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Erythorbyl laurate as a potential food additive with multi-functionalities: Interfacial characteristics and antioxidant activity

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ABSTRACT

The interfacial characteristics and antioxidant activities of erythorbyl laurate were investigated to provide information on practical applications as a multi-functional food additive. The critical micelle concentration (CMC) of erythorbyl laurate was 0.101 mM and its foam stability was three times (half-life 24.33 ± 0.94 h) higher than that of Tween 20 (8.00 ± 1.63 h). In free radical scavenging assay, the negligible decrease in EC_{50} of erythorbyl laurate compared to erythorbic acid manifested that C-5 selective esterification of erythorbic acid with an acyl group (lauric acid) did not reduce the inherent antioxidant activity of the donor (erythorbic acid). Erythorbyl laurate formed lipid peroxides slower (*i.e.* retarded oxidation) in an emulsion system than did erythorbic acid. The localization of erythorbyl laurate as an emulsifier allowed the antioxidant molecules to be concentrated at the oil-water interface where oxidation is prevalent, which led to more effective retardation of lipid oxidation.

1. Introduction

An emulsion is a heterogeneous dispersion of two immiscible liquids (*e.g.* water and lipid) wherein droplets of one phase (dispersed or internal phase) are encapsulated within another phase (continuous or external phase) in the presence of surface-active agents (*i.e.* emulsifiers) (Friberg, Larsson, & Sjoblom, 2003). For the emulsion-based products extensively used in food, cosmetic, and pharmaceutical industries, lipid oxidation and microbial contamination have been considered as the major hazards in terms of safety for human consumption (Luther et al., 2007). Under the strategy for simultaneously controlling the aforementioned hazards, our research group has performed lipase-catalyzed esterification between lauric acid and erythorbic acid to produce a novel multifunctional emulsifier with antibacterial and antioxidant activities (Park, Sung, Lee, & Chang, 2011).

Erythorbic acid is a stereoisomer of L-ascorbic acid that has been used widely as an antioxidant for various processed foods (Clark et al., 2009). On the other hand, lauric acid is a medium-chain fatty acid with a strong antimicrobial activities against a wide spectrum of food-borne pathogens (Nakatsuji et al., 2009). Therefore, erythorbyl laurate (6-*O*-lauroyl-erythorbic acid), which results from enzymatic esterification between erythorbic acid and lauric acid, was anticipated to be an amphiphilic material with multi-functionalities. And we have previously reported that subsequent studies related to the synthetic methodology for erythorbyl laurate including optimum conditions employing response surface methodology and continuous process through a packed bed enzyme reactor (Lee, Park, Choi, & Chang, 2012; Lee, Park, Choi, Shim, & Chang, 2013).

From the recent study on antibacterial susceptibility, it was confirmed that erythorbyl laurate had both bacteriostatic and bactericidal effects on Gram-positive pathogens such as *Staphylococcus aureus*, *Listeria monocytogenes*, and *Bacillus cereus*. Furthermore, the antibacterial mechanism of erythorbyl laurate was revealed in results of the Live/Dead BacLight assay based on propidium iodide dye, which enters the cell and stains cellular DNA only if the membrane is damaged and abnormally permeable. Thus, exposure of *S. aureus* to erythorbyl laurate ruptures the cytoplasmic membrane, leading to altered membrane permeability.

The primary aim of this study was to investigate the emulsifying and antioxidant activities of erythorbyl laurate and to determine the effective concentration for practical applications. First, the emulsifying activity of erythorbyl laurate was assessed based on interfacial characteristics including surface tension and foaming

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ability. We also evaluated the free radical scavenging activity of erythorbyl laurate and the retarding effect on lipid oxidation in an emulsion system.

2. Materials and methods

2.1. Materials

Erythorbic acid (⩾99.0%), dodecanoic acid (lauric acid ⩾ 99.0%), and 6-*O*-palmitoyl-L-ascorbic acid (ascorbyl palmitate ⩾ 99.0%) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). Novozym® 435 (*Candida antarctica* lipase immobilized on acrylic resin) and polyoxyethylene (20) sorbitan monolaurate (Tween 20) were kindly provided by Novozymes Korea, Ltd. (Seoul, Korea) and Ilshinwells Co. (Seoul, Korea), respectively. 1,1-Diphenyl-2-picrylhydrazyl (DPPH) and 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) were purchased from Sigma-Aldrich to assess antioxidative activity. All other chemicals were of analytical grade and were used without further purification.

2.2. Preparation of erythorbyl laurate

Enzymatic synthesis, purification, and identification of erythorbyl laurate were performed according to our previous reports (Lee et al., 2012; Park et al., 2011). Briefly, erythorbic acid and lauric acid were added to a screw-capped glass vial with acetonitrile and pre-incubated in an orbital shaking water bath. The reaction was initiated by adding immobilized lipase (Novozym® 435; Novozymes) to the mixture. After terminating the enzymatic synthesis, erythorbyl laurate was purified using a solvent separation method, and quantitative analysis and identification were carried out with a high-performance liquid chromatography system (LC-2002; JASCO, Inc., Tokyo, Japan) equipped with a Spherisorb-ODS column (5 μm, 100 Å, I.D. 4.6 × 250 mm; Waters, Milford, MA, USA) and a matrix-assisted laser desorption/ionization time-of-flight system (Auto Flex II; Bruker Daltonics, Bremen, Germany).

2.3. Emulsifying ability of erythorbyl laurate

2.3.1. Surface tension and critical micelle concentration

Because of the low water solubility of erythorbyl laurate, sample solutions were prepared with distilled water containing 1% (v/v) dimethyl sulfoxide (DMSO). Critical micelle concentration (CMC) was determined by measuring the surface tension of a sample solution at different concentrations at 25 °C with a Wilhelmy plate tensiometer and a platinum plate (K100SF, Krüss, Hamburg, Germany).

2.3.2. Foaming ability and stability

Sample solutions were prepared to a concentration of 0.05% (w/v) with distilled water containing 1% (v/v) DMSO. The 0.05% concentrations of each surfactant referred to 0.41 mM of Tween 20, 1.21 mM of ascorbyl palmitate, and 1.40 mM of erythorbyl laurate, respectively. Then, each sample solution (50 mL) was poured into a 100-mL graduated cylinder. Foam was produced by homogenization at 10,000 rpm at 25 °C for 60 s using a high-speed blender (T-18 basic; IKA, Staufen, Germany). Foam volume was measured at 30 s after homogenization to determine foaming capacity. Foam stability was evaluated as the time until the foam collapsed by 50% of its original volume (half-life).

2.4. Antioxidant properties of erythorbyl laurate

2.4.1. Free radical scavenging activity

The free radical scavenging activity of erythorbyl laurate was determined based on the DPPH method (Chen, Bertin, & Froldi, 2013) with slight modifications. Briefly, 3.75 mL of 0.1 mM DPPH in methanol was mixed with 0.25 mL surfactant solution and vortex-mixed for 10 s. After the sample mixture stood in the dark for 30 min, the absorbance was measured at 517 nm using a UV/VIS-spectrophotometer (UV-2450, Shimadzu, Kyoto, Japan). DPPH radical scavenging activity was expressed as [1 − (sample absorbance/blank absorbance)] × 100% (Miliauskas, Venskutonis, & Van Beek, 2004).

The ABTS assay was conducted according to Thaipong's method (Thaipong, Boonprakob, Crosby, Cisneros-Zevallos, & Byrne, 2006) with slight modifications. A stock solution of 7.00 mM ABTS and 2.45 mM potassium persulfate was stored in the dark for 12 h to produce proton radicals. The solution was diluted with ethanol to an absorbance of 0.70 ± 0.05 at 734 nm. A surfactant solution (0.05 mL) dissolved in methanol was reacted with 1.90 mL ABTS solution in the dark, and absorbance was measured at 734 nm after 6 min. ABTS radical scavenging activity was expressed as [1 − (sample absorbance/blank absorbance)] × 100% (Khalil, Pepato, & Brunetti, 2008). Free radical scavenging activity was calculated from a linear regression as the 50% effective concentration (EC_{50}), which is the concentration required to reduce the initial absorbance 50%. Radical scavenging activities of ascorbyl palmitate and erythorbic acid were also determined for comparison.

2.4.2. Antioxidant activity of erythorbyl laurate in an emulsion system

Oil-in-water emulsions were prepared by mixing 5% (w/v) lipid phase (soybean oil) with 95% aqueous phase (0.2% [w/v] surfactant in distilled water). To prepare the surfactant solution, surfactant was dissolved in a 2% (v/v) ethanol solution, followed by subsequent stirring for 1 h at ambient temperature to remove the trace ethanol. A coarse emulsion premix was prepared by homogenizing the lipid and aqueous phases together using a high-speed blender (T-18 basic; IKA) at 16,000 rpm for 60 s at room temperature. Then, the droplet size in the premixed emulsions was reduced by sonication for 2 min at 210 W and a duty cycle of 0.5 s at 4 °C.

To elucidate the effect of erythorbyl laurate on thermal lipid oxidation, emulsion samples (5 mL) were stored at 60 °C in the dark for up to 11 days. Meanwhile, riboflavin (100 μM) was used as a photosensitizer for photo-oxidation. Emulsion samples (1 mL) were transferred to vials (10 mL), and the samples were oxidized at 25 °C for 12 h under fluorescence light (3420 lux).

Lipid hydroperoxides, which are the primary products of lipid oxidation, were measured by the ferric thiocyanate method (Kiokias & Varzakas, 2014). The emulsion sample (20 μL) was mixed with 3 mL methanol/1-butanol (2:1, v/v) and 30 μL thiocyanate/Fe^{2+} solution. The thiocyanate/Fe^{2+} solution was prepared immediately before use by combining 0.8 mL 3.940 M ammonium thiocyanate and 0.8 mL fresh Fe^{2+} solution. The fresh Fe^{2+} solution was obtained from the supernatant of 0.8 mL 144 mM $BaCl_2$ in 400 mM HCl and 0.8 mL 144 mM $FeSO_4$. After a 20-min reaction, the absorbance of each sample was detected at 510 nm. Lipid hydroperoxides were determined based on cumene hydroperoxide.

Thiobarbituric acid-reactive substances (TBARS) were used to measure lipid oxidation reaction products, particularly malondialdehyde (MDA), as an important auto-oxidation product (Cai, Cao, Aisikaer, & Ying, 2013). A solution of trichloroacetic acid (TCA)–TBA–HCl was prepared by mixing 15 g TCA, 375 mg TBA, 1.76 mL 12 N HCl, and 82.9 mL H_2O. Two milliliter of the

TCA–TBA–HCl solution was mixed with 20 μL emulsion sample and 1 mL distilled water. After mixing, the mixture was heated in a boiling water bath for 15 min, cooled to room temperature for 10 min using tap water, and centrifuged at 2000×*g* for 15 min. Absorbance was measured at 532 nm, and the TBARS concentration was determined from a 1,1,3,3-tetraethoxypropane standard curve.

2.5. Statistical analysis

All data are presented as means and standard deviations of triplicate experiments. Analysis of variance was performed, and differences in means were detected with Duncan's multiple range test ($p < 0.05$). All statistical analyses were performed using SAS 9.3 software (SAS Institute, Cary, NC, USA).

3. Results and discussion

3.1. Interfacial characteristics of erythorbyl laurate

As CMC is one of the most useful physicochemical characteristics of a surfactant and provides highly useful information on the associations between surfactants in solution (McClements, 2005), the surface activity of erythorbyl laurate was evaluated by determining the CMC. CMC is the concentration at which surface tension is independent of sample concentration. Tween 20 and ascorbyl palmitate were used in the comparative analysis. Ascorbyl palmitate was used because ascorbic acid is an erythorbic acid isomer and has a similar molecular structure. Tween 20 was used because it has the same hydrophobic moiety (lauric acid) as erythorbyl laurate.

CMC was determined when surface tension changed slightly with increasing concentration because surfactants are fully saturated at the air–solution interface (Reis et al., 2004). Compared with surface tension of 1% (v/v) DMSO solution as a control (73.2 mN/m), the surface tension values of ascorbyl palmitate, Tween 20, and erythorbyl laurate decreased to 45.2, 37.5, and 35.3 mN/m at the CMC, respectively (Fig. 1). Ascorbyl palmitate was relatively less effective for reducing surface tension compared with erythorbyl laurate and Tween 20, which had similar surface activity. The CMCs of ascorbyl palmitate and Tween 20 were 0.120 and 0.038 mM, respectively, similar to previous findings (Graca, Bongaerts, Stokes, & Granick, 2007; Palma, Lo Nostro, Manzo, & Allemandi, 2002). The CMC of erythorbyl laurate was 0.101 mM, which was in accordance with a report that the CMC range of non-ionic surfactants is 0.01–1 mM (Lee, Kim, Lee, & Lim, 2011).

It was well documented that the CMC decreases as the alkyl chain-length of hydrophobic tail becomes longer in the case of surfactants with similar structure or the same hydrophilic moiety. (Ahmad & Xu, 2015; McClements, 2005). As described earlier, erythorbyl laurate and ascorbyl palmitate have very similar molecular structures, the only difference being their hydrophobic tail lengths (Supplementary data S1). This explains why the CMC of erythorbyl laurate (C12) was slightly higher than that of ascorbyl palmitate (C16). On the other hand, the structural characteristics including size, conformation, and configuration, of hydrophilic moiety in surfactant molecule play a significant role in the CMC. This factor (*i.e.* differences in hydrophilic group), however, do not have a direct correlation with the CMC because of the simultaneous independent variables involving molecular weight and structure, which makes difficult to predict the CMC based on the factor. Although not fully understood, it is plausible that the difference in the CMC between EL and Tween 20 was driven by distinctions in polar head region.

3.2. Foaming ability and stability

As foaming ability is in principle related to the adsorption kinetics of surfactant molecules (Weschayanwiwat, Scamehorn, & Reilly, 2005) and is very important for controlling food production processes (Stauffer, 1999), Data on the foaming ability of erythorbyl laurate are critical for its application to the food industry as an emulsifier. Foaming ability was determined at a 0.05% (w/v) concentration of surfactant over CMC, because foaming capacity is maximum at CMC and kept constant over CMC (Park & Kim, 1995). Due to the fact that ascorbyl palmitate hardly produced foams and the created foams had very short half-lives, its foaming ability was not significant and negligible (data not shown). Fig. 2 shows the results of foaming capacity and foam stability. The foam volumes of Tween 20 and erythorbyl laurate were 18.67 ± 0.94 and 18.00 ± 0.82 mL, respectively, their difference was not significant ($p < 0.05$). However, the measurement of foam stability told another story. The foam stability of erythorbyl laurate was markedly superior to that of Tween 20 (24.33 ± 0.94^{a} and 8.00 ± 1.63^{b} h for erythorbyl laurate, and Tween 20, respectively). The previous findings declared that a decrease in surface tension

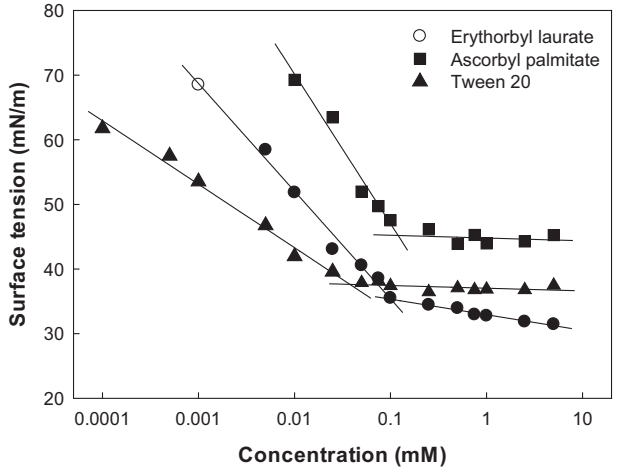

Fig. 1. Changes in surface tension of Tween 20, ascorbyl palmitate, and erythorbyl laurate at 25 °C.

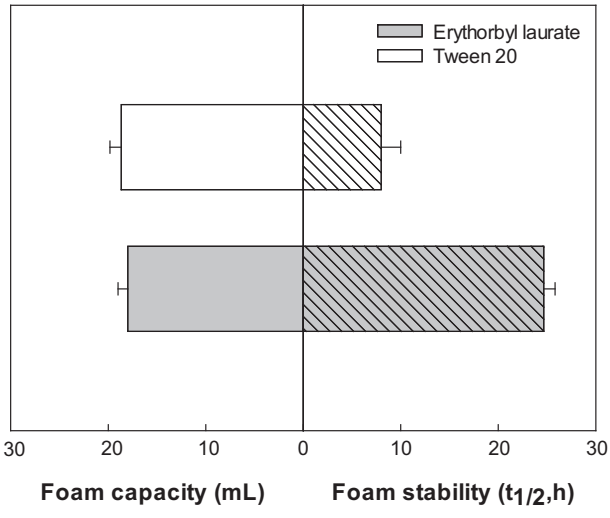

Fig. 2. Comparison of foaming ability of Tween 20 and erythorbyl laurate at 0.05% (w/v) concentration.

induces a corresponding increase in foam stability (Pugh, 1996). As aforementioned, the surface tensions of Tween 20 and erythorbyl laurate were 37.5 and 35.3 mN/m, respectively, at CMC concentrations. Therefore, although there was no great difference between those values, the lower surface tension of erythorbyl laurate compared with that of Tween 20 could be explained by its high foam stability. However, this finding is insufficient to explain this phenomenon, considering the large gap between the foam stabilities and the small difference in surface tension between Tween 20 and erythorbyl laurate. Surfactant type and the kinetic process, such as film thinning, drainage, and rupture, affect foaming capacity and foam stability (Pugh, 1996). Surface rheological properties (viscosity and elasticity) of the adsorption layer are the main factors involved in foam stability. In particular, the liquid film of the foam should have good elastic properties. This hypothesis suggests that although erythorbyl laurate and Tween 20 had similar surface tension above the CMC, the elastic properties of the foam film created by erythorbyl laurate could be higher than those of the film created by Tween 20. No significant difference in foaming capacity was detected between the surfactants tested, and the much higher foam stability of erythorbyl laurate relative to Tween 20 suggests that erythorbyl laurate is as good an emulsifier as commonly used industrial surfactants. In particular, the high foam stability of erythorbyl laurate indicates that it can be used in foods, such as ice cream, to enhance foam stability (Dickinson, 2010).

3.3. Free radical scavenging activity

The antioxidant activity of erythorbyl laurate was determined using the DPPH and ABTS assays. Erythorbic acid and ascorbyl palmitate were used in the comparative analysis. DPPH radical scavenging activity is shown in Fig. 3A. The scavenging effect increased with increasing sample concentration. The DPPH radical scavenging activities of erythorbyl laurate were 17.48, 36.34, and 74.83% at concentrations of 125, 250, and 500 μM, respectively. The EC_{50} values of ascorbyl palmitate, erythorbic acid, and erythorbyl laurate were 306.20, 288.13, and 331.42 μM, respectively. Moreover, the cation radical scavenging capacity was evaluated against ABTS (Fig. 3B), and a similar pattern was observed as with DPPH assay. The ABTS radical scavenging activities of erythorbyl laurate were 18.84, 34.65, and 64.39% at concentrations of 125, 250, and 500 μM, respectively. The EC_{50} value of ascorbyl palmitate, erythorbic acid, and erythorbyl laurate were 378.83, 380.83, and 425.95 μM, respectively.

Although EC_{50} of erythorbic acid was slightly lower than that of erythorbyl laurate, the antioxidant activity after esterification of erythorbic acid was retained to a considerable degree, and the small difference in antioxidant activity between erythorbic acid and erythorbyl laurate was negligible. A previous study stated that esterification of ascorbic acid with an acyl chain retains or even enhances its antioxidant activity as measured by the DPPH method (LoNostro et al., 2000), indicating that the introduction of lauric acid to hydroxyl group of erythorbic acid had no or little negative effect on the antioxidant activity of erythorbic acid.

3.4. Antioxidant activity of erythorbyl laurate in emulsion systems

The antioxidant activity of erythorbyl laurate was determined in emulsion systems because it is expected to be a multifunctional food additive with emulsifying and antioxidant activities. Prior to the analysis, the particle size distribution of the emulsion formed by erythorbyl laurate was confirmed using dynamic light scattering and transmission electron microscopic analyses (Supplementary data S2). Measuring particle size and its distribution is important for optical properties and rheology because droplet size affects emulsion stability (McClements, 2007). Spherical and

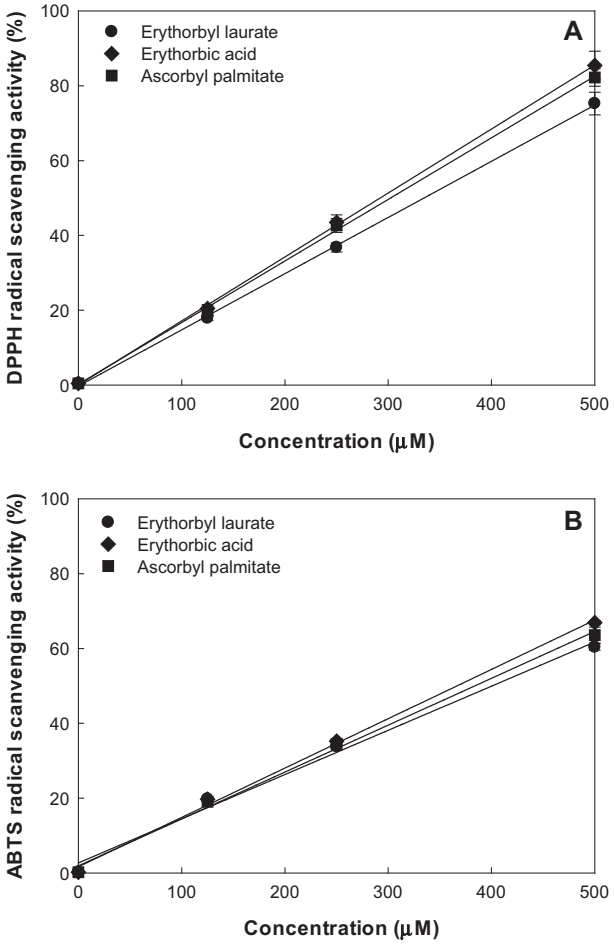

Fig. 3. Effect of antioxidant concentration on the decrease in DPPH (A) and ABTS (B) radicals of ascorbyl palmitate, erythorbic acid, and erythorbyl laurate.

monodispersed emulsions were prepared with erythorbyl laurate. The average droplet size (d_{32}) was 750 ± 40 nm, and no significant fluctuations were detected during 2 weeks of storage at room temperature. Thermal oxidation (Fig. 4) and photo-oxidation (Fig. 5) were applied to evaluate the antioxidant activity of erythorbyl laurate in the emulsion systems.

Monitoring of lipid peroxides during thermally accelerated oxidation (Fig. 4A) showed that the SDS-stabilized emulsion oxidized rapidly during the first 4 days, and the oxidation rate decreased gradually thereafter. The maximum oxidation rate of the Tween 20-stabilized emulsion was observed after 8 days of storage, following a slow oxidation rate during the early time period, and it decreased with time after the maximum. However, the oxidation rate of the erythorbyl laurate-stabilized emulsion remained near zero during the entire experiment, indicating that erythorbyl laurate effectively inhibited production of lipid peroxides. The concentrations of lipid peroxides in the SDS-, Tween 20-, and erythorbyl laurate-stabilized emulsions were 26.84^{c}, 8.45^{b}, and 0.66^{a} meq/kg oil, respectively, after 4 days of incubation, and they were 17.15^{c}, 27.44^{b}, and 0.11^{a} meq/kg oil after 8 days of incubation. The oxidative profiles determined by TBARS were similar to those determined by lipid peroxides (Fig. 4B). The only difference was the time needed to reach maximum level. Lipid molecules take up oxygen during the early stages of oxidation, forming the primary oxidation products called lipid peroxides, which are converted to TBARS, mainly MDA, secondary oxidation products (Friberg et al., 2003). The results of the comparison of SDS- and

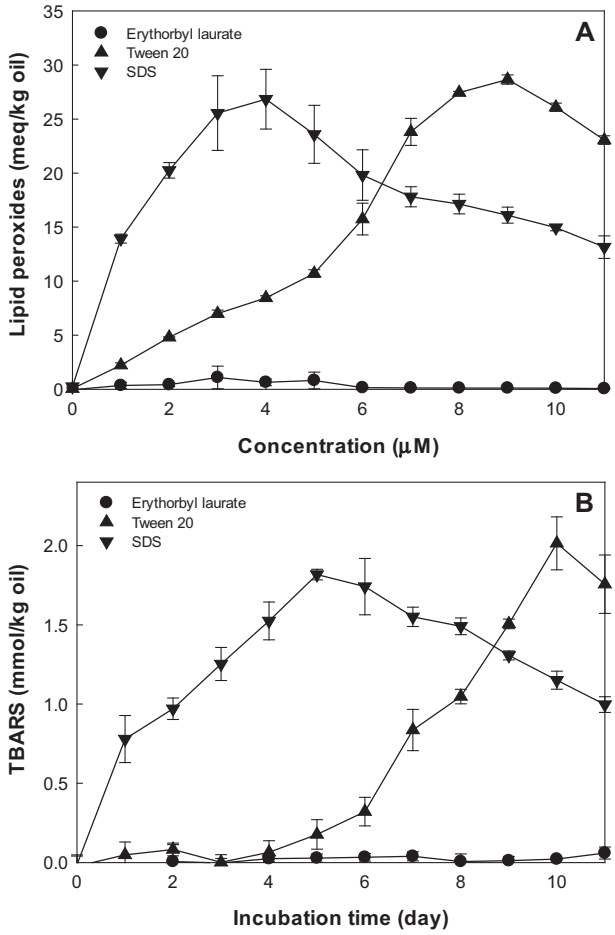

Fig. 4. Formation of lipid peroxides (A) and TBARS (B) in SDS-, Tween 20-, and erythorbyl laurate-stabilized emulsions during thermally accelerated oxidation at 60 °C.

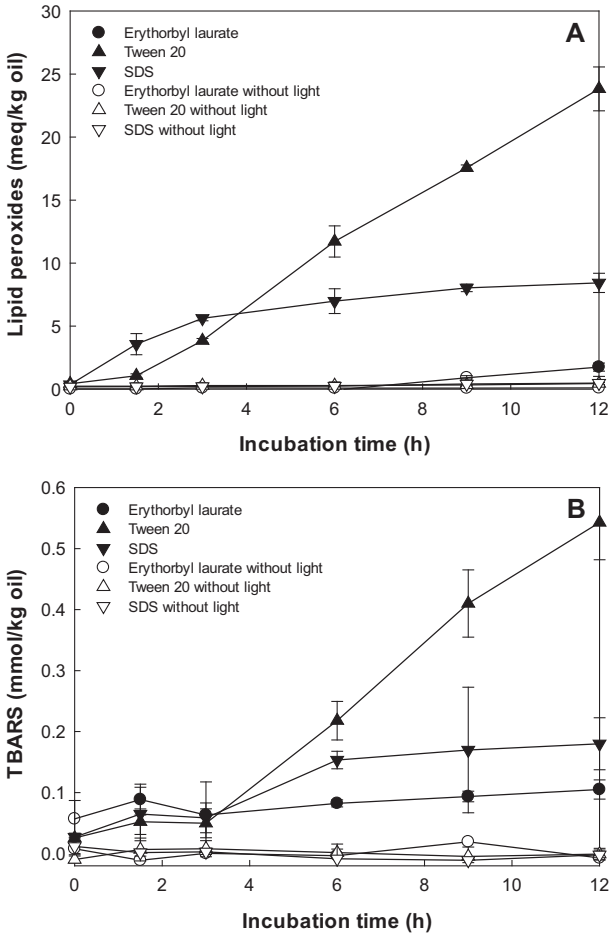

Fig. 5. Formation of lipid peroxides (A) and TBARS (B) in SDS-, Tween 20-, and erythorbyl laurate-stabilized emulsions during riboflavin-sensitized photo-oxidation at 25 °C.

Tween 20-stabilized emulsions suggests that non-ionic surfactants effectively inhibit oxidation of emulsified oils in emulsion systems better than anionic surfactants do (Mei, McClements, & Decker, 1999). Cationic trace metals are active pro-oxidants that affect anionic more than non-ionic surfactants (McClements & Decker, 2000; Mei et al., 1999). The negative surface charge for droplets stabilized with SDS could potentially attract transition metal ions to the droplet surface, where they would accelerate lipid oxidation.

To accelerate photo-oxidation, riboflavin was employed because this photosensitizer can generate free radicals by absorption of electrons or hydrogen (Type 1 pathway) or by formation of singlet oxygen from triplet oxygen transferring energy (Type 2 pathway) (Kim, Decker, & Lee, 2012; Min & Boff, 2002). As the emulsions were treated with fluorescence light for 12 h at 25 °C, lipid peroxides increased in all emulsions (Fig. 5A). Similar to the result of thermal oxidation, rates of photo-oxidation in emulsions stabilized with Tween 20 and SDS were faster than that in the erythorbyl laurate emulsion. Totals of 23.83^{c}, 8.43^{b}, and 1.75^{a} meq/kg oil of lipid peroxides formed in Tween 20-, SDS-, and erythorbyl laurate-stabilized emulsions during 12 h, respectively. The oxidation profiles of the emulsions stabilized with erythorbyl laurate did differed significantly from those of the emulsions stabilized with Tween 20 or SDS under the fluorescence light treatment, indicating that erythorbyl laurate was highly effective for inhibiting photo-oxidation in emulsion systems.

Polar paradox theory explains the behavior of antioxidants (Shahidi & Zhong, 2011). According to this theory, relatively non-polar antioxidants prevent the lipid oxidation of emulsions more effectively than do polar antioxidants because they could be concentrate at the water–oil interface, where lipid oxidation occurs. This observation suggests that enriching antioxidants at the interface is an effective way to prevent and retard lipid oxidation in emulsions; this could easily be addressed by developing a surfactant with antioxidant activity (Chaiyasit, Elias, McClements, & Decker, 2007). Considering these findings, as erythorbyl laurate has antioxidant activity and was highly concentrated at the emerging water–oil interface (Supplementary data S3), it could be a perfect alternative to simply mixing an emulsifier and antioxidant to prevent lipid oxidation in emulsions. To verify this hypothesis, the Tween 20-stabilized emulsion containing 5.57 mM erythorbic acid (the same moles of erythorbic acid moiety in the erythorbyl laurate-stabilized emulsions) was prepared as a comparative sample. After 11 days of thermal oxidation, the level of lipid peroxides in Tween 20-stabilized emulsion with erythorbic acid drastically dropped to 4.30 meq/kg oil, which differed from the level (23.06 meq/kg oil) in Tween 20-stabilized emulsion without erythorbic acid (Fig. 6A). Although both erythorbyl laurate and Tween 20 with erythorbic acid showed inhibitory effects on thermal oxidation, it is worthy of note that the level of lipid peroxides in Tween 20-stabilized emulsion containing erythorbic acid was relatively higher than that of erythorbyl laurate-stabilized emulsion. The profiles of lipid peroxides formation during the photo-oxidation was also consistent with the result of thermal oxidation (Fig. 6B).

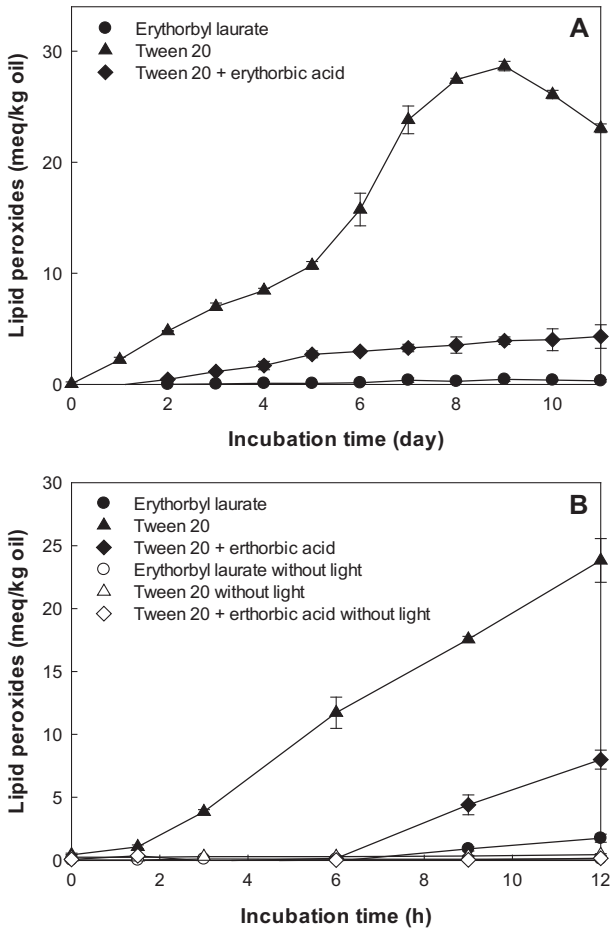

Fig. 6. Effect of the erythorbic acid moiety locus on the formation of lipid peroxides during thermally accelerated oxidation (A) and riboflavin-sensitized photo-oxidation (B).

This phenomenon could be attributed to the locations of the antioxidant molecules in the emulsions. In emulsions, since many of the compounds including transition metals, enzymes, etc, responsible to accelerate lipid oxidation originate in the aqueous phase, such pro-oxidants come into close contact with the lipids at the droplet surface. It indicates that the formation of lipid hydroperoxides and the decomposition of these hydroperoxides into high reactive radicals mainly occur at the oil-water interface of oil droplets. Erythorbyl laurate was surface active and oriented at the oil–water interface to better prevent oils from oxidation. On the other hand, erythorbic acid in the Tween 20-stabilized emulsion was diluted in the aqueous phase, thus its concentration at the oil–water interface was relatively low to effectively protect oil against oxidation. Therefore, relatively low lipid oxidation degree of erythorbyl laurate-stabilized emulsion compared with Tween 20-stabilized emulsion containing erythorbic acid can be explained by the higher concentration of antioxidant molecules at the oil-water interfaces in erythorbyl laurate-stabilized emulsion than Tween 20-stabilized emulsion containing erythorbic acid.

4. Conclusions

An investigation of interfacial characteristics showed that erythorbyl laurate was surface active and had remarkable foam stability. The DPPH and ABTS assays indicated that introducing lauric acid to erythorbic acid by esterification did not decrease the antioxidant activity of erythorbic acid. Erythorbyl laurate effectively retarded the development of lipid peroxides in soybean oil emulsions. The surfactant properties of erythorbyl laurate drive its high concentration at the oil–water interface, and the enriched antioxidant functional groups on erythorbyl laurate at the interface could be pivotal in inhibiting lipid oxidation in emulsions. Therefore, the emulsifying and antioxidant activities of erythorbyl laurate make it a promising candidate as a multi-functional additive for emulsified food systems. Furthermore, these particular properties facilitate its use in a micellar vehicle to solubilize and stabilize hydrophobic functional food ingredients.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2016.07.174.

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