Stability of sunflower and rapeseed oil-in-water emulsions supplemented with ethanol-treated rapeseed meal protein isolate

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Abstract A protein isolate (ERPI) was prepared from ethanol-treated rapeseed meal and used as a stabilizing agent in sunflower and rapeseed oil-in-water emulsions. The aim of the current study was to explore the influence of protein and oil concentrations on initial stability of sunflower and rapeseed oil-in-water emulsions by evaluating Gibbs free energy (ΔG) and particle size distribution. The 7-day dynamics of emulsion stability was investigated by turbidity measurement as well. A 3^2 factorial design was applied to assess the significance of oil (5%, 10% and 15% w/w) and ERPI protein (0.25%, 0.5% and 1.0% w/w) addition on stability of the emulsions. The results demonstrated that the increase of oil concentrations from 5 to 15% positively influenced the initial stability of sunflower and rapeseed oil-in-water emulsions. In both oil types, ERPI protein supplementation at all levels resulted in significant differences in the stability of 5% and 10% oil emulsions but did not alter the initial stability of the emulsions prepared with either 15% sunflower or rapeseed oil. With a few exceptions, there was a good agreement between Gibbs

free energy data and microstructural profiles of the emulsions. Overall, emulsions with all sunflower oil concentrations and 1.0% ERPI protein exhibited better initial and a 7-day stability dynamics compared to all rapeseed oil-based emulsions. The study demonstrated the potential of ethanol-treated rapeseed meal protein isolate to serve as an emulsifying agent in sunflower and rapeseed oil containing emulsions.

Keywords Ethanol-treated rapeseed meal protein isolate · Gibbs free energy · Stability dynamics · Sunflower oil-in-water emulsion · Rapeseed oil-in-water emulsion

Introduction

Currently, rapeseed crop is intended for the production of vegetable oil. Rapeseed meal, the remaining by-product of the process, is generated in significant amounts which may reach more than 50% of the mass of the seeds (Kreps et al. 2014). It is mainly used as a feed ingredient, but only at limited inclusion levels due to high fiber and antinutrient contents (Nega and Woldes 2018). Although the rapeseed meal has been indicated by Tan et al. (2011) as suitable raw material for preparation of protein-rich ingredients for food industry, the high concentrations of glucosinolates and polyphenols may remain as a part of the final product and thus impact negatively its nutritive quality and functional properties (Das Purkayastha et al. 2014). To increase the applicability of this by-product, Liu et al. (1994) suggested a pre-treatment of the rapeseed meal aiming at reduction of antinutrients. By using a 4-step extraction of rapeseed meal with 75% ethanol aqueous solution, Adem et al. (2014) obtained a rapeseed meal concentrate with sufficiently reduced antinutrients to partially replace a fish meal in

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diets for rainbow trout, turbot, common carp and wels catfish. However, it should be noted that due to denaturing and solvating effect of the reagent, ethanol-based antinutrient reduction may affect protein characteristics and alter techno-functional profile of protein-rich products prepared from the ethanol-treated rapeseed meal (Kalaydzhiev et al. 2019a). Shevkani et al. (2014a) reported altered physicochemical, pasting and functional properties of amaranth flours from six cultivars after lipid removal with hexane. Since processing treatment of plant materials or environmental growth conditions highly influence protein characteristics, their impact should be considered when the protein-rich sources are further used for the preparation of functional ingredients for the food industry (Shevkani et al. 2014b, 2015a, b).

Oil-in-water emulsions are frequently used in food production. Along with corn and olive oils, sunflower and rapeseed oils are among the most consumed edible plant oils worldwide and more specifically at Eastern Mediterranean region (Konuskan et al. 2019). Due to their relatively high thermal and storage stability, sunflower and rapeseed oils are preferred constituents of mayonnaise, salad dressings and margarines.

Oil-in-water emulsions are comprised of two immiscible liquids, oil and water, and addition of an emulsifier is needed to provide stability for a desired shelf life and physicochemical properties of the product. Plant proteins have been shown to possess sufficient emulsifying capacity and, as a consequence, are efficiently used in food formulation for stabilizing oil-in-water emulsions (Nikiforidis et al. 2014; Ghumman et al. 2016; Singh et al. 2016). Due to their amphiphilic nature, proteins tend to rapidly adsorb and rearrange at the oil/water interface. They form a viscoelastic film over oil droplets, which enhances the repulsive steric forces between oil droplets, thus providing relatively high stability of the emulsions (Nikiforidis et al. 2014). The potential of protein isolates/concentrates, prepared from rapeseed and canola meals, as emulsifiers is described in detail by Aider and Barbana (2011), Tan et al. (2011), Wanasundara et al. (2016) and Campbell et al. (2016). However, suitability of oil-in-water emulsions prepared with an ethanol-treated industrial rapeseed meal protein isolate as an emulsifying agent has not yet been evaluated.

In our laboratory, ethanol-treated rapeseed meal was used as a source for concomitant production of two protein-containing products, namely a protein isolate and an acid soluble protein-rich ingredient. While the later exhibited high foamability and thermal stability (Ivanova et al. 2018), the protein isolate was distinctive by its emulsifying properties (Kalaydzhiev et al. 2019b). The aim of the current study was to explore the influence of protein and oil concentrations on initial stability of sunflower and rapeseed

oil-in-water emulsions by evaluating Gibbs free energy (ΔG) and particle size distribution. The 7-day dynamics of emulsion stabilities was investigated by turbidity measurement as well.

Materials and methods

Material

Ethanol-treated rapeseed meal protein isolate (ERPI) was prepared from industrially produced rapeseed meal after treatment with ethyl alcohol (Ivanova et al. 2017). Cooking grade sunflower and rapeseed oils, used in the study, were bought from a local store. All remaining reagents were of analytical grade.

Preparation of the model food emulsions

Sunflower and rapeseed oils were used for the preparation of model food emulsions. For each of the two types of oil, the study was carried out using a 3^2 factorial design to assess the significant effect of two variables, oil concentration (5%, 10% and 15% w/w) and protein concentration (0.25%, 0.5% and 1.0% w/w), on stability of oil-in-water emulsions. The protein concentrations were achieved by the addition of ERPI containing 86.86% crude protein (Ivanova et al. 2017). All emulsions were prepared in a phosphate buffer (100 mM, pH 6) and constant homogenization at 1000 rpm (ISOLAB Laborgeräte GmbH, Germany) for 2 min. Sodium benzoate (0.5% w/w) and potassium sorbate (0.1% w/w) were added as preservatives to simulate food systems and minimize microbial development.

Evaluation of Gibbs free energy (ΔG , kJ/mol)

Gibbs free energy was calculated by the following equation:

$$\Delta G = -RT \ln K \quad (1)$$

where R is the universal gas constant ($R = 8.314 \text{ J/(K mol)}$) and T is the absolute temperature (K). The equilibrium constant K was experimentally established by using the so called “dilution method” as described by Kendrow et al. (2009). For this purpose, serial dilutions of each emulsion with increasing bulk concentrations from 0.2 to 1.0% (v/v), with an increment of 0.2, were prepared and their absorbance measured at 350 nm by using an UV/Vis spectrophotometer (1000E, Pharmacia Biotech UltroSpec, Cambridge, UK). The wavelength of measurement for each emulsion was preliminary established as the wavelength associated with maximum absorption in a

spectrum generated after scanning the absorbance of 0.2% emulsion (v/v bulk concentration) from 350 to 850 nm with a wavelength path of 25 nm. The equilibrium constant K was determined as the slope of the plot.

Image analysis

Microstructural characteristics of the emulsions were determined within 5 min of emulsion preparation by using digital image processing as previously described (Ivanova et al. 2018).

Evaluation of emulsion stability by turbidity measurement

Emulsions were stored at room temperature (23 ± 0.2 °C) and their stability was evaluated during a 7-day period with a 2-day increment by measuring emulsion turbidity (Ly et al. 2008). Unstable emulsions tend to form a relatively clear serum layer at the bottom of the tube, due to upward movement of oil droplets. An aliquot of 0.2 ml from the bottom part of an emulsion was pipetted and diluted in a 100-ml volumetric flask with a phosphate buffer (100 mM, pH 6). The turbidity was measured at 350 nm against a control not containing oil and ERPI. The emulsion stability was evaluated by changes in sample turbidity relative to initial turbidity of the sample at room temperature (23 ± 0.2 °C) and multiplied by 100 to express in percent. The decrease in turbidity (%) was used as an indicator for instability of the emulsions.

Statistical analyses

Statistical analyses were performed by using Statistica® 6.0 (StatSoft, USA). Results are presented as means of at least three independent determinations $\pm$ standard deviation (SD). Mean differences were established by Fisher's least significant difference test for paired comparison with a significance level $\alpha = 0.05$.

Results and Discussion

Gibbs free energy

Gibbs free energy and microstructure of the emulsions were determined within 5 min of their preparation in an attempt to relate the initial stability of the systems to the stability observed during a 7-day period evaluated by turbidity alteration. The “dilution method”, used in the study, is a well-established approach for the estimation of equilibrium constant K (Singh et al. 1993; Bayrak 2004; Zheng et al. 2007), which is an important characteristic of the

interface composition determining the formation and stability of the emulsions (Mehta and Kaur 2011). As shown in Eq. 1, at a fixed temperature, ΔG is determined by the value of the equilibrium constant K and therefore, this parameter could be used as an indicator for the stability of the emulsions. Thermodynamically, the negative values of ΔG describe spontaneous formation of the emulsions. As Mehta and Kaur (2011) postulated, the higher the negative value of ΔG , the more stable emulsions are. In the present study, the increase of oil concentrations enhanced the stability of the emulsions as evidenced by the increase of the negative values of ΔG (Table 1). Positive effect of soybean oil concentration increase on stability of emulsions containing soybean protein isolate or casein as emulsifying agents was observed by Cortés-Muñoz et al. (2009), Gandova and Balev (2016) and Hebishy et al. (2017). Our data agreed with those reported by Al-Malah et al. (2000), who used a conductivity technique to investigate the stability of oil-in-water emulsions with bovine serum albumin (BSA) as an emulsifying agent. They observed that the increase of oil volume fraction from 0.25 to 0.56 (v/v) increased the stability of the all four emulsions prepared either with corn, olive, soybean or sunflower oils. However, no clear trend of the effect of BSA concentration enhancement on the emulsions stability was reported.

In current study, ERPI supplementation affected significantly ΔG at low oil concentrations (5% and 10%) but not of the emulsions prepared with either 15% sunflower or rapeseed oils (Table 1). According to Guo and Mu (2011), increased oil concentration may impede protein diffusion and decrease the adsorption rate of the proteins at the oil/water interface making the protein concentration enhancement inefficient. Hebishy et al. (2017) observed a linear decrease of whey protein isolate surface concentration on oil droplets of emulsions prepared with a colloid mill in response to increasing sunflower and olive oil concentrations from 10 to 50%.

While ERPI addition could be minimized by combining with 15% oil in both types of oil-in-water emulsions, a better stability of the emulsion, prepared with 5 or 10% sunflower oil, could be achieved by providing relatively high ERPI protein concentration (Fig. 1a). In contrast, when using 5 or 10% rapeseed oil for preparing emulsions, low ERPI protein concentrations were needed to achieve more negative values of ΔG (Fig. 1b). In addition, the initial stabilities of 5% and 10% rapeseed oil-in-water emulsions were lower than those prepared with 5% and 10% sunflower oil as indicated by the smaller negative values of the Gibbs free energy (ΔG , Table 1). These results implied a possible effect of the oil type. It might be attributed to differences in oil composition and the specificities of the interaction between lipid molecules and proteins, although more experiments are needed to explain

Table 1 Influence of oil and ERPI protein concentrations on Gibbs free energy (ΔG)

Nº sample	Oil type	Oil concentration (%)	ERPI protein concentration (%)	ΔG (kJ/mol)
1	Sunflower oil	5	0.25	-2.86 ± 0.05^a
2		5	0.5	-3.95 ± 0.03^c
3		5	1.0	-3.18 ± 0.00^b
4		10	0.25	-3.67 ± 0.05^a
5		10	0.5	-4.22 ± 0.00^b
6		10	1.0	-4.14 ± 0.05^b
7		15	0.25	-4.55 ± 0.00^a
8		15	0.5	-4.64 ± 0.03^a
9		15	1.0	-4.63 ± 0.03^a
1	Rapeseed oil	5	0.25	-2.36 ± 0.03^b
2		5	0.5	-2.31 ± 0.02^b
3		5	1.0	-1.63 ± 0.55^a
4		10	0.25	-3.49 ± 0.05^b
5		10	0.5	-3.47 ± 0.01^b
6		10	1.0	-3.26 ± 0.04^a
7		15	0.25	-4.40 ± 0.42^a
8		15	0.5	-4.35 ± 0.41^a
9		15	1.0	-4.48 ± 0.01^a

^{a–c}Means in a column for a specific oil concentration with different lowercase letters differ significantly ($p \leq 0.05$)

the exact mechanisms. Taha et al. (2018) established that the content of adsorbed soybean protein in oil-in-water emulsions, containing medium-chain triglycerides and long chain triglycerides (palm, soybean and rapeseed oils), differed significantly. The same authors noted that medium-chain triglyceride emulsions contained thickest protein membrane around oil droplet that may explain why in this present study higher protein concentrations (0.5% and 1.0%) were needed for achieving more negative ΔG values of 5 and 10% sunflower oil-in-water emulsions. As established by Konuskan et al. (2019), sunflower oil contains medium-chain fatty acids (C_{16} to C_{18}) in higher amounts than rapeseed oil. Taha et al. (2018) also suggested that lower molecular weight of the medium-chain triglycerides reduced more efficiently interfacial tension, thus contributing better for formation of a stable emulsion which might partially explain the higher negative values of ΔG , respectively the better stability of sunflower oil-in-water emulsions for all levels of oil and ERPI supplementations in present study (Table 1). Zorba and Kurt (2008) also observed dependence of selected meat emulsifying capacity and emulsion stability on the type of the plant oils used. According to McClements (2016), diversity of the physicochemical properties (viscosity, solubility, interfacial tension) of the oil kinds affects emulsion characteristics and their stability as a consequence.

Emulsions microstructure

Microstructure profiles of all emulsions studied revealed monomodal lipid particle size distribution (Fig. 2 and 3). Small globules, ranging from 1 to 4.99 μm , prevailed in the emulsions indicating relatively high stability. Fernández-Ávila et al. (2015) attributed the physical stability of soybean oil-in-water emulsions containing either 10% or 20% oil and 4% soy protein isolate to the small size globules (3.2 μm) achieved after homogenization. According to Hebishy et al. (2017), small size droplets and homogeneous distribution in size facilitate protein adsorption on lipid droplets which in turn prevents their coalescence and destabilization. With the exception of emulsions prepared with 15% rapeseed oil (Fig. 3), there was a good agreement between initial emulsion stability, evaluated by Gibbs free energy, and emulsion microstructure. Microstructural profiles of sunflower oil-in-water emulsions containing 5% and 10% oil (Fig. 2) and ERPI at 0.5% and 1.0% protein concentrations demonstrated higher portion of small size particles (1–4.99 μm) and more uniform distribution of lipid globules. High similarity in the microstructural profiles of the three emulsions prepared with 15% sunflower oil, but with different ERPI protein concentrations, was observed (Fig. 2), which is in agreement with Gibbs free energy of the emulsions prepared with this type of vegetable oil (Table 1). With respect to rapeseed oil, microstructural analyzes confirmed the higher initial stability of the emulsions prepared with 5% and 10% oil

Fig. 1 Combined effect of oil and protein concentrations on sunflower oil-in-water (a) and rapeseed oil-in-water (b) emulsion Gibbs free energy (ΔG)

(Fig. 3) when supplemented with smaller protein concentrations (0.25% and 0.5%). However, no agreement between Gibbs free energy and microstructural profiles of emulsions prepared with 15% rapeseed oil and different ERPI concentrations was observed (Fig. 3, Table 1). While Gibbs free energy of the three emulsions did not differ significantly ($p < 0.05$) (Table 1), microstructural profiles showed different prevalence of the globules, sizing 1–4.99 μm , and particle distribution in size (Fig. 3). Data showed that the 15% rapeseed oil-in-water emulsion supplemented with 1% ERPI protein was the most stable one as indicated by the high percentage of small lipid particles (72%) and high homogeneity in the size of the droplets. In contrast, Gibbs free energy analysis did not demonstrate significant influence of ERPI concentrations on the initial

stability of 15% rapeseed oil-in-water emulsions. Discrepancies between microstructural features and rheological characteristics of decane/water emulsions stabilized with β -casein were observed by Figueiredo et al. (2008). According to them, interactions between protein and lipid molecules at the interface do not always reflect droplet morphology, since the phenomenon is highly influenced by both physicochemical properties and concentrations of the oil and the protein used as a stabilizing agent. Still, more experiments are needed to clarify the discrepancy in the stability of the emulsions at 15% rapeseed oil evaluated by Gibbs free energy and microstructural analyzes.

Fig. 2 Lipid particle size distribution of emulsions prepared with 5%, 10% and 15% sunflower oil and different ERPI protein concentrations (0.25%, 0.5% and 1.0%)

Dynamics of emulsion stability

Emulsion stability along time is a very important technological characteristic, since it influences organoleptic properties of food products during storage and, as a consequence, customers' sensorial perception (McClements 2007). Being amphiphilic compounds, proteins are able to adsorb at oil/water interface and develop viscoelastic layer surrounding lipid droplets, which is expected to prevent flocculation and coalescence during long-term storage (Hebshy et al. 2017). In present study, emulsions were prepared and characterized at pH 6 to evaluate potential applicability of ERPI supplementation in low acidic type foods, such as milk, meat and bakery products (McGlynn 2003; Wanasundara et al. 2016). Data in Fig. 4 clearly demonstrated superior stability of sunflower oil-in-water emulsions at all oil concentrations when supplemented with 1.0% ERPI protein for the entire 7-day period at ambient temperature. A 34% decrease in turbidity was observed at the end of the study. With the exception for the 5% oil emulsion, these findings corresponded to the initial

Fig. 3 Lipid particle size distribution of emulsions prepared with 5%, 10% and 15% rapeseed oil and different ERPI protein concentrations (0.25%, 0.5% and 1.0%)

stability evaluated by Gibbs free energy (Table 1) and microstructural profiles (Fig. 2). At 15% sunflower oil-in-water emulsions, however, the stability dynamics of the samples supplemented at the three protein concentration levels differed, regardless of the similarity in microstructural profiles (Fig. 2) and statistically same ΔG values (Table 1). The observed stability dynamics is better than the ones reported for the oil-in-water beverage emulsions, stabilized with polysaccharides, where the turbidity at day 7 decreased more than 70% (Mikkonen et al. 2009).

At each oil concentration, rapeseed oil-in-water emulsions prepared with different ERPI protein concentrations exhibited similar trend in dynamics of the emulsion stability, as evidenced by turbidity alteration (Fig. 5). However, in contrast to sunflower oil-based emulsions, increase in rapeseed oil concentration resulted in emulsions with higher emulsion stability over the entire period studied. As shown in Fig. 5, the 15% rapeseed oil emulsion was the most stable with a decrease in turbidity of 40% at day 7, followed by 10% and 5% rapeseed oil emulsions with decrease in turbidity of 46% and 54%, respectively.

Fig. 4 Stability dynamics of emulsions prepared with 5%, 10% and 15% sunflower oil and different ERPI protein concentrations (0.25%, 0.5% and 1.0%). The averages are based on three independent measurements. Standard deviations do not exceed 0.36

Fig. 5 Stability dynamics of emulsions prepared with 5%, 10% and 15% rapeseed oil and different ERPI protein concentrations (0.25%, 0.5% and 1.0%). The averages are based on three independent measurements. Standard deviations do not exceed 0.28

Compared to sunflower oil-in-water emulsions prepared with 1.0% ERPI protein (Fig. 4), all rapeseed oil emulsions were less stable at day 7, as evidenced by the higher decreases in turbidity (Fig. 5). The better stability of the emulsions, containing sunflower oil, might be due to the prevalence of medium-chain fatty acids and lower viscosity of the same compared to rapeseed meal oil (Diamante and Lan 2014; Konuskan et al. 2019). According to Molet-Rodríguez et al. (2018), vegetable oils with such physico-chemical characteristics are more efficient in formation of stable emulsions. Data suggest that sunflower oil combined with 1.0% ERPI protein is more applicable for the production of foods where emulsion stability is needed for a longer period. In addition, the different pattern in the stability of sunflower and rapeseed oil-in-water emulsions implies a lack of a uniform trend in oil and protein concentration significance and a need of a separate investigation when oils and proteins different from those used in the study are to be used for food production.

Conclusion

The results from this study demonstrated that the increase of oil concentrations from 5 to 15% positively influenced the initial stability of sunflower and rapeseed oil-in-water emulsions. In both oil types, ERPI protein supplementations (0.25%, 0.5%, and 1.0%) resulted in significant differences in the stability of 5% and 10% oil emulsions but did not alter the initial stability of the emulsions prepared with either 15% sunflower or rapeseed oil. With a few exceptions, there was a good agreement between Gibbs free energy data and microstructural profiles of the emulsions. Overall, there was a correspondence between initial stability of the emulsions and their 7-day dynamics. However, it should be noted that some divergences can be expected depending on oil type and concentrations. Most probably, the different pattern in the stability of sunflower and rapeseed oil-in-water emulsions is due to differences in the oil composition and the specificities of the interaction between lipid molecules and proteins. The emulsions at all

sunflower oil concentrations supplemented with 1.0% ERPI protein exhibited better initial and a 7-day stability dynamics compared to all rapeseed oil-based emulsions. Therefore, these types of emulsions could be used for the production of foods that need a longer storage. The study demonstrated the potential of ethanol-treated rapeseed meal protein isolate to serve as an emulsifying agent in sunflower and rapeseed oil containing emulsions in low acidic type foods. However, since emulsions stability and applicability in food processing depend on multiple factors, additional studies involving different pH values, salt concentrations, types of homogenization and longevity might be performed to complete the emulsifying profile of the protein isolate prepared from ethanol-treated industrial rapeseed meal.

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References

- Adem HN, Tressel R, Pudiel F, Slawski H, Schulz C (2014) Rapeseed use in aquaculture. *OCL* 21(1):D105–D113
- Aider M, Barbana C (2011) Canola proteins: composition, extraction, functional properties, bioactivity, applications as a food ingredient and allergenicity: a practical and critical review. *Trends Food Sci Technol* 22:21–39
- Al-Malah KI, Azzam MOJ, Omari RM (2000) Emulsifying properties of BSA in different vegetable oil emulsions using conductivity technique. *Food Hydrocoll* 14:485–490
- Bayrak Y (2004) Interfacial composition and formation of w/o microemulsion with different amphiphiles and oils. *Colloids Surf Physicochem Eng Aspects* 247:99–103
- Campbell L, Rempel CB, Wanasundara JPD (2016) Canola/Rapeseed protein: future opportunities and directions: workshop proceedings of IRC 2015. *Plants* 5:17–23
- Cortés-Muñoz M, Chevalier-Lucia D, Dumay E (2009) Characteristics of submicron emulsions prepared by ultra-high pressure homogenisation: effect of chilled or frozen storage. *Food Hydrocoll* 23:640–654
- Das Purkayastha M, Gogoi J, Kalita D, Chattopadhyay P, Nakhuru KS, Goyary D, Mahanta CL (2014) Physicochemical and functional properties of rapeseed protein isolate: influence of antinutrient removal with acidified organic solvents from rapeseed meal. *J Agric Food Chem* 62:7903–7914
- Diamante LM, Lan T (2014) Absolute viscosities of vegetable oils at different temperatures and shear rate range of 64.5 to 4835 s⁻¹. *J Food Process*. <https://doi.org/10.1155/2014/234583>
- Fernández-Ávila C, Escrivá R, Trujillo AJ (2015) Ultra-high pressure homogenization enhances physicochemical properties of soy protein isolate-stabilized emulsions. *Food Res Int* 75:357–366
- Figueiredo EN, Arêas J, Arêas PG (2008) Rheology of decane/water and triglyceride/water emulsions stabilized by β -casein and sodium caseinate. *J Braz Chem Soc* 19(7):1336–1346
- Gandova V, Balev D (2016) Properties of emulsions based in soybean oil stabilized by different proteins. *Int J Inn Sci Eng Technol* 3:293–297
- Ghumman A, Kaur A, Singh N (2016) Functionality and digestibility of albumins and globulins from lentil and horse gram and their effect on starch rheology. *Food Hydrocoll* 61:843–850
- Guo Q, Mu TH (2011) Emulsifying properties of sweet potato protein: effect of protein concentration and oil volume fraction. *Food Hydrocoll* 25:98–106
- Hebishi E, Zamora A, Buffa M, Blasco-Moreno A, Trujillo A (2017) Characterization of whey protein oil-in-water emulsions with different oil concentrations stabilized by ultra-high pressure homogenization. *Processes* 5:6. <https://doi.org/10.3390/pr5010006>
- Ivanova P, Kalaydzhev H, Rustad T, Silva CLM, Chalova VI (2017) Comparative biochemical profile of protein-rich products obtained from industrial rapeseed meal. *Emir J Food Agric* 29:170–178
- Ivanova P, Kalaydzhev H, Dessev TT, Silva CL, Rustad T, Chalova VI (2018) Foaming properties of acid-soluble protein-rich ingredient obtained from industrial rapeseed meal. *J Food Sci Technol* 55:3792–3798
- Kalaydzhev H, Ivanova P, Stoyanova M, Pavlov A, Rustad T, Silva CLM, Chalova VI (2019a) Waste biomass valor. <https://doi.org/10.1007/s12649-018-00553-1>
- Kalaydzhev H, Ivanova P, Silva CLM, Chalova VI (2019b) Functional properties of protein isolate and acid soluble protein-rich ingredient co-produced from ethanol-treated industrial rapeseed meal. *Pol J Food Nutr Sci* 69:129–136
- Kendrow C, Baum JC, Marzzacco CJ (2009) Investigating the thermodynamics of charge-transfer complexes. A physical chemistry experiment. *J Chem Educ* 86:1330
- Konuskan DB, Arslan M, Oksuz A (2019) Physicochemical properties of cold pressed sunflower, peanut, rapeseed, mustard and olive oils grown in the Eastern Mediterranean region. *Saudi J Biol Sci* 26:340–344
- Kreps F, Vrbíková L, Schmidt Š (2014) Industrial rapeseed and sunflower meal as source of antioxidants. *Int J Eng Res Appl* 4:45–54
- Liu Y, Zhou M, Liu M (1994) A survey of nutrients and toxic factors in commercial rapeseed meal in China and evaluation of detoxification by water extraction. *Anim Feed Sci Technol* 45:257–270
- Ly MH, Aguedo M, Goudot S, Le M, Cayot P, Teixeira J, Le T, Belin J, Waché Y (2008) Interactions between bacterial surfaces and milk proteins, impact on food emulsions stability. *Food Hydrocoll* 22:742–751
- McClements DJ (2007) Critical review of techniques and methodologies for characterization of emulsion stability. *Crit Rev Food Sci Nutr* 47:611–649
- McClements DJ (2016) Food emulsions: principles, practices, and techniques. CRC Press, Boca Raton
- McGlynn WG (2003) The importance of food pH in commercial canning operations. Division of Agricultural Sciences and Natural Resources, Oklahoma State University, Oklahoma Cooperative Extension Service, Stillwater
- Mehta SK, Kaur G (2011) Microemulsions: thermodynamic and dynamic properties. In: Tadashi M (ed) *Thermodynamics*. Intech Open, Rijeka, pp 381–406
- Mikkonen KS, Tenkanen M, Cooke P, Xu C, Rita H, Willför S, Holmbom B, Hicks KB, Yadav MP (2009) Mannans as stabilizers of oil-in-water beverage emulsions. *LWT Food Sci Technol* 42:849–855
- Molet-Rodríguez A, Salvia-Trujillo L, Martín-Belloso O (2018) Beverage emulsions: key aspects of their formulation and physicochemical stability. *Beverages* 4:70–80
- Nega T, Woldes Y (2018) Review on nutritional limitations and opportunities of using rapeseed meal and other rape seed by-products in animal feeding. *J Nutr Health Food Eng* 8:43–48

- Nikiforidis CV, Matsakidou A, Kiosseoglou V (2014) Composition, properties and potential food applications of natural emulsions and cream materials based on oil bodies. *RSC Adv* 4:25067–25078
- Shevkani K, Singh N, Kaur A, Rana JC (2014a) Physicochemical, pasting, and functional properties of amaranth seed flours: effects of lipids removal. *J Food Sci* 79:C1271–C1277
- Shevkani K, Singh N, Rana JC, Kaur A (2014b) Relationship between physicochemical and functional properties of amaranth (*Amaranthus hypochondriacus*) protein isolates. *Int J Food Sci Technol* 49:541–550
- Shevkani K, Singh N, Kaur A, Rana JC (2015a) Structural and functional characterization of kidney bean and field pea protein isolates: a comparative study. *Food Hydrocoll* 43:679–689
- Shevkani K, Kaur A, Kumar S, Singh N (2015b) Cowpea protein isolates: functional properties and application in gluten-free rice muffins. *LWT Food Sci Technol* 63:927–933
- Singh HN, Prasad D, Kumar S (1993) Water solubilization in microemulsions containing amines as cosurfactant. *J Am Oil Chem Soc* 70:69–73
- Singh JP, Kaur A, Singh N (2016) Development of eggless gluten-free rice muffins utilizing black carrot dietary fibre concentrate and xanthan gum. *J Food Sci Technol* 53:1269–1278
- Taha A, Hu T, Zhang Z, Bakry AM, Khalifa I, Pan S, Hu H (2018) Effect of different oils and ultrasound emulsification conditions on the physicochemical properties of emulsions stabilized by soy protein isolate. *Ultrason Sonochem* 49:283–293
- Tan SH, Mailer RJ, Blanchard CL, Agboola SO (2011) Canola proteins for human consumption: extraction, profile, and functional properties. *J Food Sci* 76:R16–R28
- Wanasundara JPD, McIntosh TC, Perera SP, Withana-Gamage TS, Mitra P (2016) Canola/rapeseed protein-functionality and nutrition. *OCL* 23:D407–D422
- Zheng O, Zhao J, Yan H, Gao S (2007) Dilution method study on the interfacial composition and structural parameters of water/C12–EO_x–C12:2Br/n-hexanol/n-heptane microemulsions: effect of the oxyethylene groups in the spacer. *J Colloid Interface Sci* 310:331–336
- Zorba Ö, Kurt Ş (2008) The effects of different plant oils on some emulsion properties of beef, chicken and turkey meats. *Int J Food Sci Technol* 43:229–236

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