Macedonian Journal of Chemistry and Chemical Engineering, Vol. **45**, No. 1, pp. xx–xx (2026)

MJCCA9 –

ISSN 1857-5552
e-ISSN 1857-5625
DOI: 10.20450/mjcce.2026.3455
Original scientific paper

Received: February 12, 2026
Accepted: May 21, 2026

IMPACT OF OIL EXTRACTION METHOD AND GENOTYPE ON THE TECHNO- AND BIO-FUNCTIONAL PROPERTIES OF CAMELINA (*CAMELINA SATIVA* L.) SEED CAKE

Ivan M. Savić[1*], Ivana M. Savic Gajic[1], Slađana Rakita[2], Nedeljka Spasevski[2], Aleksandra Bajić[2]

[1]*University of Niš, Faculty of Technology in Leskovac, Bulevar Oslobodjenja 124, 16000 Leskovac, Serbia*
[2]*University of Novi Sad, Institute of Food Technology, Bulevar Cara Lazara 1, 21000 Novi Sad, Serbia*
savicivan@tf.ni.ac.rs

Oilseed cakes are significant by-products of the oil-processing industry with considerable potential for further valorization. This study systematically investigated the effects of genotype (NS Zlatka and NS Slatka) and oil extraction method (Soxhlet extraction with *n*-hexane versus cold pressing) on the nutritional composition, techno- and bio-functional properties of camelina (*Camelina sativa* L.) seed cake. Basic nutritional parameters, water and oil absorption capacities, as well as gelling, foaming, and emulsifying properties, were evaluated. The results demonstrated that both genotype and oil extraction method significantly affected the composition and techno-functional properties of camelina seed cake ($p < 0.05$). Cakes obtained using Soxhlet extraction exhibited higher protein (41.80–42.50 %) and ash (6.11–6.32 %) contents, along with enhanced water (573–699 %) and oil (218–244 %) absorption capacities. In contrast, the resulting cold-pressed cakes retained a higher proportion of residual oil (14.80–16.20%). Although total phenolic content was relatively similar among samples (approximately 0.55 g gallic acid equivalent (GAE)/100 g dry matter), the qualitative and quantitative composition of individual phenolic compounds varied markedly depending on genotype and oil extraction method. The cold-pressed cakes, particularly the NS Zlatka genotype, were characterized by high gallic acid content (140.58 mg/100 g dry matter) and the most pronounced antiradical activity ($IC_{50} = 0.080$ mg/ml) determined by 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay. These findings indicate that Soxhlet-extracted cakes are superior for applications requiring high protein content and hydration properties, while cold-pressed cakes from the NS Zlatka genotype offer higher antioxidant potential. This study provides a strategic basis for selecting specific genotypes and processing methods to tailor the functional profile of camelina by-products for the food and pharmaceutical industries.

Key words: camelina seed cake; nutritional composition; techno-functional properties; phenolic profile; antiradical activity.

ВЛИЈАНИЕ НА МЕТОДОТ НА ЕКСТРАКЦИЈА НА МАСЛО И ГЕНОТИПОТ ВРЗ ТЕХНОЛОШКО-ФУНКЦИОНАЛНИТЕ И БИОЛОШКО-ФУНКЦИОНАЛНИТЕ СВОЈСТВА НА ПОГАЧА ОД СЕМЕ НА КАМЕЛИНА (*CAMELINA SATIVA* L.)

Погачите од маслодајни семиња претставуваат значајни нуспроизводи на индустријата за преработка на масла и поседуваат значителен потенцијал за понатамошна валоризација. Во ова истражување систематски беа испитани влијанијата на генотипот (NS Zlatka и NS Slatka) и методот на екстракција на масло (Сокслетова екстракција со *n*-хексан наспроти ладно пресување) врз нутритивниот состав, како и врз технолошко-функционалните и биолошко-функционалните својства на погачата од семе на камелина (*Camelina sativa* L.). Беа анализирани основните нутритивни параметри, капацитетот за апсорпција на вода и масло, како и својствата на гелирање, пенење и емулгирање. Резултатите покажаа дека и генотипот и методот на екстракција на масло значајно влијаат врз составот и технолошко-функционалните својства на погачата од камелина ($p < 0,05$). Погачите добиени со Сокслетова екстракција покажаа повисока содржина на протеини (41,80–42,50 %) и пепел (6,11–6,32 %), како и подобрен капацитет за апсорпција на вода (573–699 %) и масло (218–244 %). Наспроти тоа, погачите добиени со ладно пресување задржаа поголем удел на остаточно масло (14,80–16,20 %). Иако вкупната содржина на фенолни соединенија беше

релативно слична кај сите примероци (приближно 0,55 g еквивалент на гална киселина (GAE) на 100 g сува материја), квалитативниот и квантитативниот состав на поединечните фенолни соединенија значително варираше во зависност од генотипот и методот на екстракција на масло. Погачите добиени со ладно пресување, особено од генотипот NS Zlatka, се карактеризираа со висока содржина на гална киселина (140,58 mg/100 g сува материја) и најизразена антирадикалска активност (IC_{50} = 0,080 mg/ml), утврдена со методот на 2,2-дифенил-1-пикрилхидразил (DPPH). Овие резултати укажуваат дека погачите добиени со Сокслетова екстракција се посоодветни за примени што бараат висока содржина на протеини и добри хидратациски својства, додека ладно пресуваните погачи од генотипот NS Zlatka нудат поголем антиоксидациски потенцијал. Ова истражување обезбедува стратешка основа за избор на специфични генотипови и методи на преработка со цел насочено обликување на функционалниот профил на нуспроизводите од камелина за примена во прехранбената и фармацевтската индустрија.

Клучни зборови: погача од семе на камелина; нутритивен состав; технолошко-функционални својства; фенолен профил; антирадикалска активност.

1. INTRODUCTION

Seed oil cakes, generated as by-products of seed oil extraction, are heterogeneous materials with a complex chemical and structural composition that largely depends on the type of plant raw material, the applied oil extraction method, and processing conditions.[1] Because of their high content of nutritionally and functionally valuable components, oil cakes have attracted increasing attention from both the scientific and industrial communities, particularly in the context of sustainable production and the valorization of agro-industrial by-products. Oil cake composition typically includes proteins of high biological value, significant amounts of residual oil with a characteristic fatty acid profile, carbohydrates, dietary fiber, minerals, and various classes of secondary plant metabolites, such as phenolic compounds, phytosterols, and tocopherols.[2] These components contribute to antioxidant activity, water- and oil-binding capacity, and emulsifying and gelling properties, rendering them suitable for application in the development of innovative food products and functional ingredients.[3] From a technological perspective, oil cakes represent a promising raw material for the fractionation and extraction of individual components, particularly proteins[4] and bioactive compounds, using advanced separation and extraction methods.[5] In addition to their applications in the food industry, oil cakes are widely utilized in the pharmaceutical and cosmetic industries as sources of natural antioxidants and other bioactive substances,[6] as well as in animal nutrition owing to their high protein content[7] and metabolizable energy value.[8]

Camelina (*Camelina sativa* L.) is an oilseed crop that has gained increasing attention owing to the high quality of oil obtained from its seeds.[9] This oil is characterized by a favorable fatty acid profile, notably a high proportion of polyunsaturated fatty acids (PUFAs), as well as the presence of numerous biologically active phytoconstituents exhibiting significant pharmacological potential.[10] The oil yield, along with the quantity and chemical composition of the resulting oil cake, largely depends on agroecological cultivation conditions, plant genotype, and the applied oil extraction method.[11] Furthermore, prior research has demonstrated that the nutritional and functional properties of camelina oil cake vary significantly with particle size and varietal affiliation (*C. sativa* var.).[12] Camelina oil cake is rich in nutritionally and functionally valuable components, primarily proteins, residual oil with a favorable fatty acid composition, dietary fiber, and various bioactive compounds,[13] which supports its broad applicability across multiple industrial sectors. Owing to its functional properties, particularly high water absorption capacity, camelina seed cake is well-suited for use as an ingredient in meatballs, where optimized hydration allows up to 20% replacement of meat with plant-based protein and fiber without compromising the sensory quality of the product.[12] In livestock nutrition, camelina seed cake represents a promising protein-energy feed ingredient capable of partially replacing conventional feed sources.[14] Moreover, owing to the favorable rheological and film-forming properties of its protein fraction, camelina seed cake has been recognized as a suitable raw material for the development of biodegradable and active packaging materials.[15]

This study aimed to systematically evaluate how oil extraction methods and specific genotypes (NS Slatka and NS Zlatka) influence the quality and valorization potential of camelina oil cake as a functional raw material. Within this framework, camelina seed cake was not considered merely as a by-product of oil production, but rather as a differentiated raw material whose properties and potential applications could be strategically tailored through the selection of genotype and extraction process. The findings of this study provide a novel basis for the rational and sus-

tainable valorization of camelina oil cake in the development of value-added products, thereby addressing existing research gaps and furthering the concept of the circular economy within the oil processing industry. The conceptual framework in Figure 1 summarizes the innovative aspects of this study, illustrating how genotype and extraction method determine the functional properties and valorization potential of camelina oil cake, thus transforming it from a conventional by-product into a value-added raw material.

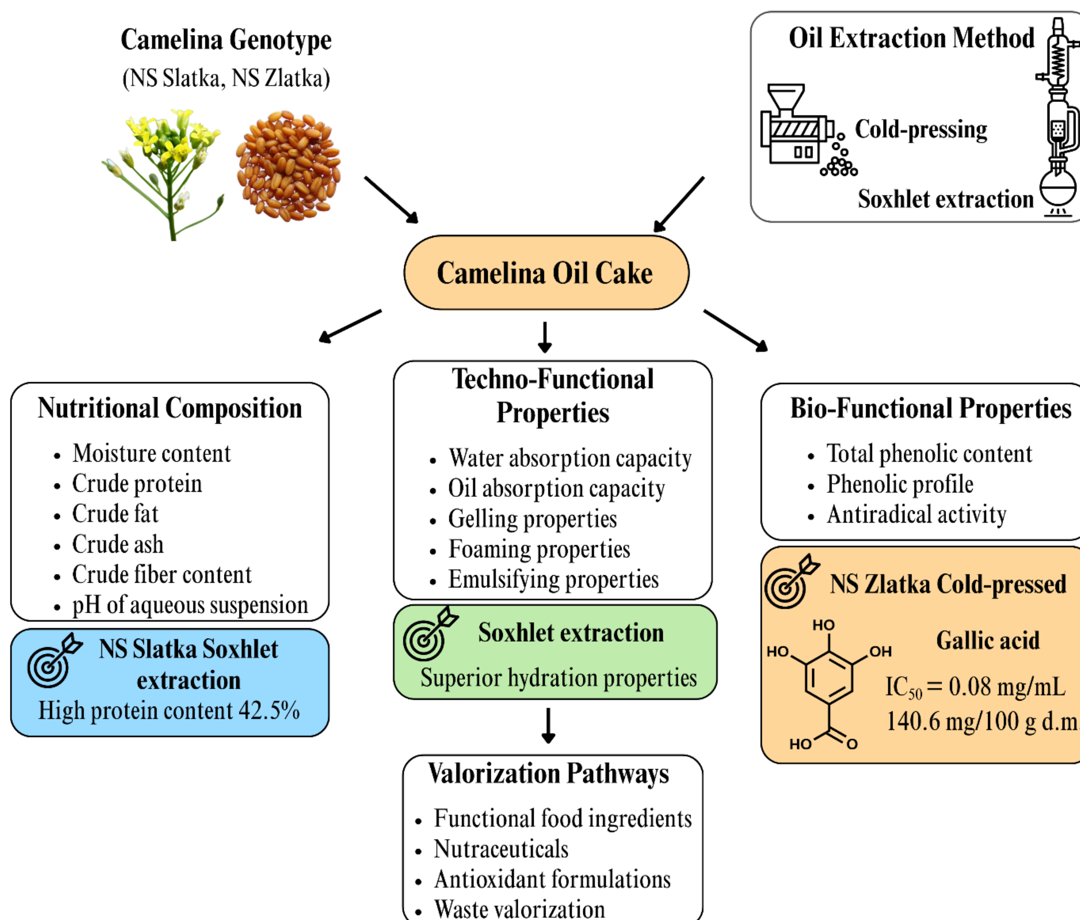

Fig. 1. Conceptual model of camelina oil cake valorization: integrated effects of genotype and oil extraction method on quality and valorization potential within a circular economy framework

2. MATERIALS AND METHODS

2.1. *Chemicals and reagents*

The study utilized the following chemicals and reagents: absolute ethanol, sodium carbonate (Zorka Pharma, Šabac, Serbia); *n*-hexane (Appli Chem, Darmstadt, Germany); Folin–Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl (DPPH), methanol (HPLC grade); and standard phenolic compounds, including gallic acid, syringic acid, caffeic acid, and sinapic acid (Sigma-Aldrich, St. Louis, MO, USA).

2.2. *Preparation of camelina seed cakes*

Camelina (*Camelina sativa* L.) seed cakes from the NS Zlatka and NS Slatka genotypes (Figure 2a) were prepared using two different methods: Soxhlet extraction with *n*-hexane and cold pressing. Soxhlet extraction was conducted at the solvent's boiling temperature for 4 h, while cold pressing was executed using a screw press (Ulimac Machine, Ankara, Türkiye; 1.5 kW, capacity 5 – 45 kg/h) operated at temperatures below 50 °C. The resulting camelina seed cakes were dried in an oven at 45 °C for 24 h and subsequently ground in an Bosch MKM6000 electric mill (Bosch, BSH Hausgerate GmbH, Slovenia) to a particle size of 0.5 mm (Fig. 2b). The obtained fine cake powder was stored at room temperature in a moisture-protected environment until further use.

Fig. 2. Camelina seeds before **(a)** and after **(b)** oil extraction

2.3. *Nutritional composition*

The moisture content,[16] crude protein,[17] crude fat,[18] and crude ash[19] of camelina seed cakes from the NS Zlatka and NS Slatka genotypes were determined. Crude fiber content was assessed using the previously described protocol[20] with an Ankom 2000 Fiber Analyzer (Ankom Technology, Fairport, NY, USA). The pH of an aqueous cake suspension was determined according to the official methods of analysis of AOAC International.[21]

2.4. *Determination of techno-functional properties*

The techno-functional properties of camelina seed cakes were evaluated based on their water absorption capacity (WAC) and oil absorption capacity (OAC), as well as their gelling, foaming, and emulsifying properties. These parameters were assessed using standard analytical methods, ensuring consistency, reproducibility, and comparability with previously reported studies.

The water absorption capacity (WAC) of camelina seed cakes was measured according to the method described by Sosulski[22]. In brief, a 1.0 g sample of cake was suspended in 10 mL of distilled water, vortexed for 5 min, allowed to stand for 15 min at room temperature, and subsequently centrifuged at 3500 rpm for 30 min. After decanting the excess water, the drained precipitate was weighed, and the WAC was calculated as grams of water per gram of sample (g/g).

The oil absorption capacity (OAC) of camelina seed cakes was determined as follows: a 0.5 g sample of ground cake was suspended in 10 ml of corn oil and incubated for 30 min at room temperature with occasional mixing. The mixture was then centrifuged at 4000 rpm for 15 min.[23] The supernatant was decanted, and the precipitate was dried and weighed. OAC was calculated as grams of oil bound per gram of sample (g/g).

The minimum gelling concentration of camelina seed cakes was determined according to the procedure described by Coffmann and Garciaj[24]. Suspensions of camelina seed cake at various concentrations (2 %, 4 %, 6 %, 8 %, and 10 %, *w/v*) were prepared in distilled water. The suspensions were heated in a boiling water bath for 1 h and subsequently cooled rapidly under a cold-water jet, followed by refrigeration at 4 °C for 3 h. The minimum gelling concentration was identified as the lowest concentration at which the suspension showed no leakage or flow when the tube was inverted.

The foaming capacity (FC) and foam stability (FS) of camelina seed cakes were assessed according to the method of Lawhon, et al.[25] A 3 g sample of camelina seed cake was suspended in 100 ml of distilled water, and the pH of the suspension was adjusted to 7.0. The mixture was then stirred using a KA RW 20 Digital Dual-Range Mixer System (IKA-Werke GmbH & Co. KG, Germany) for 5 min. Immediately after mixing, the suspension and resulting foam were transferred into a 250 ml graduated cylinder, and the foam volume was recorded after 30 s. FC was calculated as the percentage increase in volume (Eq. 1). FS was determined by measuring the foam volume after 30 min (Eq. 2).

$$\text{FC}(\%) = \frac{\text{Volume after mixing} - \text{Volume before mixing}}{\text{Volume before mixing}} \times 100 \quad (1)$$

$$\text{FS}(\%) = \frac{\text{Volume of foam after time}}{\text{Initial volume of foam}} \times 100 \quad (2)$$

The emulsifying activity (EA) of camelina seed cakes was evaluated according to Yasumatsu et al.[26] In brief, a 0.7 g sample of camelina seed cake was suspended in 10 ml of distilled water and homogenized. Then, 10 ml of refined peanut oil was added, and the mixture was further homogenized in an electric blender for 5 min. The emulsion was subsequently centrifuged at 2000 rpm for 5 min. After centrifugation, the contents were transferred to a 50 ml graduated cylinder and left to stand for several minutes to allow stable emulsified layers to form. EA was calculated using Eq. 3.

$$\text{EA}(\%) = \frac{\text{Height of emusified layer}}{\text{Height of total content in cylinder}} \times 100 \quad (3)$$

Emulsion stability (ES) of camelina seed cakes was evaluated by centrifuging the emulsion a second time, followed by heating to 80 °C for 30 min and subsequently cooling to 15 °C. After centrifugation, the emulsion was transferred to a 50 ml graduated cylinder and allowed to stand for several minutes to stabilize the layers. ES was expressed as a percentage of the total volume of the remaining emulsion after the heating process (Eq. 4).

$$\mathrm{ES}(\%) = \frac{\text{Height of emulsified layer after heating}}{\text{Height of total content in cylinder}} \times 100 \quad (4)$$

2.5. *Determination of biofunctional properties*

The biofunctional properties of camelina seed cakes were evaluated through the determination of total phenolic content (TPC), phenolic profiles, and antiradical activity using a spectrophotometric method, (reversed-phase high performance liquid chromatography) RP-HPLC analysis and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, respectively.

The ultrasound-assisted extraction of polyphenols from the analyzed camelina seed cakes was performed using 60% (v/v) ethanol at 60 °C with a liquid- to- solid ratio of 10 ml/g for 45 min. An 8- L ultrasonic bath (Sonic, Niš, Serbia) operating at 40 kHz and 150 W was used to facilitate the extraction. After extraction, the solid phase was separated from the liquid phase by vacuum filtration through a Büchner funnel. To determine the dry matter content, a 3 ml aliquot of the resulting extracts was dried to constant weight in a BIOBASE BOV-30V laboratory oven (BIOBASE Group, China) at 105 °C. The remaining extract was stored at 4 °C until further analysis.

The TPC was determined spectrophotometrically with Folin–Ciocalteu reagent according to the method described by Savic Gajic et al.[27] Results were expressed as milligrams of gallic acid equivalents (GAE) per 100 g of dry matter (mg GAE/100 g d.m.). Sample preparation involved mixing 0.1 ml of extract with 1 ml of a tenfold-diluted Folin–Ciocalteu reagent and 1 ml of a 7 % (*w/v*) sodium carbonate solution. The mixture was incubated in the dark for 90 min, after which absorbance was measured at 760 nm using a Varian Cary 100 spectrophotometer (Mulgrave, Victoria, Australia). A blank was prepared by replacing the sodium carbonate solution with an equal volume of distilled water.

The phenolic profile of ethanolic extracts from camelina seed cake was determined using HPLC according to the method described by Nour et al.[28] Separation was carried out on a Zorbax Eclipse XDB-C18 column (4.6 × 250 mm, 5 µm; Agilent Technologies, Santa Clara, CA, USA). Phenolic compounds were identified by comparing retention times and UV spectra with standards (gallic, syringic, caffeic, and sinapic acids). The quantification of individual phenolic compounds was conducted using previously constructed calibration curves and results were expressed as milligrams per 100 g of dry matter.

The antiradical activity of ethanolic extracts from camelina seed cake was assessed using the DPPH assay.[27] Stock solutions of the extracts were diluted to prepare a series of varying concentrations (0.1563 – 0.0195 mg/ml for NS Slatka genotype and 0.1656 – 0.0207 mg/ml for NS Zlatka genotype). To a 2.5 ml sample, 1 ml of a 3×10^{-4} mol/l ethanolic solution of DPPH radicals was added. Blank samples were prepared by replacing the DPPH solution with an equivalent volume of 96% (*v/v*) ethanol. After incubation in the dark at room temperature for 30 min, the absorbance of the samples was measured at 517 nm against 96% (*v/v*) ethanol. The percentage of DPPH radical inhibition (I_{DPPH}) was calculated using Eq. 5 and plotted as a function of sample concentration.

$$I_{\mathrm{DPPH}}(\%) = \frac{A_{\mathrm{C}} - A_{\mathrm{S}}}{A_C} \times 100 \quad (5)$$

where A_{S} is the absorbance of the sample solution and A_{C} is the absorbance of the control solution.

The antiradical activity of the ethanolic extracts from camelina seed cakes was evaluated using the half maximal inhibitory concentration (IC_{50}) value. This parameter represents the concentration needed to inhibit 50 % of the initial DPPH radicals in solution. The IC_{50} was determined by linear interpolation from the plots of inhibition percentage versus sample concentration, using the two closest points that bracket the 50 % inhibition level. All calculations and graphical representations were conducted using Microsoft Excel 2024 (Microsoft Corp., Redmond, WA, USA).

2.6. *Statistical analysis*

All data were presented as the mean ± standard deviation of three measurements. Statistical analysis was performed using IBM SPSS Statistics (version 27, Armonk, NY, USA). A two-way analysis of variance (ANOVA) was conducted at a 95% confidence level ($p < 0.05$) to evaluate the main effects of genotype and extraction method, along with their potential interaction. Significant differences between treatment means were identified using Tukey's honestly significant difference post hoc test at $p < 0.05$.

3. RESULTS AND DISCUSSION

The present study examined camelina seed cakes of the NS Zlatka and NS Slatka genotypes, prepared using two different oil extraction methods: Soxhlet extraction and cold pressing. The investigation evaluated the combined effects of genotype and extraction method through analysis of the basic nutritional composition, along with detailed examination of key techno-functional properties, including water absorption capacity (WAC). oil absorption capacity (OAC), emulsifying activity (EA), and emulsion stability (ES). Furthermore, the phenolic profile of the cakes was characterized, and their antiradical activity was quantified. The results were subsequently used to evaluate the potential for their further application.

3.1. *Nutritional composition of camelina seed cakes*

Table 1 shows the nutritional analysis results for camelina seed cakes, including moisture content, crude protein, crude fat, crude ash, and crude fiber content, as well as the pH of their aqueous suspensions. These data enabled a comparative assessment of the effects of genotype and extraction method.

T a b l e 1

Nutritional parameters (%, dry weight basis) and pH of NS Zlatka and NS Slatka camelina seed cakes prepared by Soxhlet extraction and cold pressing

Parameters	**Soxhlet extraction**		**Cold-pressing**		**Factor**	***p*-value**	η_p^2
	NS Zlatka	**NS Slatka**	**NS Zlatka**	**NS Slatka**			
Moisture	7.90 ± 0.16^{a,b}	8.30 ± 0.21^{b}	7.70 ± 0.18^{a}	7.80 ± 0.13^{a}	G	0.036	0.441
					M	0.008	0.607
					G×M	0.036	0.441
Crude protein	41.80 ± 0.57^{c}	42.50 ± 0.49^{c}	35.10 ± 0.02^{a}	36.30 ± 0.15^{b}	G	0.003	0.697
					M	<0.001	0.991
					G×M	0.291	0.138
Crude fat	3.80 ± 0.10^{a}	4.10 ± 0.09^{b}	16.20 ± 0.04^{d}	14.80 ± 0.06^{c}	G	<0.001	0.951
					M	<0.001	1.000
					G×M	<0.001	0.979
Crude ash	6.32 ± 0.13^{b}	6.11 ± 0.11^{b}	4.84 ± 0.02^{a}	4.77 ± 0.05^{a}	G	0.026	0.480
					M	<0.001	0.989
					G×M	0.212	0.187
Crude fiber	28.85 ± 0.23^{a,b}	28.45 ± 0.18^{a}	28.96 ± 0.29^{a,b}	29.03 ± 0.15^{b}	G	0.228	0.175
					M	0.026	0.482
					G×M	0.100	0.302
pH value	5.57 ± 0.13^{a}	5.88 ± 0.13^{a}	6.70 ± 0.13^{b}	6.61 ± 0.13^{b}	G	0.181	0.212
					M	<0.001	0.950
					G×M	0.029	0.470

All values are expressed as % except pH, which is dimensionless. Different superscript letters (a, b, c, d) in the rows represent statistically significant differences ($p < 0.05$) between the groups according to Tukey's post hoc test. G: Genotype effect; M: Extraction method effect; G×M: Interaction effect between genotype and extraction method. η_p^2: Partial eta squared.

3.1.1. *Moisture content of camelina seed cakes*

The moisture content of camelina seed cakes from both genotypes remained low (< 8.30 %), well within the recommended range of 10–12 % for ensuring storage stability and preventing microbial growth.[29] However, two-way ANOVA (Table 1) revealed that the moisture content differed significantly with both genotype ($p = 0.036$) and extraction method ($p = 0.008$). Cakes produced by Soxhlet extraction contained significantly higher moisture (7.90–8.30 %) compared with cold-pressed cakes (7.70–7.80 %). This variation likely stems from the low affinity of nonpolar organic solvents for water molecules during Soxhlet extraction, resulting in less efficient dehydration relative to the mechanical pressure applied during cold pressing. A significant genotype-by-method interaction (G×M, $p = 0.036$) was observed, primarily due to the NS Slatka genotype.

3.1.2. *Total crude protein content of camelina seed cakes*

Nutritional analysis demonstrated that crude protein constituted the most abundant component in camelina seed cakes. Soxhlet extraction significantly enhanced protein concentration (up to 42.50 %), making these cakes superior for high-protein food formulations relative to cold-pressed samples (Table 1). These findings corresponded to previous reports indicating that camelina seed cakes produced by solvent extraction contain approximately 40–45 % protein, while cold-pressed cakes show reduced protein content owing to their higher residual oil levels.[30] Two-way ANOVA revealed that both genotype and extraction method significantly influenced crude protein content (Table 1). However, the extraction method exerted a substantially greater effect (η_p^2= 0.991) than genotype (η_p^2 = 0.697). No significant genotype-by-method interaction (G×M, p = 0.291) was observed, indicating that the extraction method's effect was consistent across both genotypes. Thus, the extraction method emerged as a critical determinant of the camelina seed cakes' nutritional quality, particularly regarding their potential as protein-rich raw materials. Additionally, recent studies have demonstrated that instant controlled pressure drop (DIC) technology can significantly improve protein recovery, yielding isolated protein at approximately 70 %.[31]

3.1.3. *Total crude fat content of camelina seed cakes*

The cold-pressed camelina seed cakes contained approximately four times more crude fat than those produced using Soxhlet extraction (Table 1). These results confirmed the high efficiency of Soxhlet extraction in lipid removal from camelina seeds, whereas cold-pressed cakes retained a substantial proportion of oil. This finding aligns with previous studies, which have consistently demonstrated significantly higher crude fat contents in cold-pressed camelina seed cakes relative to those obtained by solvent extraction.[32] Statistical analysis revealed that both genotype ($p < 0.001$, $\eta_p^2 = 0.951$) and extraction method ($p < 0.001$, $\eta_p^2 = 0.951$) significantly affected total crude fat content. The significant G×M interaction ($p < 0.001$) suggested that the genotypes exhibited different responses to extraction method variations.

3.1.4. *Total crude ash content of camelina seed cakes*

Crude ash content serves as an important indicator of the mineral composition of oil cakes and plays a significant role in assessing their nutritional value, particularly when utilized as animal feed or as functional ingredients in the food industry.[21] Higher ash content generally indicates increased levels of inorganic minerals (e.g., Ca, Mg, K, and P), while lower values may suggest a greater proportion of organic components, such as lipids and proteins. In this study, ash content was higher in cakes produced by Soxhlet extraction (6.11–6.32 %) compared with those obtained by cold pressing (4.77–4.84 %) (Table 1). During Soxhlet extraction, inorganic minerals remained in the solid residue, causing a relative increase in ash content.[33] Similar ash levels (6.34 %) have been reported for camelina seed cakes defatted with *n*-hexane in Türkiye.[34] Statistical analysis demonstrated that the extraction method exerted a greater influence ($p < 0.001$, $\eta_p^2 = 0.989$) on total crude ash content than did camelina genotype. No significant G×M interaction was observed, suggesting that both genotypes responded consistently to variations in the extraction method. Mollaei et al.[35], in a comparative study of commercial and non-commercial cold-pressed oil cakes, reported the lowest ash content in *Carthamus tinctorius* cake and the highest in *Chrozophora tinctoria* cake, while the ash content of cold-pressed camelina seed cake was comparable to that of *Lallemantia royleana* cake produced using the same method. These variations in ash content may have important implications for industrial and food applications. Cakes with higher ash content can function as valuable mineral sources in animal nutrition or feed formulations. However, elevated mineral levels may also affect sensory attributes and processing characteristics, and should therefore be carefully evaluated in relation to the intended end use.

3.1.5. *Total crude fiber content of camelina seed cakes*

The total crude fiber content of camelina seed cakes exhibited high stability, with values reaching up to 29 %. In contrast to the previous parameters, genotype exerted no statistically significant effect (p = 0.228). While the extraction method demonstrated a statistically significant impact (p = 0.026), its influence was substantially less pronounced than that observed for other parameters. Notably, considerably lower crude fiber contents have been reported in the literature. For example, cold-pressed camelina seed cake from the F8CALG28 line cultivated in Italy showed a crude fiber content of approximately 11 %.[36] Comparable values were documented for *n*-hexane-defatted camelina seed cake from Türkiye.[34] When compared with these findings, the results of this study revealed markedly higher crude fiber content in the cakes of

both analyzed camelina genotypes, which may be attributed to differences in genetic background and agroecological growing conditions. The high crude fiber levels observed suggest that cakes from both camelina genotypes constitute an exceptionally rich source of dietary fiber. Dietary fiber contributes to improved digestive function and gastrointestinal health. It exerts regulatory effects on metabolism, making a stable and high fiber content a desirable characteristic in the formulation of animal feed[37] or nutritional supplements.[38]

3.1.6. *pH values of aqueous suspensions of camelina seed cakes*

The pH values of aqueous suspensions of camelina seed cakes varied significantly with the preparation method ($p < 0.001$, $\eta_p^2 = 0.950$). Cakes produced by Soxhlet extraction displayed lower pH values, reflecting a more pronounced acidic character of the suspensions. Conversely, cold-pressed cakes exhibited pH values closer to neutrality (Table 1). These variations likely result from compositional changes induced by the extraction process. Olukomaiya et al.[39] reported that the pH of non-fermented camelina seed cake was approximately 6.07. They observed that fungal fermentation with *Aspergillus* spp. significantly reduced this value through organic acids production. This effect is commonly associated with solid-state fermentation systems.

Overall, the defatting method exerted a more pronounced effect on all analyzed parameters than did the camelina genotype. The most significant genotype effect was observed exclusively in the analysis of crude fat. Cold-pressed camelina seed cakes represented a superior lipid source, whereas cakes produced by Soxhlet extraction proved more suitable for applications requiring elevated protein and mineral contents.

3.2. *Techno-functional properties of camelina seed cakes*

The techno-functional properties of defatted camelina seed cakes from NS Slatka and NS Zlatka genotypes, prepared by Soxhlet extraction and cold pressing, are shown in Table 2.

Table 2

Techno-functional properties of NS Zlatka and NS Slatka seed cakes obtained through Soxhlet extraction and cold pressing

Property	**Soxhlet extraction**		**Cold-pressing**		**Factor**	***p*-value**	η_p^2
	NS Zlatka	**NS Slatka**	**NS Zlatka**	**NS Slatka**			
WAC (%)	699.00 ± 12.43^{d}	573.00 ± 24.56^{c}	502.00 ± 23.13^{b}	428.00 ± 26.54^{a}	G	<0.001	0.883
					M	<0.001	0.957
					G×M	0.078	0.338
OAC (%)	244.00 ± 0.43^{d}	218.00 ± 0.79^{b}	231.00 ± 0.66^{c}	202.00 ± 0.83^{a}	G	<0.001	0.998
					M	<0.001	0.994
					G×M	<0.001	0.636
FC (%)	9.09 ± 0.34^{b}	8.27 ± 0.27^{a,b}	8.76 ± 0.41^{a,b}	8.14 ± 0.25^{a}	G	0.005	0.650
					M	0.253	0.159
					G×M	0.607	0.035
FS (%)	84.00 ± 0.11^{a}	85.00 ± 0.54^{b}	85.00 ± 0.43^{b}	85.00 ± 0.26^{b}	G	0.042	0.424
					M	0.042	0.424
					G×M	0.042	0.424
EA (%)	47.50 ± 0.14^{a}	47.10 ± 0.67^{a}	47.80 ± 0.41^{a}	47.40 ± 0.23^{a}	G	0.136	0.255
					M	0.249	0.162
					G×M	1.000	0.000
ES (%)	101.10 ± 1.31^{a}	101.60 ± 1.27^{a}	100.80 ± 1.37^{a}	100.90 ± 1.12^{a}	G	0.695	0.020
					M	0.518	0.054
					G×M	0.793	0.009

Water Absorption Capacity (WAC), Oil Absorption Capacity (OAC), Foaming Capacity (FC), Foam Stability (FS), Emulsifying Activity (EA), and Emulsion Stability (ES). Different superscript letters (a, b, c, d) in the rows represent statistically significant differences ($p < 0.05$) between the groups according to Tukey's post hoc test. G: Genotype effect; M: Extraction method effect; G×M: Interaction effect between genotype and extraction method. η_p^2: Partial eta squared.

3.2.1. *Water and oil absorption capacity*

Water absorption capacity (WAC) indicates the ability of proteins and other hydrophilic constituents (e.g., mucilage) present in the camelina seed cake matrix[12] to bind and retain water.[40] This characteristic is determined by several factors, including particle size and morphology, protein conformation, surface charge, and the balance between hydrophilic and hydrophobic interactions, along with the presence of residual lipids and carbohydrates.[41] The results demonstrated that both genotype and extraction method significantly influenced WAC values ($p < 0.001$). The effect of extraction method ($\eta_p^2 = 0.957$) was marginally greater than that of genotype ($\eta_p^2 = 0.883$). This pattern remained consistent across genotypes, as no statistically significant G×M interaction was observed. Cakes produced by Soxhlet extraction displayed markedly higher WAC values than those obtained through cold pressing, irrespective of genotype. For both defatting methods, the NS Zlatka genotype consistently exhibited higher WAC values compared with NS Slatka (Table 2). These findings suggest inherent genotype-related differences in protein composition or the presence of additional hydrophilic constituents, including non-starch polysaccharides.

Oil adsorption capacity (OAC), which indicates the ability of proteins to bind with non-polar compounds, is primarily determined by amino acid composition, protein structure, and surface hydrophobicity.[42] Similar to WAC, OAC values varied significantly with both genotype and extraction methods ($p < 0.001$). Given that the G×M interaction was statistically significant ($p < 0.001$, $\eta_p^2 = 0.636$), the extraction method exerted a significant but different effect on OAC values across genotypes. Furthermore, the NS Zlatka genotype consistently exhibited superior OAC relative to NS Slatka, further underscoring the role of genetic background in determining functional properties. Notably, OAC values remained consistently lower than WAC values for all samples, suggesting the predominance of hydrophilic compounds in camelina seed cake. This property indicates a strong affinity for water over oil, which proves advantageous for applications requiring moisture retention and textural enhancement. Owing to the limited availability of literature data on camelina seed cake techno-functional properties, direct comparisons remain scarce. Nevertheless, the WAC value reported by Olukomaiya et al.[39] for non-fermented camelina seed cake (650%) was comparable to the values obtained in this study. Specifically, the Soxhlet-defatted cake of the NS Zlatka genotype displayed approximately 8 % higher WAC, while the remaining samples exhibited lower values. Conversely, OAC values reported by Olukomaiya et al.[39] were nearly two-fold lower than those observed in the present study, suggesting greater availability of hydrophobic amino acid residues for oil binding in the analyzed samples. Overall, the high WAC and OAC of camelina seed cakes, particularly those obtained by Soxhlet extraction, demonstrate their potential as functional ingredients. These characteristics are especially valuable for improving moisture retention and for stabilizing colloidal systems through gel formation.

3.2.2. *Gelling of camelina seed cakes*

Gelation in seed cakes describes the ability to form a gel, a process mediated by the aggregation of denatured protein molecules.[31] Protein denaturation exposes hydrophilic and hydrophobic regions, facilitating interactions among the protein molecules with one another and with cake components, including polysaccharides and lipids. These interactions, which involve disulfide linkages and hydrophobic interactions, serve to stabilize the gel structure and enhance its strength and viscosity. The minimum gelation concentrations determined for camelina seed cakes across various preparation methods are shown in Table 3.

Table 3

Minimum gelation concentrations of camelina seed cakes by genotype and extraction method

Concentration (%, *m/v*)	**NS Zlatka**	**NS Slatka**	**NS Zlatka**	**NS Slatka**
	Soxhlet extraction		**Cold-pressing**	
2	–	–	–	–
4	+	+	+	+
6	++	++	++	++
8	+++	+++	+++	+++
10	+++	+++	+++	+++

– No gel, + Weak gel, ++ Strong gel, +++ Very strong gel

None of the camelina seed cakes analyzed formed gels at a concentration of 2% (m/v). At 4% (m/v), the cakes produced weak gels, whereas at 6% (m/v), they demonstrated strong gelation. Concentrations of 8% (m/v) and 10% (m/v) yielded very strong gels. In all samples examined, the combination of proteins, lipids, polysaccharides, and mucilage exerted a synergistic process, affecting both gel strength and moisture retention capacity. The gel network formation represents a crucial property for various food and industrial applications, where water retention and texture enhancement are essential. Consistent with these findings, Olukomaiya et al.[39] reported a swelling capacity of approximately 4 % for camelina seed cake, further corroborating that camelina seed cakes possess techno-functional properties amenable to gel-forming applications. Tienda-Vazquez et al.[31] isolated proteins from *C. sativa* cake using instant controlled pressure drop (DIC) technology and showed that extraction conditions significantly influenced the gelation properties of the resulting proteins.

3.2.3. *Foaming properties of camelina seed cakes*

Foaming capacity (FC) and foam stability (FS) represent key parameters for evaluating the ability of oil cakes to form and stabilize foams. FC reflects the maximum foam volume generated when the material is subjected to mechanical stress, such as mixing.[4] This property depends primarily on protein structure and the presence of surface-active components within the cake matrix, which facilitate hydrophilic and hydrophobic interactions. FS, by contrast, describes foam's ability to maintain its structure over time, resisting collapse caused by gravitational forces or mechanical stress.[4] Both parameters are critically important for applications in the food industry and biotechnology, where foam formation plays a significant role in processes such as emulsification and product stabilization.

All analyzed camelina seed cakes produced relatively dense foams. FC values ranged from 8.14 % to 9.09 % (Table 2), with the lowest FC observed in the cake derived from NS Slatka genotype via cold pressing. In contrast to the extraction method, genotype exerted a significant effect on FC (p = 0.005). No significant G×M interaction was detected (p = 0.607), suggesting genotype differences remained consistent regardless of extraction method. The FC values obtained were comparable to those reported for camelina seed cake processed using the DIC technology.[31]

The analyzed cakes exhibited high FS values ranging from 84 % to 85 % (Table 2), demonstrating that the formed foams remained largely intact under the testing conditions. Both genotype and extraction method significantly influenced FS (p = 0.042). These high FS values indicate that camelina seed cakes, despite their moderate FC, possess considerable potential for applications requiring prolonged foam integrity, including food emulsions and foaming agents.

In comparison, proteins isolated from camelina seed cake using DIC technology displayed extremely low FS (0.09–2.53 %), as reported by Tienda-Vazquez et al.[31] These values were lower than those obtained in this study, where FS values reached approximately 85 % for all analyzed camelina seed cake samples. This discrepancy likely results from variations in processing intensity and sample composition. Tienda-Vazquez et al.[31] examined isolated proteins and showed that DIC treatment induced significant structural alterations, including marked denaturation and aggregation, which reduced their capacity to form stable interfacial networks.

While isolated proteins may demonstrate good FC, their FS is often limited due to the absence of additional stabilizing components. Conversely, this study investigated whole camelina seed cakes, which constitute complex matrices comprising not only proteins but also dietary fibers and residual lipids. These components act synergistically by increasing continuous phase viscosity and reducing foam liquid drainage, thereby significantly improving FS. Specifically, dietary fibers may contribute to stabilization of the mechanical foam, while residual lipids at low concentrations can strengthen the interfacial film.

Furthermore, the harsh operating conditions of DIC technology, characterized by high pressures and rapid temperature changes, can promote protein aggregation and decrease molecular flexibility, adversely affecting the formation of elastic, resilient films at the air-water interface. By contrast, the milder processing conditions employed in this work preserved the techno-functional properties of the proteins within the natural cake matrix. Overall, these findings demonstrate that both processing intensity and the presence of matrix components play a decisive role in determining FS.

3.2.4. *Emulsifying properties of camelina seed cakes*

The emulsifying properties of camelina seed cakes were evaluated through emulsifying activity (EA) and emulsion stability (ES) (Table 2). EA values averaged approximately 47 %, whereas ES values remained consistently high, exceeding 100%, demonstrating a strong capacity to form and maintain

stable oil-water emulsions. The relatively similar EA values suggest that camelina seed cakes exhibit a moderate but consistent ability to adsorb at the oil-water interface and promote emulsion formation. This behavior primarily resulted from the presence of surface-active proteins that reduced interfacial tension through the exposure of both hydrophilic and hydrophobic domains. The high and comparable ES values observed across all samples underscore the excellent emulsion-stabilizing potential of camelina seed cakes. ES quantifies the capacity of adsorbed proteins to form cohesive and elastic interfacial films that inhibit droplet coalescence and phase separation over time. Two-way ANOVA results revealed that neither genotype nor extraction method significantly affected the emulsifying properties of camelina seed cake (EA and ES values). The observed EA and ES values indicate the potential of camelina seed cakes as functional ingredients in formulations requiring stable emulsion formation and maintenance.

3.3. *Bifunctional properties of camelina seed cakes*

The phenolic profile and antiradical activity of camelina seed cakes were analyzed to assess their biofunctional properties. Total phenolic content (TPC) was quantified using the spectrophotometric Folin–Ciocalteu method, the phenolic profile was characterized by RP-HPLC, and the antiradical activity was evaluated using the DPPH assay.

3.3.1. *Phenolic composition of camelina seed cakes*

Recent research has increasingly emphasized the utilization of natural resources, particularly in the pharmaceutical and food industries. As a result, scientific efforts have focused on investigating under-explored plant species and processing by-products to enable valorization and facilitate potential industrial application. This study examined the phenolic potential of camelina seed cakes, thereby advancing knowledge of their chemical composition as an agricultural by-product.

For camelina seed cakes produced by Soxhlet extraction, TPC measured 0.58 ± 0.09 g GAE/100 g d.m. for the NS Zlatka genotype and 0.57 ± 0.19 g GAE/100 g d.m. for NS Slatka. A comparable pattern emerged in cold-pressing cakes obtained, with TPC values of 0.56 ± 0.11 g GAE/100 g d.m. for NS Zlatka and 0.53 ± 0.13 g GAE/100 g d.m. for NS Slatka. Two-way ANOVA revealed that neither genotype (p = 0.793, η_p^2 = 0.09) nor extraction method (p = 0.695, η_p^2 = 0.02) significantly influenced TPC. Given that the G×M interaction (p = 0.793, η_p^2 = 0.09) was not statistically significant, it was concluded that the extraction method exerted a consistent effect on TPC across both genotypes. The marginally lower values in cold-pressed cakes likely resulted from minor variations in processing conditions.

The TPC values observed in this study agreed with those reported in the literature[43,44] though minor variations were present. These discrepancies may be attributed to differences in genotype, agroecological growing conditions, oil extraction methods, and the specific parameters employed for polyphenol extraction from the cake. Rodríguez-Castillo et al.[45] documented a TPC of approximately 1.575 mg GAE/100 g d.m. in ethanolic extracts of camelina seed cakes defatted using DIC technology, approximately three times higher than the values obtained in this investigation. This marked difference indicates that DIC technology can significantly enhance the availability and extractability of polyphenolic compounds.

RP-HPLC was employed to identify and quantify phenolic compounds in the ethanolic extracts of camelina seed cakes. This analysis detected four phenolic acids, gallic, syringic, caffeic, and sinapic acid, with marked variations in abundance among samples (Table 4). Both genotype and extraction method significantly influenced individual phenolic contents ($p < 0.001$). The G×M interaction proved significant for all compounds except caffeic acid ($p >$ 0.05), which also exhibited the lowest partial η^2 value (η_p^2 = 0.631). This finding indicates that caffeic acid content remained consistent across various genotypes when altering the extraction method.

Gallic acid was detected in all analyzed camelina seed cake samples except in the NS Zlatka genotype following Soxhlet extraction. Conversely, exceptionally high gallic acid content was observed in the same genotype when prepared by cold pressing (140.58 mg/100 g d.m.). A comparable pattern emerged for the NS Slatka genotype, where gallic acid content in the cold-pressed cake (55.87 mg/100 g d.m.) exceeded that of the Soxhlet-extracted cake by severalfold. Syringic acid content proved higher in cold-pressed samples than in those obtained through Soxhlet extraction, ranging from 4.05 mg/100 g d.m. to 21.61 mg/100 g d.m. Caffeic acid ranked among the predominant phenolic compounds in the extracts, with concentrations spanning 10.06 mg/100 g d.m. to 15.68 mg/100 g d.m., with statistically higher values ($p < 0.05$) in cold-pressed samples. Unlike gallic acid, caffeic acid demonstrated greater stability during Soxhlet extraction. Sinapic acid appeared at very low concentrations across genotypes and extraction

methods, though statistically higher levels (p < 0.05) were noted in cold-pressed samples.

Cold-pressed cakes contained higher levels of individual phenolic compounds compared with those produced by Soxhlet oil extraction. The NS Zlatka genotype exhibited markedly higher gallic acid content, whereas NS Slatka displayed higher syringic acid concentrations. These findings confirm that both genotype and extraction method served as key determinants of phenolic compound composition and distribution in camelina seed extracts.

Tavarini et al.[46] reported glucoarabin, glucocamelinin, and quercetin-derived glycosides in an 80% (v/v) methanolic extract of Italian camelina seeds cake following *n*-hexane Soxhlet extraction. The absence of flavonoid glycosides in the present samples may reflect differences in extraction solvent, analytical methodology, genotype, or agroecological growing conditions. Similarly, Kramar et al.[44] identified rutin and other quercetin glycoside derivatives, along with hydroxycinnamic and hydroxybenzoic acids, in ethanolic cake extracts of Ukrainian camelina seed cakes. In contrast to their findings, flavonoid glycosides were not detected in this study, while phenolic acids constituted the dominant polyphenolic group. Nevertheless, the detection of hydroxycinnamic and hydroxybenzoic acids by Kramar et al.[44] aligned with the present results. Caffeic and sinapic acids (hydroxycinnamic acids) and gallic and syringic acids (hydroxybenzoic acids) were identified in all or most samples.

These results suggest that genotype selection coupled with milder processing methods enhances phenolic acid preservation and extraction. Furthermore, these findings advance the understanding of camelina's phenolic composition and underscore its considerable potential as a source of biologically active compounds for food and pharmaceutical applications.

Table 4

Content of major phenolic compounds in ethanolic extracts of camelina seed cakes by genotype and extraction method

Compound	λ [nm]	Rt [min]	Concentration [mg/100 g d.m.]				Factor	*p*-value	η_p^2
			Soxhlet extraction		Cold-pressing				
			NS Zlatka	NS Slatka	NS Zlatka	NS Slatka			
Gallic acid	278	5.38	/	0.86 ± 0.03^a	140.58 ± 0.87^b	55.87 ± 1.03^a	G	<0.001	0.997
							M	<0.001	0.996
							G×M	<0.001	0.980
Syringic acid	278	37.58	4.05 ± 0.09^a	10.20 ± 0.21^c	8.25 ± 0.23^b	21.61 ± 0.54^d	G	<0.001	0.997
							M	<0.001	0.996
							G×M	<0.001	0.980
Caffeic acid	300	30.92	12.23 ± 0.11^b	10.06 ± 0.12^a	15.68 ± 0.31^c	12.54 ± 0.29^b	G	<0.001	0.981
							M	<0.001	0.985
							G×M	0.06	0.631
Sinapic acid	300	51.12	0.180 ± 0.004^a	0.170 ± 0.003^a	0.430 ± 0.011^c	0.370 ± 0.009^b	G	<0.001	0.890
							M	<0.001	0.997
							G×M	<0.001	0.805

Different superscript letters (a, b, c, d) in the rows represent statistically significant differences (p < 0.05) between the groups according to Tukey's post hoc test. G: Genotype effect; M: Extraction method effect; G×M: Interaction effect between genotype and extraction method. η_p^2: Partial eta squared.

3.3.2. *Antiradical activity of camelina seed cakes*

The antiradical activity of camelina seed cake extracts, assessed using the DPPH assay, revealed that all analyzed extracts possessed strong free radical scavenging capacity, with statistically significant differences (p < 0.05) observed between genotype and the cake production method (Table 5).

The lowest IC_{50} values, indicating the highest antiradical activity, were observed in the extracts from cold-pressing camelina seed cakes, particularly for the NS Zlatka genotype (0.080 mg/ml) (Table 5). Conversely, extracts from Soxhlet-extracted cakes

displayed statistically significant, weaker antiradical activity, with the NS Slatka genotype exhibiting the lowest activity (0.198 mg/ml). These results demonstrate that milder extraction conditions enhance the preservation of bioactive compounds responsible for antiradical activity. Furthermore, both genotype and extraction method significantly influenced antiradical activity ($p < 0.001$). A significant G×M interaction was also detected ($p = 0.027$, $\eta_p^2 = 0.475$), suggesting that the effect of extraction method on IC_{50} values differed between genotypes.

Table 5

Half-maximal inhibitory concentration (IC_{50}) of ethanolic extracts of camelina seed cakes determined by DPPH assay

Parameter	**Soxhlet extraction**		**Cold-pressing**		**Factor**	***p*-value**	η_p^2
	NS Zlatka	**NS Slatka**	**NS Zlatka**	**NS Slatka**			
IC_{50} [mg/ml]	0.125 ± 0.010^b	0.198 ± 0.009^c	0.080 ± 0.008^a	0.123 ± 0.011^b	G	<0.001	0.931
					M	<0.001	0.935
					G×M	0.027	0.475

Different superscript letters (a, b, c, d) in the rows represent statistically significant differences ($p < 0.05$) between the groups according to Tukey's post hoc test. G: Genotype effect; M: Extraction method effect; G×M: Interaction effect between genotype and extraction method. η_p^2: Partial eta squared.

Although TPC remained relatively consistent across genotypes and extraction methods (0.53–0.58 g GAE/100 g d.m.), the observed variations in antiradical activity suggested that this activity did not derive solely from phenolic compounds. This effect may also result from γ- tocopherol present in camelina seed cake.[12] Rather, the qualitative composition of the phenolic fraction, specifically the presence and relative abundance of individual phenolic acids, played a critical role in determining antiradical efficacy. In this regard, gallic acid emerged as particularly significant. Its exceptionally high concentration in cold-pressed cakes, especially from the NS Zlatka genotype, substantially contributed to the pronounced antiradical activity observed. Gallic acid is well-documented for its free radical stabilization capacity, which correlates with lower IC_{50} values.[47] Accordingly, samples containing the highest gallic acid content also demonstrated the strongest antiradical activity. Conversely, the reduced antioxidant potential in Soxhlet- extracted samples likely resulted from the absence or markedly lower, concentration of gallic acid, a thermolabile compound susceptible to degradation or reduced extractability under the elevated temperatures and prolonged solvent exposure associated with this method.

Beyond gallic acid, other identified phenolic acids, primarily caffeic and syringic acids, also contributed to overall antiradical activity. While sinapic acid occurred at relatively low concentrations, it may exert synergistic effects when combined with other phenolic acids. These results confirm that camelina seed cake antiradical activity stems from the synergistic action of multiple phenolic compounds. The predominance of hydroxybenzoic and hydroxycinnamic acids in the phenolic profile thus accounts for the pronounced antioxidant potential of the extracts, particularly those from cold-pressed cakes.

Previous investigations have similarly reported a strong correlation between camelina seed cake phenolic content and antiradical activity.[44] Technological or agronomic approaches that increase TPC generally enhance antiradical activity.[45] Moreover, growing conditions and seed genotype have been shown to significantly influence camelina seed cake antiradical activity.[46] Given their TPC and pronounced natural antiradical properties, camelina seed cake extracts represent a promising source of natural antioxidants and reducing agents. These extracts have demonstrated practical applicability, notably in inhibiting biodiesel oxidation, where they reduced the oxidation process by approximately 20 % in acid number compared with pure biodiesel.[44] These results further support the potential valorization of camelina seed cake as a high-value functional raw material, thereby contributing to sustainability and advancing the circular bioeconomy.

4. CONCLUSIONS

The camelina seed cakes obtained proved to be complex raw materials whose nutritional, techno-functional, and biofunctional properties were significantly influenced by both genotype and extraction method ($p < 0.05$). Soxhlet extraction produced cakes with higher protein (approximately 42 %) and ash (about 6 %) contents, along with

enhanced water (573–700 %) and oil (218–244 %) absorption capacities. The characteristics render the cakes suitable for applications requiring improved technological and textural properties. By contrast, cold-pressed cakes retained a higher proportion of residual oil (about 15 %) and contained elevated levels of individual phenolic compounds, particularly gallic acid (140.58 mg/100 g d.m. for the NS Zlatka genotype). This composition directly correlated with their significantly higher antiradical activity (IC_{50} = 0.080 mg/ml). Although total phenolic content (TPC) remained relatively consistent among the examined samples (approximately 0.55 g GAE/100 g d.m.), the pronounced differences in antiradical activity could not be attributed to TPC alone.

The findings demonstrate that camelina seed cake can be strategically modified as a functional raw material for diverse industrial applications, including the food, pharmaceutical, and chemical sectors. Thus, camelina seed cake should not be viewed merely as a by-product of oil production, but rather as a valuable resource. Future research should focus on more detailed, compound-specific analyses using advanced chromatographic techniques. Such approaches would facilitate precise elucidation of individual phenolic compound behavior in relation to genotype and processing conditions, thereby enhancing the understanding of chemical transformations during processing. This knowledge could enable process optimization aimed at selectively enriching the camelina seed cake with target bioactive compounds, thereby increasing both its functional and market value.

Funding. This research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Grant no. 451-03-136/2025-03/200222, 451-03-34/2026-03/200133, and 451-03-136/2025-03/200032) and by the Science Fund of the Republic of Serbia, #17807, The Loess Plateau Margins: Towards Innovative Sustainable Conservation – LAMINATION.

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