21] was excluded after full-text verification showed that the antioxidant extracts it described had been tested on a vegetable or fish oil model system rather than on a meat matrix, and therefore fell outside the scope of the present review.

For each of the 22 retained studies, the following information was extracted in a standardized format directly from the full text of the original publication: meat species and product type (meat matrix); coffee by-product and physical form applied (powder, aqueous extract, ethanolic extract, encapsulated preparation); concentration(s) tested; storage conditions and duration; lipid- and

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

protein-oxidation indicators measured (e.g., TBARS, peroxide value, protein carbonyls, volatile aldehydes); other physicochemical and microbiological indicators (pH, instrumental colour, microbial counts); sensory evaluation, where performed; the main quantitative results; and an overall qualitative judgment of the effect on oxidative stability. No data were extrapolated, estimated or added beyond what was explicitly reported in the original sources; where a given parameter was not reported or not assessed in a particular study, this is indicated as such in the synthesis below rather than inferred.

RESULTS AND DISCUSSION

The 22 retained experimental studies span publication years 2015–2026 and cover four main categories of coffee by-product applied to meat matrices: spent coffee grounds in its regular, roasted or cold-brew forms (9 studies), green (unroasted) coffee bean powders or extracts (6 studies), coffee silverskin (4 studies) and coffee husk (2 studies), together with one review article compiling data on coffee-fruit-processing residues more broadly [22]. In terms of meat matrix, pork-based products were the most frequently investigated (9 studies), followed by beef (6 studies), chicken (3 studies) and mutton (1 study), with one further study covering both raw and cooked meat systems as well as an oil-emulsion model [23]. Table 1 summarizes the meat matrix, coffee by-product and form, dose, storage conditions and main oxidative outcome reported in each of the 22 studies.

Spent coffee grounds (regular, roasted and cold-brew forms)

Spent coffee grounds, in either their native form or after roasting and brewing, were the most extensively tested by-product. In minced beef, an aqueous or ethanolic SCG extract incorporated at concentrations of 1–5% (w/w) significantly inhibited the increase in TBARS and protein carbonyls relative to the untreated control over 14 days of refrigerated storage, while also slowing spoilage-bacteria growth and preserving red colour (a*) [24]. In raw and cooked meat systems and in an oil emulsion, SCG extract obtained with hot or cold ethanol reached a DPPH radical-scavenging activity of 90–91% at 1000 ppm, performing similarly to the synthetic positive control BHA [23]. In fresh pork patties, an aqueous SCG extract significantly reduced TBARS values compared with a BHT-treated control over 9 days of dark, refrigerated storage, while also stabilizing pH and preventing discoloration [25]. In ground pork patties stored under modified-atmosphere packaging for 21 days, SCG obtained from light- and dark-roasted coffee (added as lyophilized brew or lyophilized grounds at 1 g/kg) significantly lowered TBARS values from day 7 onward and performed comparably to a 0.02% rosemary extract reference, although a trained sensory panel using the tetrad method could already detect the presence of coffee from day 3 of storage [26]. In beef patties, 1% dried SCG powder produced the lowest TBARS values at day 7 among all tested groups together with a significant increase in dietary fibre content, with molecular-docking analysis identifying chlorogenic acid as the compound with the highest predicted binding affinity for the oxidative target protein COX-2 [27]. In chicken breast fillets, a 0.1–0.2% ethanolic SCG extract performed comparably to 0.02% BHT in delaying oxidative spoilage while also fully preventing bacterial, fungal and Salmonella sp. growth over 15 days of refrigerated storage [28]. In raw ground beef (top round), 0.1% roasted coffee reduced TBARS and the volatile markers hexanal and pentanal over 7 days, counteracting the pro-oxidant effect of added NaCl; dark-roast coffee, richer in melanoidins, was the most effective treatment and equalled or exceeded a rosemary oleoresin positive control [29]. In low-fat pork sausage, 1% cold-brew SCG extract increased DPPH radical-scavenging activity (159.76 µM Trolox/100 g) and total phenolic content (18.07 mg GAE/100 g) in the final product while keep-

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

ing TBARS low and preserving sensory acceptability [30]. Finally, in frozen cooked pork patties stored for three months, lyophilized light- and dark-roast coffee brew most effectively reduced the volatile aldehydes hexanal, octanal and nonanal, with an inhibitory effect on lipid oxidation comparable to rosemary oleoresin and no significant impact on protein thiol content [31].

Table 1. Summary of the 22 experimental studies retained on the use of coffee by-products as antioxidants in meat and meat-product matrices.

Ref. No.	Meat matrix	Coffee by-product (form)	Dose	Storage / duration	Main oxidative outcome
[24]	Minced beef	SCG extract (aqueous/etha-nolic)	1–5% w/w	4 °C, 14 d	↓ TBARS, ↓ protein car-bonyls vs. control
[23]	Raw/cooked meat sys-tems; oil emulsion	SCG residue ex-tract (hot/cold ethanol, aque-ous)	up to 1000 ppm	n.r.	DPPH 90–91% at 1000 ppm, ≈ BHA
[25]	Raw pork patties	SCG aqueous extract	n.r. (vs. BHT)	4 °C, dark, 9 d	↓ TBARS vs. BHT-treated control (P<0.05)
[26]	Ground pork patties (MAP)	Roasted coffee (lyophilized brew/SCG)	1 g/kg	4 °C, MAP, 21 d	↓ TBARS from day 7; ≈ rosemary 0.02%; coffee detectable sensorially from day 3
[27]	Beef patties	SCG powder	1%	4 °C, 7 d	Lowest TBARS at day 7; fi-bre ↑; porous/fibrous tex-ture
[28]	Chicken breast fillets	SCG ethanolic extract	0.1–0.2% (vs. BHT 0.02%)	4 °C, 15 d	≈ BHT; full control of bacte-rial/fungal/Salmonella growth
[29]	Raw ground beef (top round)	Roasted ground coffee (light/me-dium/dark)	0.1%	4 °C, 7 d	↓ TBARS, hexanal, pen-tanal; counters NaCl pro-oxidant effect; dark roast best
[30]	Low-fat pork sausage	Cold-brew SCG extract	1%	4 °C, 14 d	↑ DPPH (159.76 µM Trolox/100 g), ↑ TPC (18.07 mg GAE/100 g); rancidity blocked
[31]	Frozen cooked pork patties	Lyophilized roasted coffee brew (light/dark)	1 g/kg	frozen, 3 months	↓ hexanal/octanal/nonanal ≈ rosemary oleoresin; thi-ols stable
[32]	Pork burgers	Non-compliant defatted green coffee bean ex-tract	0.15 / 0.30 / 0.60%	4 °C, 14 d (raw+cooke d)	Best effect at 0.15%; no colour/sensory penalty
[20]	Fresh pork sausage	Green coffee (Robusta) ex-tract, RSM-opti-mized	0.32%	refriger-ated, 20 d	MDA <0.70 mg/kg; sensory score >7.16/10
[33]	Ground beef	Green coffee bean extract (aqueous/etha-nolic)	n.r.	—, day 7 analysed	↓ TBARS 40–48.57%; anti-microbial vs. S. aureus/E. coli; colour/pH altered
[34]	Beef burgers	Green coffee powder	3 / 6 / 10%	4 °C, 7 d	DPPH 82.98%; TBARS 0.65–0.81 vs 1.96 mg MA/kg control; fibre ↑ to 12.56%
[35]	Beef meat-balls	Green coffee powder	250 / 500 / 1000 ppm	4 °C, 14 d	≥500 ppm > ascorbic acid (hydrocarbons); 1000 ppm only dose <2.5 mg MDA/kg; colour darkened

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Ref. No.	Meat matrix	Coffee by-product (form)	Dose	Storage / duration	Main oxidative outcome
[36]	Restructured mutton blocks	Green coffee bean extract + Colocasia escu-lenta binder	1% (+3% binder)	4±1 °C, n.r.	↓ TBARS, ↓ FFA; improved microbiological/sensory quality
[37]	Ground pork	Fermented coffee silverskin extract	1.5 / 3.0%	n.r.	↓ TBARS, ↓ MetMb, ↓ mes-ophilic/psychrotrophic counts; sensory not evalu-ated
[38]	Pork meat homogenate (induced oxi-dation)	Silverskin aque-ous extract (vs. BHT 500 ppm)	250 / 500 ppm	1 h induced oxidation	↓ pH change, TBARS, MetMb ≈ BHT (P<0.05)
[39]	Chicken burgers	Coffee silverskin (CSS)	1.5 / 3%	4 °C, 72 h	Hexanal 55.1%→11.7%→0%; cooking loss 23.85%→10.5–11.05%; WOF prevented
[40]	Frankfurter sausages	Silverskin extract / powder	12.5 mL/kg / 5 g/kg	4 °C, 21 d	MDA 0.144 / 0.143 vs 0.162 mg/kg control; ≈ ascorbic acid (0.139)
[41]	Fresh pork sausages (AEP/MAP)	Coffee husk pow-der	1 / 2%	4 °C, MAP, 23 d	TBARS <2.5 mg MDA/kg at 2% (MAP); no effect on protein carbonyls
[42]	Chicken burgers	Coffee husk ex-tract (CAE)	100 / 200 ppm	frozen, 45 d	↓ TBARS at 200 ppm; no effect on protein carbonyls
[22]	Fresh/pro-cessed meat (review: pork, lamb, chicken, burgers, sau-sages)	Husk, pulp, sil-verskin, SCG (re-view)	variable (review)	variable (re-view)	Consistently positive effect on oxidative stability across compiled studies

Note: SCG = spent coffee grounds; TBARS = thiobarbituric acid reactive substances; DPPH = 2,2-diphenyl-1-picrylhydrazyl; MDA = malondialdehyde; FFA = free fatty acids; MetMb = metmyoglobin; WOF = warmed-over flavour; MAP = modified atmosphere packaging; RSM = response surface meth-odology; n.r. = not reported in the source publication.

Taken together, these nine studies show that SCG-derived preparations consistently reduce TBARS and related lipid-oxidation markers across beef, pork and chicken ma-trices, at concentrations ranging from as low as 0.1% to 1000 ppm or up to 5% w/w, gen-erally matching the performance of BHA, BHT or rosemary-based references. The de-gree of roasting and the brewing method ap-pear to modulate efficacy, with dark-roast preparations (richer in Maillard-reaction melanoidins) performing particularly well against metal-catalysed oxidation [29, 31], while the earliest detectable sensory impact of coffee notes was reported from day 3 of storage in one study [26], indicating that sensory masking, rather than chemical effi-cacy, may be the main technological con-straint on SCG dose.

Green (unroasted) coffee bean prod-ucts

Because roasting partially degrades na-tive chlorogenic acids, several studies spe-cifically tested unroasted or non-compliant (rejected) green coffee beans. In pork burg-ers, a defatted green-coffee-bean extract tested at 0.15%, 0.30% and 0.60% was most effective at the lowest dose (0.15%), signif-icantly increasing antioxidant activity in both raw and cooked burgers without a measurable colour or sensory penalty, while the highest dose (0.60%) altered native product characteristics [32]. In fresh pork sausage, a Robusta green coffee extract op-timized by response-surface methodology at 0.32% kept malondialdehyde content be-low 0.70 mg/kg over 20 days of refrigerated storage, with consumer sensory scores above 7.16/10, successfully replacing so-

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

dium erythorbate without loss of acceptability [20]. In ground beef, aqueous and ethanolic green coffee bean extracts inhibited lipid oxidation by 40–48.57% at day 7 and showed antimicrobial activity against Staphylococcus aureus (31.11% inhibition) and Escherichia coli (41.94% inhibition), although the extracts measurably altered the colour and pH of the meat [33]. In beef burgers, green coffee powder added at 3%, 6% and 10% produced a DPPH-scavenging activity of 82.98% and reduced TBARS to 0.65–0.81 mg malonaldehyde/kg at day 7, against 1.96 mg/kg in the untreated control, while dietary fibre content rose from 6.75% to 12.56% at the 3% dose; a molecular-docking analysis again identified chlorogenic acid as the most strongly binding compound against the COX-2 oxidative target [34]. In beef meatballs, green coffee powder at 250, 500 and 1000 ppm outperformed ascorbic acid in reducing carcinogenic aliphatic hydrocarbons at doses ≥500 ppm (87.4–87.6% reduction versus 84.0% for ascorbic acid), and only the 1000 ppm dose kept TBARS below the 2.5 mg MDA/kg acceptability threshold throughout 14 days of storage; however, the treatment measurably reduced red colour intensity (a*) and increased brown metmyoglobin formation, because the chlorogenic acid present reacts with myoglobin pigments [35]. Finally, in restructured mutton blocks formulated with Colocasia esculenta as a binding agent (3%), a 1% green coffee bean extract significantly reduced TBARS and free-fatty-acid values and improved microbiological and sensory quality during refrigerated storage [36].

These six studies indicate that green coffee bean products are effective at comparatively low doses (0.15–1%, or 250–1000 ppm), in several cases outperforming ascorbic acid, which is consistent with their higher native chlorogenic acid content relative to roasted by-products. However, this same reactivity is also responsible for the main technological limitation identified across this group: at higher doses, the interaction between chlorogenic acid and meat myoglobin consistently produced a measurable darkening or greening of colour [33, 34, 35], indicating that dose optimization toward the lower, still-effective end of the tested range - rather than maximization - is the more appropriate strategy for this by-product category.

Coffee silverskin

Coffee silverskin, the thin tegument released during roasting, was tested in four studies. In ground pork, a fungal-fermentation-derived silverskin extract at 1.5% and 3.0% improved both oxidative stability (lower TBARS and metmyoglobin formation) and microbiological stability, reducing the growth of mesophilic and psychrotrophic bacteria; the authors explicitly noted that the sensory impact of the treatment had not yet been evaluated and recommended this as a priority for future research [37]. In a pork-meat homogenate model with chemically induced oxidation, a silverskin aqueous extract at 250 and 500 ppm reduced pH changes, TBARS and metmyoglobin formation as effectively as a 500 ppm BHT control [38]. In chicken burgers, coffee silverskin added at 1.5% and 3% reduced the primary lipid-oxidation marker hexanal from 55.1% (control, immediately after cooking) to 11.7% (1.5% CSS) and to a complete absence at 3% CSS, while also sharply reducing cooking losses (from 23.85% in the control to 10.50–11.05% with silverskin) and preventing the development of warmed-over flavour [39]. In frankfurter-type sausages, silverskin extract (12.5 mL/kg) or powder (5 g/kg) reduced malondialdehyde to 0.144 and 0.143 mg/kg respectively, against 0.162 mg/kg in the untreated control, performing comparably to a 0.139 mg/kg ascorbic-acid reference over 21 days of refrigerated storage, with good sensory acceptance reported [40].

Across these four studies, coffee silverskin performed particularly well against volatile secondary lipid-oxidation markers such as hexanal, and was associated with

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

generally favourable or neutral sensory outcomes, including in processed, emulsified products such as sausages and burgers. This profile, combined with the fact that silverskin is comparatively under-represented in the literature relative to spent coffee grounds, positions it as a promising sub-strate warranting further, more systematic sensory and microbiological validation [37].

Coffee husk

Coffee husk, the outer covering removed during dry processing of the coffee cherry, was the least represented by-product in the retained dataset, with only two studies. In fresh pork sausages, coffee husk powder at 1% and 2%, combined with modified-atmosphere packaging (20% CO_2 + 80% N_2), kept TBARS below the 2.5 mg MDA/kg critical acceptability threshold throughout 23 days of storage at the 2% dose; the modified atmosphere itself somewhat reduced consumer liking scores, an effect attributable to the packaging rather than to the husk, while the husk had no significant effect on protein oxidation (carbonyl content) [41]. In chicken burgers, an organic coffee husk extract at 100 and 200 ppm significantly improved lipid-oxidative stability (lower TBARS) over 45 days of frozen storage at the higher dose, while - consistently with the pork-sausage study - showing no significant pro- or antioxidant effect on protein carbonyl formation [42].

Although based on only two studies, this pattern is notable: coffee husk extracts were effective against lipid oxidation even under frozen storage and at low ppm-level doses, but in both available studies failed to exert a measurable effect on protein oxidation, suggesting that coffee husk polyphenols act preferentially through lipid-phase radical scavenging and metal chelation rather than through protection of the sarcoplasmic and myofibrillar protein fraction.

Cross-cutting observations

Several patterns emerge when the 22 studies are considered together. First, the effective dose range verified across the retained dataset spans approximately 0.025% (250 ppm; [38], [35]) to 10% w/w [34], a considerably wider interval than the 0.3–4% range sometimes assumed in preliminary summaries of this literature, reflecting genuine heterogeneity in by-product form (crude powder versus purified extract) and target matrix rather than a narrow, universally optimal dose. Second, dose-response was not always monotonic: in several studies the lowest tested concentration performed as well as, or better than, higher doses [20, 32], while in others higher doses were specifically required to reach the acceptability threshold [35]. Third, sensory and colour trade-offs were concentrated at the higher end of the tested dose ranges and were most pronounced for green-coffee-derived products, where chlorogenic acid–myoglobin interactions darkened or greened the product [33, 34, 35]; one study on SCG-derived dietary fibre in beef patties also reported that, despite an improved odour profile, the treated product became more porous and fibrous in texture [27], confirming that "no negative sensory effect" cannot be generalized across all coffee by-products and doses, and should instead be assessed case by case. Fourth, where synthetic or reference antioxidants were used as positive controls (BHA, BHT, ascorbic acid, rosemary extract or oleoresin), coffee-derived treatments matched or exceeded their performance in the majority of the 22 studies, supporting the technological viability of this substitution. Fifth, lipid oxidation was more consistently and more frequently assessed, and more consistently reduced, than protein oxidation; where protein carbonyls were specifically measured, coffee husk extracts showed no significant protective effect [41, 42], in contrast with the significant carbonyl reduction reported for an SCG extract in minced beef [24], indicating that the effect on protein oxidation is by-product- and matrix-dependent rather than a general property of coffee-derived antioxidants.

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

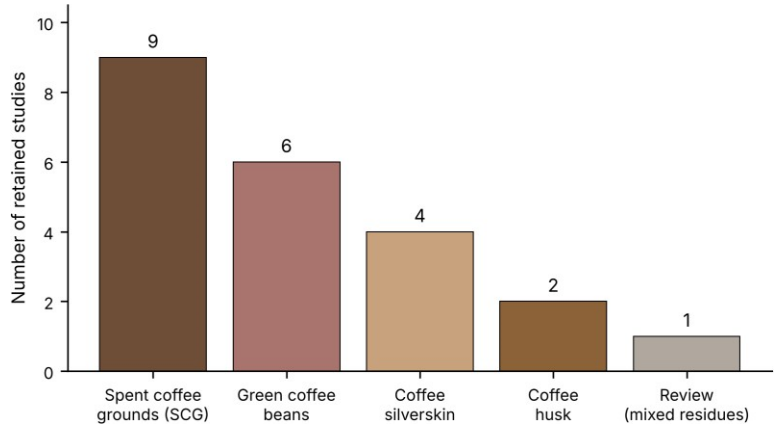


Fig. 1. Distribution of the 22 retained experimental studies by coffee by-product category

Finally, a formal sensory evaluation was performed in only about half of the 22 studies, and stor-age conditions, duration and oxidative end-points varied widely across studies, which - consistent with an earlier observation made in a broader review of coffee by-prod-uct valorization [3] - continues to compli-cate direct, quantitative cross-study com-parison and points to a clear need for meth-odological standardization in future re-search.

CONCLUSIONS

The literature reviewed here, covering 22 independent experimental studies published between 2015 and 2026, consistently shows that coffee by-products - spent cof-fee grounds, green (unroasted) coffee beans, coffee silverskin and coffee husk - are effective, renewable sources of antioxidant compounds capable of controlling lipid oxidation in diverse meat and meat-product matrices, including beef, pork, chicken and mutton. In the majority of the studies reviewed, coffee-derived treatments matched or exceeded the performance of established synthetic antioxidants (BHA, BHT) and commercial references (ascorbic acid, rosemary extract), supporting their technological viability as "clean-label" substitutes.

The effective dose range is considerably wider than previously assumed, spanning approximately 0.025% to 10% w/w depending on the by-product form, and dose optimization - rather than dose maximization - emerges as the critical variable: at higher concentrations, several studies, particularly those using green coffee bean products, reported measurable darkening, greening or textural changes linked to chlorogenic acid–myoglobin interactions. Lipid oxidation was controlled more consistently than protein oxidation, with coffee husk extracts in particular showing no measurable protective effect on protein carbonyl formation in either of the two studies available.

Coffee silverskin and coffee husk, although comparatively under-represented in the current experimental literature relative to spent coffee grounds and green coffee, show a particularly favourable profile against volatile secondary lipid-oxidation markers and, in the case of silverskin, generally neutral-to-positive sensory outcomes, positioning them as promising substrates for further valorization. At the same time, the considerable heterogeneity in storage conditions, durations and oxidative endpoints used across the reviewed studies limits direct quantitative comparison and underlines the need for more standardized experimental protocols, more systematic sensory evaluation, and dedicated studies on protein-oxidation endpoints in future re-

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

search. From an applied perspective, the evidence synthesized in this review supports the continued development of coffee by-products as functional, circular-economy-aligned antioxidant ingredients for the meat industry, provided that dose selection is guided by matrix-specific sensory and technological validation rather than by antioxidant efficacy alone.

REFERENCES

1. Franca, A.S.; Oliveira, L.S. Potential Uses of Spent Coffee Grounds in the Food Industry. Foods, 11(14), 2064. doi.org/10.3390/foods11142064
2. Choe, U. Valorization of spent coffee grounds and their applications in food science. Current Research in Food Science, 10, 101010. doi.org/10.1016/j.crfs.2025.101010
3. Lestari, W.; Hasballah, K.; Listiawan, M.Y.; Sofia Coffee by-products as the source of antioxidants: a systematic review. F1000Research. doi.org/10.12688/f1000re-search.107811.1
4. Andrade, C.; Perestrelo, R.; Câmara, J.S. Bioactive Compounds and Anti-oxidant Activity from Spent Coffee Grounds as a Powerful Approach for Its Valorization. Molecules, 27(21), 7504. doi.org/10.3390/molecules27217504
5. Panusa, A.; Zuorro, A.; Lavecchia, R.; Marrosu, G. Recovery of Natural An-tioxidants from Spent Coffee Grounds. Journal of Agricultural and Food Chemistry, 61(17), 4162–4168. doi.org/10.1021/jf4005719
6. Narita, Y.; Inouye, K. High antioxi-dant activity of coffee silverskin ex-tracts obtained by the treatment of coffee silverskin with subcritical wa-ter. FoodChemistry. doi.org/10.1016/j.food-chem.2012.05.078
7. Munguía Ameca, G.; Ortega Cerrilla, M.E.; Zetina Córdoba, P.; Díaz Cruz, A.; Soto Hernández, M.; Herrera Haro, J. Chemical composition and antioxidant capacity of coffee pulp. Ciência e Agrotecnologia, 42(3), 307–313 doi.org/10.1590/1413-70542018423000818
8. Cañas, S.; Rebollo-Hernanz, M.; Cano-Muñoz, P.; Aguilera, Y.; Benítez, V.; Braojos, C.; Gila-Díaz, A.; Rodríguez-Rodríguez, P.; Monedo Cobeta, I.; López de Pablo, Á.L.; González, M.d.C.; Arribas, S.M.; Martin-Cabrejas, M.A. Critical Eval-uation of Coffee Pulp as an Innova-tive Antioxidant Dietary Fiber Ingre-dient: Nutritional Value, Functional Properties, and Acute and Sub-Chronic Toxicity. Proceedings (MDPI),70(1),65. doi.org/10.3390/foods_2020-07623
9. Mussatto, S.I.; Ballesteros, L.F.; Mar-tins, S.; Teixeira, J.A. Extraction of antioxidant phenolic compounds from spent coffee grounds. Separa-tion and Purification Technology, 83, 173–179. doi.org/10.1016/j.sep-pur.2011.09.036
10. Rochín-Medina, J.J.; Ramírez, K.; Rangel-Peraza, J.G.; Bustos-Terro-nes, Y.A. Increase of content and bio-activity of total phenolic compounds from spent coffee grounds through solid state fermentation by Bacillus clausii. Journal of Food Science and Technology, 55(3), 915–923. doi.org/10.1007/s13197-017-2998-5
11. Budryn, G. Antioxidant Properties of Arabica and Robusta Coffee Extracts Prepared under Different Condi-tions. Deutsche Lebensmittel-Rund-schau: Zeitschrift für Lebensmit-telkunde und Lebensmittelrecht, 104(2), 69–78.
12. Balzano, M.; Loizzo, M.R.; Tundis, R.; Lucci, P.; Nuñez, O.; Fiorini, D.; Giardinieri, A.; Frega, N.G.; Pacetti, D. Spent espresso coffee grounds as a source of anti-proliferative and antioxidant compounds. Innovative Food Science & Emerging Technolo-gies, 59, 102254. doi.org/10.1016/j.ifset.2019.102254
13. Araújo, C.d.S.; Vimercati, W.C.; Macedo, L.L.; Saraiva, S.H.; Teixeira, L.J.Q.; da Costa, J.M.G.; Pimenta, C.J. Encapsulation of phenolic and anti-oxidant compounds from spent cof-fee grounds using spray-drying and freeze-drying and characterization of dried powders. Journal of Food Science, 87(9), 4056–4067. doi.org/10.1111/1750-3841.16281
14. Kanha, N.; Lamaphrom, K.; Boonma, P.; Supasorn, P.; Panyasim, P.; Jaimun, R.; Laokuldilok, T. Sustaina-ble valorization of spent coffee grounds via microwave-assisted extraction and spray-dried microen-capsulation. Food Chemistry: X, 36, 103918. doi.org/10.1016/j.fochx.2026.103918
15. Chongsrimsirisakhol, O.; Pirak, T. Polyphenol Release and Antioxidant Activity of the Encapsulated Antiox-idant Crude Extract from Cold Brew Spent Coffee Grounds under Simu-lated Food Processes and an In Vitro Static Gastrointestinal Model. Foods, 12(5), 1000. doi.org/10.3390/foods12051000
16. Vázquez-Sánchez, K.; Martinez-Saez, N.;

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Rebollo-Hernanz, M.; del Castillo, M.D.; Gaytán-Martínez, M.; Campos-Vega, R. In vitro health pro-moting properties of antioxidant dietary fiber extracted from spent cof-fee (Coffea arabica L.) grounds. Food Chemistry. doi.org/10.1016/j.food-chem.2018.04.064

17. Montoya-Hernández, D.; Dufoo-Hurtado, E.; Cruz-Hernández, A.; Campos-Vega, R. Spent coffee grounds and its antioxidant dietary fiber promote different colonic mi-crobiome signatures: Benefits for subjects with chronodisruption. Mi-crobial Pathogenesis. doi.org/10.1016/j.micpath.2023.10643 1

18. Vargas-Sánchez, R.D.; Torres-Mar-tínez, B.d.M.; Torrescano-Urrutia, G.R.; Sánchez-Escalante, A. Physico-chemical, techno-functional and an-tioxidant characterization of coffee silverskin. Biotecnia, 25(1), 43–50. doi.org/10.18633/bio-tecnia.v25i1.1755

19. Fetsch, V.T. Obtenção de extrato de café para aplicação como antioxi-dante natural em linguiça toscana (Master's thesis). UTFPR, Programa de Pos-Graduacao em Tecnologia de Alimentos, campus Medianeira (teza). [DOI indisponibil]

20. Fetsch, V.T.; Kalschne, D.L.; Canan, C.; Flores, É.L.d.M.; Viegas, M.C.; Peiter, G.C.; Zara, R.F.; Amaral, J.S.; Corso, M.P. Coffee Extract as a Nat-ural Antioxidant in Fresh Pork Sau-sage—A Model Approach. Foods, 13(9), 1409. doi.org/10.3390/foods13091409

21. Paidech, C. Development of antioxi-dant from spent coffee ground and its application (thesis; exact original title not independently re-verified). Chulalongkorn University (teză). doi.org/10.58837/chula.the.2023.953

22. Terán-Rivera, S.C.; Torres-Martínez, B.M.; Torrescano-Urrutia, G.R.; Esqueda, M.; Sánchez-Escalante, A.; Vargas-Sánchez, R.D. Residuos del procesamiento del fruto de café como fuente natural de antioxi-dantes para la industria cárnica [Cof-fee fruit processing residues as a nat-ural source of antioxidant for meat industry]. TIP. Revista Especializada en Ciencias Químico-Biológicas, 26, e540. doi.org/10.22201/fesz.23958723e.202 3.540

23. Kim, J.-H.; Ahn, D.U.; Eun, J.B.; Moon, S.H. Antioxidant Effect of Ex-tracts from the Coffee Residue in Raw and Cooked Meat. Antioxi-dants, 5(3), 21. doi.org/10.3390/an-tiox5030021

24. Zouari Ayadi, D.; Chaari, M.; El-hadef, K.; Abid, C.; Ennouri, M.; Var-zakas, T.; Smaoui, S. Spent coffee grounds extract as an effective ap-proach for prolonging the shelf life of minced beef: chemometric modeling of quality attributes. Quality Assur-ance and Safety of Crops & Foods, 18(1), 16–35. doi.org/10.15586/qas.v18i1.1598

25. Murillo Hernández, J.L.; Vargas Sánchez, R.D.; Torres Martínez, B.M.; Huerta Leidenz, N.; Tor-rescano Urrutia, G.R.; Sánchez Escalante, A. Effect of spent coffee grounds aqueous extract as an anti-oxidant in raw pork patties during refrigerated storage. Revista Mexi-cana de Ciencias Pecuarias, 15(4), 833–847. doi.org/10.22319/rmcp.v15i4.6630

26. Hashimoto, T.A.; Caporaso, F.; Toto, C.; Were, L. Antioxidant capacity and sensory impact of coffee added to ground pork. European Food Re-search and Technology, 245(5), 977–986. doi.org/10.1007/s00217-018-3200-7

27. Dilek, N.M. Utilization of Spent Cof-fee Grounds as an Antioxidant Die-tary Fiber in Beef Patties: Oxidative Stability, Texture Properties, and Molecular Docking. Food Science & Nutrition. doi.org/10.1002/fsn3.70919

28. El-Chaghaby, G.A.; Shehta, H.A.; Rashad, S.; Rawash, E.-S.A.; Eid, H.R. Evaluation of the antioxidant and antimicrobial activities of the spent coffee extracts and their appli-cations as natural food preservatives of chicken fillets. Novel Research in Microbiology Journal. doi.org/10.21608/nrmj.2024.339900

29. Lin, C.; Toto, C.; Were, L. Antioxi-dant effectiveness of ground roasted coffee in raw ground top round beef with added sodium chloride. LWT - Food Science and Technology, 60(1), 29–35. doi.org/10.1016/j.lwt.2014.08.010

30. Chongsrimsirisakhol, O.; Pirak, T. Total polyphenol content and antiox-idant properties of cold brew coffee extracts as affected by ultrasound treatment and their application in low fat pork sausage. International Journal of Food Properties. doi.org/10.1080/10942912.2022.20561 97

31. Jully, K.M.M.; Toto, C.S.; Were, L. Antioxidant effect of spent, ground, and lyophilized brew from roasted coffee in frozen cooked pork patties. LWT - Food Science and Technology, 66, 244–251. doi.org/10.1016/j.lwt.2015.10.046

32. Bergamaschi, M.; Simoncini, N.; Spezzano, V.M.; Ferri, M.; Tassoni, A. Antioxidant and Sensory Proper-ties of Raw and Cooked Pork

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Meat Burgers Formulated with Extract from Non-Compliant Green Coffee Beans. Foods, 12(6), 1264. doi.org/10.3390/foods12061264

33. Atondo-Echeagaray, W.A.; Torres-Martínez, B.M.; Vargas-Sánchez, R.D.; Torrescano-Urrutia, G.R.; Huerta-Leidenz, N.; Sánchez-Es-calante, A. Green Coffee Bean Extracts: An Alternative to Improve the Microbial and Oxidative Stability of Ground Beef. Resources, 14(6), 95. doi.org/10.3390/resources14060095

34. Doğaner, E.N.; Dilek, N.M.; Aytar, E.C. Green Coffee Powder as a Clean-Label Functional Ingredient in Meat Systems: Antioxidant Perfor-mance, Molecular Docking Mecha-nisms, and Technological Properties. Food Biophysics, 20(4), art. 162. doi.org/10.1007/s11483-025-10035-2

35. Mostafa, H.S.; El Azab, E.F. Efficacy of green coffee as an antioxidant in beef meatballs compared with ascor-bic acid. Food Chemistry: X (2022). doi.org/10.1016/j.fochx.2022.100336

36. Dilnawaz, H.M.; Kumar, S.; Bhat, Z.F. Effect of Green Coffee Bean Ex-tract on the Lipid Oxidative Stability and Storage Quality of Restructured Mutton Blocks Containing Colocasia esculenta, a Novel Binding Agent. Agricultural Research, 6(4), 443–454. doi.org/10.1007/s40003-017-0283-5

37. Terán-Rivera, S.C.; Torrescano-Urru-tia, G.R.; Torres-Martínez, B.M.; Esqueda-Valle, M.; Ibarra-Arias, F.J.; Sánchez-Escalante, A.; Vargas-Sánchez, R.D. Fungal Submerged Fermentation of Coffee Silverskin: A Sustainable Source of Natural Meat Additives. Resources, 14(1), 6. doi.org/10.3390/resources14010006

38. Vargas Sánchez, R.D.; Torres Mar-tínez, B.M.; Torrescano Urrutia, G.R.; Sánchez-Escalante, A. Utilización del extracto acuoso de cascarilla de café para mejorar la estabilidad oxidativa de homogenizados de carne de cerdo. Biotecnia, 26, e2128. doi.org/10.18633/biotecnia.v26.2128

39. Martuscelli, M.; Esposito, L.; Mastrocola, D. The Role of Coffee Sil-ver Skin against Oxidative Phenom-ena in Newly Formulated Chicken Meat Burgers after Cooking. Foods, 10(8), 1833. doi.org/10.3390/foods10081833

40. Mesárošová, A.; Jurčaga, L.; Bobková, A.; Kročko, M.; Demian-ová, A.; Poláková, K.; Lidiková, J.; Mendelová, A.; Švecová, T.; Baluch, M.; Bobko, M. Coffee Silverskin: non-traditional natural antioxidant for the meat industry. Applied Food Re-search (2025). doi.org/10.1016/j.afres.2025.101185

41. Araya-Morice, A.; Araya-Quesada, Y.; Cortés, N.; Caamaño, J.; Arroyo, L. Antioxidant potential of coffee husks in fresh pork sausage. Journal of Food Science and Technology, 60(9), 2423–2432.doi.org/10.1007/s13197-023-05764-6

42. Marques, A.D.J.F.; Tavares, J.L.; de Carvalho, L.M.; Abreu, T.L.; Pereira, D.A.; Santos, M.M.F.; Madruga, M.S.; Lucena de Medeiros, L.; Bez-erra, T.K.A. Oxidative stability of chicken burgers using organic coffee husk extract. Food Chemistry (2022). doi.org/10.1016/j.food-chem.2022.133451

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)