Phenolics against the Oxidation of o/w Emulsions

Subjects: Chemistry, Physical
Contributor: Sotirios Kiokias, Vassiliki Oreopoulou

Lipid oxidation is a serious problem for scientists since it adversely affects the product quality in the food, cosmetic, and pharmaceutical sectors.

Keywords: antioxidants ; phenolics ; emulsions

1. Introduction

Lipid oxidation is a serious problem for scientists since it adversely affects the product quality in the food, cosmetic, and pharmaceutical sectors [1]. Many common food products exist as oil-in-water (o/w) emulsions including beverages, dressings, sauces, soups, and desserts [2]. One of the main causes of the quality deterioration of these products is the oxidation of lipids [3]. The degradation of unsaturated lipids can lead to off-flavors, decreases the nutritional profile of foods, and may eventually generate toxic products [4]. In emulsified foods, lipid oxidation can occur rapidly due to their large surface area, with mechanisms that are more complex and not fully understood compared to bulk oils [5][6]. As a consequence, the food industry faces a serious problem due to the low oxidative stability of emulsified systems, which adversely impacts consumer safety and the economic viability of the products [7]. A better understanding of the endogenous and exogenous factors that monitor the microstructural and oxidative stability of food emulsions would help to maintain their desirable functional and sensory properties during the formulation, processing, and storage of relevant products [8]. In addition, emulsion systems generally mimic the amphiphilic nature of important biological membranes (such as lipoproteins) that are prone to oxidative degradation when attacked by singlet oxygen and free radicals [9]. This biochemical process eventually links to the development of serious human health conditions, such as aging, carcinogenesis, and cardiovascular diseases [10].

Over the last few years, there is a steady food market trend for the use of natural antioxidants, as a common strategy to slow down lipid oxidation in emulsified foods, increase their shelf life, and minimize bad odors [11][12]. A body of recent research [13][14] focuses on nano-emulsions that are increasingly used in various products in order to incorporate easily degradable bioactive compounds, protect them against oxidation, and enhance their bioavailability. In manufactured products (quite often heterogeneous systems containing lipids as emulsions or bulk phase) the efficiency of an antioxidant is determined not only by its chemical reactivity, but also by its physical properties and its interaction with other compounds present in the products [15].

With the term phenolics, researchers refer to a wide class of natural compounds (e.g., tocopherols, flavonoids, phenolic acids) with varying structures and antioxidant properties [16]. The application of phenolic compounds in various commercial products has attracted an increasing level of interest over the last few years from researchers in the food, pharmaceutical, and nutraceutical industries [17]. It is true, though, that certain structural characteristics (including the hydrophobic character of many phenolics) may affect their integration into real products as well as their general biological activities and their bio-absorption in human organisms [18]. Their potential to act as functional ingredients upon their addition in bulk or emulsified oils has been an area of emerging scientific interest in the last decade [19][20][21]. A few researchers in this field have focused on phenolic acids, their activity, health effects, and extraction from natural plant sources [21][22][23]. Phenolic acids are classified as hydroxybenzoic and hydroxycinnamic acids, and, depending on their structure, may present solubility in water or lipids, thus enabling their use in many products [7][14][24].

2. Overview of Studies Reporting on the Effect of Phenolics against the Oxidation of o/w Emulsions

Although most of the studies on phenolic antioxidants so far have focused on bulk oils, a body of recent research has examined the activity of various phenolic compounds in food-related o/w emulsions. In emulsified systems, the initial step of lipid oxidation takes place at the interface between the oil and water phases. Over the last few years, an increasing number of researchers have reported well-documented antioxidant activities of naturally occurring phenolics in o/w model systems [19][25].

Tocopherols are a class of natural compounds with a high nutritional value in the human diet because of their vitamin E activity. In addition, various authors have reported their well-established antioxidants activity in vitro (oil model systems) and in vivo (human clinical trials) [26][27]. Wang et al. [28], following oxidation experiments of flaxseed o/w emulsions, have noted a higher antioxidant efficiency of δ-tocopherol compared to α-tocopherol. The authors linked the superior activity of δ-tocopherol to its enhanced distribution in the interfacial area of the emulsion system. Another similar study—based on the autoxidation of shrimp o/w emulsions under storage at room temperature did not report any protective effect of α-tocopherol against oxidative destabilisation [29]. On the contrary, α-tocopherol when combined with chitooligosaccharides (at both 0.2 and 0.4 g/L concentrations) significantly delayed the oxidation process, in terms of both primary (conjugated dienes) and secondary (TBARs) oxidation products indicators [29]. Barouh et al. [15] further explored the activity of tocopherols in bulk oils and emulsion systems as a function of various physicochemical parameters (including their interaction with specific emulsifiers such as Tween 65, Tween 80, whey proteins, etc.).

Flavonoids comprise another class of widespread phenolic compounds with well-established antioxidant properties strongly related to their structure [30][31]. Common plant flavonoids such as quercetin, rutin, and hesperitin prolong the shelf life of o/w emulsions by retarding the oxidative deterioration and improving physical stability. However, only quercetin retained its antioxidant activity in the presence of ferric ions due to its structural configuration (3′4′ dihyrdoxy substitution of B ring and the presence o 3-OH) [32]. In fact, quercetin seems to be one of the most potent contributors to the antioxidant activity of plant extracts in emulsions [33]. However, quercetin has been reported to exert a pro-oxidant character in pure lipids and antioxidant activity in emulsions due to its hydroxyl group in position-3 [34]. Catechin acted as a better antioxidant than quercetin in the copper-induced oxidation of diluted, Tween-based, linoleic acid emulsion (0.02 M), while morin presented the best protective action [35]. Different metal ions may affect the activity of flavonoids in emulsions, where the pro-oxidant or antioxidant character may dependon the flavonoid structure and the metal type [36] Flavonoids have also been examined for the preparation of physically stable pickering emulsions, while also offering oxidative stability [37][38].

Plant extracts are rich in flavonoids and phenolic acids and exert a strong antioxidant activity in o/w emulsions that may be attributed to synergism among its components and also to partitioning in the aqueous phase (e.g., polar phenolic acids or flavonoid glycosides), oil-water interface (e.g., medium polarity phenolic acids and flavonoids), or the oil phase (e.g., flavonoid aglycons) of the emulsion [39][40]. Additionally, the presence of endogenous antioxidants such as α-tocopherol may affect the flavonoid activity in lipid systems; e.g., it showed a strong synergistic effect with quercetin in emulsions, and a clear antagonistic effect in bulk oil [41]. More information on the phenolic synergistic effects is given in original context.

The current research has focused on various phenolic acids available in many natural sources (e.g., in olive oil, herbs, fruits) that have been widely explored in food systems [42]. Caffeic acid (CA) is perhaps the most well-known phenolic acid widely spread in the plant kingdom [43]. CA exerted a clear antioxidant effect when added in o/w emulsion systems stabilised by Tween and prepared with various vegetable oils [44][45]. Ferulic acid (FA) is another phenolic acid -commonly present in many plant seeds [46] that was reported to act as a strong antioxidant following its addition in a range of oil-based emulsions [47][48][49].

For gallic acid (GA), which is found in high amounts in tea and berries [50] there is some contradictory evidence in the literature about its protective action against oxidation of food emulsions. GA and its alkyl esters were found to exert a clear antioxidant effect against the oxidation of rapeseed o/w nano-emulsions stabilised by SDS [51] or even double emulsions by the use of encapsulation [52]. Additionally, Zhu et al. [53] concluded a strong inhibitory effect of GA and its alkyl esters against the formation of both primary (Peroxide Values) and secondary oxidation products (hexanal content). Propyl gallate exerted a superior activity compared to gallic acid and the other gallate esters. Other studies, however, did not report any protective effect of GA in o/w emulsions [54][55].

A large variety of plants and vegetables are abundant in p-coumaric acid (p-CA) [56]. Park et al. [57] reported that roasted rice hull extracts, with a high concentration of p-CA enhanced the oxidative stability of bulk oil and o/w emulsions at 60 °C. Rosmarinic acid (RA) is the main phenolic component in various edible and aromatic herbs of the Lamiaceae family (including *Rosmarinus officinalis*, *Origanum* spp., etc.) [58]. Choulitoudi et al. [19] observed that ethanol and ethyl acetate extracts of *Satureja thymbra*—articularly rich in RA—reduced by 75–80% the oxidation rate of sunflower o/w emulsions at chilling temperature (5 °C). Other researchers reported the antioxidant activity of RA in corn oil- and soyabean oil-based emulsions [59][60] as well as in a model emulsion system based on linoleic acid [44].

Bakota et al. [61] incorporated either pure RA or RA-rich extract (from *Salvia officinalis* leaves), at a concentration of ~30 mg/g, into o/w emulsions and observed that both treatments were effective in suppressing lipid oxidation.

Vanillic acid (VA) is a phenolic acid found in several fruits, olives, and cereal grains. Keller et al. [62] observed a strong antioxidant character of VA during the autoxidation of Tween 40-based o/w systems, at pH 3.5. In addition, a few authors [28][63] reported that the addition of tannic acid (TA) enhanced the resistance of plant-based emulsions against both droplet aggregation and lipid oxidation as a result of its strong ferrous ion-binding properties.

Ascorbic acid is another phenolic compound widely present in nature and with a high nutritional value (also known as vitamin C). A number of scientists highlighted the important role of ascorbic acid in antioxidant synergies examined in both food and clinically relevant studies [64][65].

References

1. Schroder, A.; Sprakel, J.; Boerkamp, W.; Schroen, K.; Berton-Carabin, C.C. Can we prevent lipid oxidation in emulsions by using fat-based pickering particles? Food Res. Int. 2019, 120, 352–363.
2. Dimakou, C.; Oreopoulou, V. Antioxidant activity of carotenoids against the oxidative destabilization of sunflower oil-in-water emulsions. LWT Food Sci. Technol. 2012, 46, 393–400.
3. Claire, C.; Berton-Carabin, C.-C.; Ropers, M.-H.; Genot, C. Lipid oxidation in Oil-in-Water Emulsions: Involvement of the Interfacial Layer. Compreh. Rev. Food Sci. Food Saf. 2019, 13, 945–977.
4. Kiokias, S.; Gordon, M.; Oreopoulou, V. Compositional and processing factors that monitor oxidative deterioration of food relevant protein stabilized emulsions. Crit. Rev. Food Sci. Nutr. 2017, 57, 549–558.
5. Poyato, C.; Navarro-Blasco, I.-E.; Calvo, M.-I.; Cavero, R.-Y.; Astiasarán, I.; Ansorena, D. Oxidative stability of O/W and W/O/W emulsions: Effect of lipid composition and antioxidant polarity. Food Res. Int. 2013, 51, 132–140.
6. Shahidi, F.; Zhong, Y. Revisiting the polar paradox theory: A critical overview. J. Agric. Food Chem. 2011, 59, 3499–3504.
7. Costa, M.; Barreiro, S.-L.; Magalhães, J.; Monteiro, L.-S.; Bravo-Díaz, C.; Paiva-Martins, F. Effects of the Reactive Moiety of Phenolipids on Their Antioxidant Efficiency in Model Emulsified Systems. Foods 2021, 10, 1028.
8. Kiokias, S.; Varzakas, T. Innovative applications of food related emulsions. Crit. Rev. Food Sci. Nutr. 2017, 57, 3165–3172.
9. Axmann, M.; Strobl, W.-M.; Plochberger, B.; Stangl, H. Cholesterol transfer at the plasma membrane. Atherosclerosis 2019, 290, 111–117.
10. Kiokias, S. Antioxidant effects of vitamins C, E and provitamin A compounds as monitored by use of biochemical oxidative indicators linked to atherosclerosis and carcinogenesis. Int. J. Nutr. Res. 2019, 1, 1–13.
11. Farooq, S.; Hui, A.; Zhang, H.; Weiss, J. A comprehensive review on polarity, partitioning, and interactions of phenolic antioxidants at oil–water interface of food emulsions. Compreh. Rev. Food Sci. Food Saf. 2021, 20, 4250–4277.
12. Phonsatta, N.; Deetae, P.; Luangpituksa, P.; Grajeda-Iglesias, C.; Figueroa-Espinoza, M.C.; Le Comte, J.; Villeneuve, P.; Decker, E.A.; Visessanguan, W.; Panya, A. Comparison of antioxidant evaluation assays for investigating antioxidative activity of gallic acid and its alkyl esters in different food matrices. J. Agric. Food Chem. 2017, 65, 7509–7518.
13. Katsouli, M.; Polychniatou, V.; Tzia, C. Optimization of water in olive oil nano-emulsions composition with bioactive compounds by response surface methodology. LWT Food Sci. Technol. 2018, 89, 740–748.
14. Mitrus, O.; Zuraw, M.; Losada-Barreiro, S.; Bravo-Díaz, C.; Paiva-Martins, F. Targeting Antioxidants to Interfaces: Control of the oxidative stability of lipid-based emulsions. J. Agric. Food Chem. 2019, 67, 3266–3274.
15. Barouh, N.; Bourlieu-Lacanal, C.; Figueroa-Espinoza, M.C.; Durand, E.; Villeneuve, P. Tocopherols as antioxidants in lipid-based systems: The combination of chemical and physicochemical interactions determines their efficiency. Compr. Rev. Food. Sci. Food Saf. 2022, 21, 642–648.
16. Arancibia, M.; Giménez, B.; López-Caballero, M.-E.; Gómez-Guillén, M.-C.; Montero, P. Release of cinnamon essential oil from polysaccharide bilayer films and its use for microbial growth inhibition in chilled shrimps. LWT Food Sci. Technol. 2014, 59, 989–995.
17. Liudvinaviciute, D.; Rutkaite, R.; Bendoraitiene, J.; Klimaviciute, R. Thermogravimetric analysis of caffeic and rosmarinic acid containing chitosan complexes. Carb. Polym. 2019, 222, 115003.

18. Garavand, F.; Jalai-Jivan, M.; Assadpour, E.; Jafari, S.M. Encapsulation of phenolic compounds within nano/microemulsion systems: A review. Food Chem. 2021, 3641, 130376.

19. Choulitoudi, E.; Xristou, M.; Tsimogiannis, D.; Oreopoulou, V. The effect of temperature on the phenolic content and oxidative stability of o/w emulsions enriched with natural extracts from Satureja thymbra. Food Chem. 2021, 349, 129206.

20. Lisete-Torres, P.; Losada-Barreiro, S.; Albuquerque, H.; Sanchez-Paz, V.; Paiva-Martins, F.; Bravo-Diaz, C. Distribution of hydroxytyrosol and hydroxytyrosol acetate in olive oil emulsions and their antioxidant efficiency. J. Agric. Food Chem. 2012, 60, 7318–7325.

21. Liu, Y.; Carver, J.-A.; Calabrese, A.-N.; Pukala, T.-L. Gallic acid interacts with α-synuclein to prevent the structural collapse necessary for its aggregation. Biochim. Biophys. Acta (BBA) Prot. Proteo. 2014, 1844, 1481–1485.

22. Kiokias, S.; Oreopoulou, V. A review on the health protective effects of phenolic acids against a range of severe pathologic conditions (incl Coronovrus based infections). Molecules 2021, 26, 5405.

23. Oreopoulou, A.; Papavassilopoulou, E.; Bardouki, H.; Vamvakias, M.; Bimpilas, A.; Oreopoulou, V. Antioxidant recovery from hydrodistillation residues of selected Lamiaceae species by alkaline extraction. J. Appl. Res. Medic. Aromat. Plants 2018, 8, 83–89.

24. Tsimogiannis, D.; Oreopoulou, V. Classification of phenolic compounds in plants. In Polyphenols in Plants Isolation Purification and Extract Preparation, 2nd ed.; Watson, R.R., Ed.; Elsevier Inc.: London, UK, 2019; pp. 263–284.

25. Kiokias, S.; Proestos, C.; Oreopoulou, V. Phenolic acids of plant origin—A review on their antioxidant activity in vitro (o/w emulsion systems) along with their in vivo health biochemical properties. Foods 2020, 9, 534.

26. Traber, G.-M.; Jeffrey, A. Vitamin E, antioxidant and nothing more. Free Radic. Biol. Med. 2007, 43, 4–15.

27. Kim, S.-K.; Im, G.-J.; An, Y.-S.; Lee, S.-H.; Jung, H.-H.; Park, S.-Y. The effects of the antioxidant α-tocopherol succinate on cisplatin-induced ototoxicity in HEI-OC1 auditory cells. Int. J. Pediatr. Otorhin. 2016, 86, 9–14.

28. Wang, L.; Yu, X.; Geng, F.; Cheng, C.; Yang, J.; Deng, Q. Effects of tocopherols on the stability of flaxseed oil-in-water emulsions stabilized by different emulsifiers: Interfacial partitioning and interaction. Food Chem. 2022, 374, 131691.

29. Rajasekaran, B.; Singh, A.; Nagarajan, M.; Benjakul, S. Effect of chitooligosaccharide and α-tocopherol on physical properties and oxidative stability of shrimp oil-in water emulsion stabilized by bovine serum albumin-chitosan complex. Food Contr. 2022, 137, 108899.

30. Tsimogiannis, D.; Oreopoulou, V. Defining the role of flavonoid structure on cottonseed oil stabilization: Study of A- and C-ring substitution. J. Am. Oil Chem. Soc. 2007, 84, 129–136.

31. Oh, W.Y.; Ambigaipalan, P.; Shahidi, F. Quercetin and its ester derivatives inhibit oxidation of food, LDL and DNA. Food Chem. 2021, 364, 130394.

32. Yang, D.; Wang, X.Y.; Lee, J.H. Effects of flavonoids on physical and oxidative stability of soybean oil O/W emulsions. Food Sci. Biotechnol. 2015, 24, 851–858.

33. Valerga, J.; Reta, M.; Lanari, M.C. Polyphenol input to the antioxidant activity of yerba mate (Ilex paraguariensis) extracts. LWT Food Sci. Technol. 2012, 45, 28–35.

34. Skerget, M.; Kotnik, P.; Hadolin, M.; Hras, A.; Simonic, M.; Knez, Z. Phenols, pronahtocyaninds, flavones, and flavonols in some plant materials and their antioxidant activities. Food Chem. 2005, 89, 191–198.

35. Beker, B.-Y.; Bakir, T.; Filiz, I.; Apak, R. Antioxidant protective effect of flavonoids on linoleic acid peroxidation induced by copper (II)/ascorbic acid. Chem. Phys. Lipids 2011, 164, 732–739.

36. Roedig-Penman, A.; Gordon, M.H. Antioxidant properties of myricetin and quercetin in oil and emulsions. J. Am. Oil Chem. Soc. 1998, 75, 169–180.

37. Duffus, L.J.; Norton, J.E.; Smith, P.; Norton, I.T.; Spyropoulos, F. A comparative study on the capacity of a range of food-grade particles to form stable O/W and W/O Pickering emulsions. J. Coll. Interfac. Sci. 2016, 473, 9–21.

38. Tong, Q.; Yi, Z.; Ran, Y.; Chen, X.; Chen, G.; Li, X. Green tea polyphenol-stabilized gel-like high internal phase pickering emulsions. ACS Sustain. Chem. Eng. 2021, 9, 4076–4090.

39. Skowyra, M.; Gallego, M.G.; Segovia, F.; Almajano, M.P. Antioxidant properties of Artemisia annua extracts in model food emulsions. Antioxidants 2014, 3, 116–128.

40. García-Iñiguez de Ciriano, M.; Rehecho, S.; Calvo, M.I.; Cavero, R.Y.; Navarro, I.; Astiasarán, I.; Ansorena, D. Effect of lyophilized water extracts of Melissa officinalis on the stability of algae and linseed oil-in-water emulsion to be used as a functional ingredient in meat products. Meat Sci. 2010, 85, 373–377.

41. Becker, E.M.; Ntouma, G.; Skibsted, L.H. Synergism and antagonism between quercetin and other chain-breaking antioxidants in lipid systems of increasing structural organisation. Food Chem. 2007, 103, 1288–1296.

42. Kiokias, S.; Proestos, C.; Oreopoulou, V. Effect of natural Food Antioxidants against LDL and DNA Oxidative damages. Antioxidants 2018, 7, 133.

43. Sugahara, S.; Chiyo, A.; Fukuoka, K.; Ueda, Y.; Tokunaga, Y.; Nishida, Y.; Kinoshita, H.; Matsuda, Y.; Igoshi, K.; Ono, M.; et al. Unique antioxidant effects of herbal leaf tea and stem tea from Moringa oleifera L. especially on superoxide anion radical generation systems. Biosci. Biotechnol. Biochem. 2018, 82, 1973–1984.

44. Terpinc, P.; Polak, T.; Šegatin, N.; Hanzlowsky, A. Antioxidant properties of 4-vinyl derivatives of hydroxycinnamic acid. Food Chem. 2011, 128, 62–69.

45. Conde, E.; Gordon, M.-H.; Moure, A.; Dominguez, H. Effects of caffeic acid and bovine serum albumin in reducing the rate of development of rancidity in oil-in-water and water-in-oil emulsions. Food Chem. 2011, 129, 1652–1659.

46. Mojica, L.; Meyer, A.; Berhow, M.; González, E. Bean cultivars (Phaseolus vulgaris L.) have similar high antioxidant capacity, in vitro inhibition of α-amylase and α-glucosidase while diverse phenolic composition and concentration. Food Res. Int. 2015, 69, 38–48.

47. Oehlke, K.; Heins, A.; Stöckmann, H.; Schwarz, K. Impact of emulsifier microenvironments on acid–base equilibrium and activity of antioxidants. Food Chem. 2010, 118, 48–55.

48. Maqsood, S.; Benjakul, S. Comparative studies of four different phenolic compounds on in vitro antioxidative activity and the preventive effect on lipid oxidation of fish oil emulsion and fish mince. Food Chem. 2010, 119, 123–132.

49. Shin, J.-A.; Jeong, S.-H.; Jia, C.-H.; Hong, S.-T.; Lee, K.-T. Comparison of antioxidant capacity of 4-vinylguaiacol with catechin and ferulic acid in oil-in-water emulsion. Food Sci. Biotechnol. 2019, 28, 35–41.

50. Pandurangan, A.-K.; Mohebali, N.; Norhaizan, M.-E.; Looi, C.-Y. Gallic acid attenuates dextran sulfate sodium-induced experimental colitis in BALB/c mice. Drug Des. Dev. Ther. 2015, 9, 3923–3934.

51. Da Silveira, T.F.; Laguerre, M.; Bourlieu-Lacanal, C.; Lecomte, J.; Durand, E.; Figueroa-Espinoza, M.C.; Barea, B.; Barouh, N.; Castro, I.A.; Villeneuve, P. Impact of surfactant concentration and antioxidant mode of incorporation on the oxidative stability of oil-in-water nanoemulsions. LWT Food Sci. Technol. 2021, 141, 110982.

52. Evangeliou, V.; Panagopoulou, E.; Mandala, I. Encapsulation of EGCG and esterified EGCG derivatives in double emulsions containing Whey Protein Isolate, Bacterial Cellulose and salt. Food Chem. 2019, 281, 171–177.

53. Zhu, M.; Wu, C.; Chen, Y.; Xie, M. Antioxidant effects of different polar gallic acid and its alkyl esters in oil-in-water emulsions. J. Chin. Instit. Food Sci. Technol. 2019, 19, 13–22.

54. Bou, R.; Boo, C.; Kwek, A.; Hidalgo, D.; Decke, E.A. Research ArticleEffect of different antioxidants on lycopene degradation inoil-in-water emulsions. Eur. J. Lipid Sci. Technol. 2011, 113, 724–729.

55. Alavi Rafiee, S.; Farhoosh, R.; Sharif, A. Antioxidant activity of gallic acid as affected by an extra carboxyl group than pyrogallol in various oxidative environments. Eur. J. Lipid Sci. Technol. 2018, 120, 1800319.

56. Trisha, S. Role of hesperdin, luteolin and coumaric acid in arthritis management: A Review. Inter. J. Phys. Nutr. Phys. Educ. 2018, 3, 1183–1186.

57. Park, J.; Gim, S.-Y.; Jeon, J.-Y.; Kim, M.-J.; Choi, H.-K.; Lee, J. Chemical profiles and antioxidant properties of roasted rice hull extracts in bulk oil and oil-in-water emulsion. Food Chem. 2019, 272, 242–250.

58. Yashin, A.; Yashin, Y.; Xia, X.; Nemzer, B. Antioxidant activity of spices and their impact on human health: A review. Antioxidants 2017, 6, 70.

59. Alamed, J.; Chaiyasit, W.; McClements, D.-J.; Decker, E.-A. Relationships between free radical scavenging and antioxidant activity in foods. J. Agric. Food Chem. 2009, 257, 2969–2976.

60. Panya, A.; Kittipongpittaya, K.; Laguerre, M.; Bayrasy, C.; Lecomte, J.; Villeneuve, P.; Decker, E.-A. Interactions between α-tocopherol and rosmarinic acid and its alkyl esters in emulsions: Synergistic, additive, or antagonistic effect? J. Agric. Food Chem. 2012, 60, 10320–10330.

61. Bakota, E.-L.; Winkler-Moser, J.-K.; Berhow, M.-A.; Eller, F.-J.; Vaughn, S.-F. Antioxidant activity and sensory evaluation of a rosmarinic acid-enriched extract of Salvia officinalis. J. Food Sci. 2015, 80, 711–717.

62. Keller, S.; Locquet, N.; Cuvelier, M.E. Partitioning of vanillic acid in oil-in-water emulsions: Impact of the Tween®40 emulsifier. Food Res. Int. 2016, 88, 61–69.

63. Li, R.; Dai, T.; Zhou, W.; Fu, G.; Wan, Y.; McClements, D.J.; Li, J. Impact of pH, ferrous ions, and tannic acid on lipid oxidation in plant-based emulsions containing saponin-coated flaxseed oil droplets. Food Res. Int. 2020, 136, 109618.

64. Jayasinghe, C.; Gotoh, N.; Wada, S. Pro-oxidant/antioxidant behaviours of ascorbic acid, tocopherol, and plant extracts in n-3 highly unsaturated fatty acid rich oil-in-water emulsions. Food Chem. 2013, 141, 3077–3084.
65. Narra, M.-R.; Rajendar, K.; Rudra, R.; Rao, J.-V.; Begum, G. The role of vitamin C as antioxidant in protection of biochemical and haematological stress induced by chlorpyrifos in freshwater fish Clarias batrachus. Chemosphere 2015, 132, 172–178.