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Lipid oxidation in mayonnaise and the role of natural antioxidants: a review

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Abstract

Background: Mayonnaise, a high-oil containing product, is susceptible to oxidation resulting in quality deterioration and the formation of undesirable components such as free radicals and reactive aldehydes. A better understanding of the factors affecting lipid oxidation and ways of retarding oxidation in mayonnaise is essential in order to improve the shelf-life of mayonnaise.

Scope and approach: This review presents up-to-date knowledge on the factors affecting lipid oxidation and strategies to retard lipid oxidation in mayonnaise, with an emphasis on natural antioxidants, and application to other similar emulsions. Eliminating possible factors, which will reduce the induction period and hasten rancidity, can increase the shelf life of mayonnaise but one of the most effective means of retarding lipid oxidation in mayonnaise is to incorporate antioxidants. Due to the negative effects and perceptions of synthetic antioxidants, there has been a growing interest in improving oxidative stability of food products with natural ingredients. Therefore, to provide a better base for food engineers to design an effective natural antioxidant system for mayonnaise, in this review the emphasis is given to using natural antioxidants in mayonnaise.

Key findings and conclusion: Recent studies showed that incorporation of natural antioxidants in mayonnaise could increase its oxidative stability. However, natural antioxidants may exert a negative effect on sensory properties and further studies are needed to identify, quantify and overcome this problem. Manipulating the interfacial layer of the oil droplet also shows promise for retarding oxidation; however, there is a lack of literature addressing this area.

Key words: Natural antioxidant; Mayonnaise; Oil auto-oxidation; Polar paradox; Sensory value

General introduction to lipid oxidation in food emulsion systems such as mayonnaise

Oxidation of unsaturated fatty acids has been the main focus of research that targets chemical instability of emulsions. Mayonnaise is a low-pH oil in water emulsion consisting of three different components: 70-80% oil (the dispersed phase), vinegar (the continuous phase) and egg yolk as an emulsifier at the interface (Li, Kim, Li, Lee, & Rhee, 2014). As in the case of all high oil-containing foods, mayonnaise is susceptible to deterioration due to auto-oxidation of the unsaturated fats in the oil. Auto-oxidation proceeds through three steps: during the initiation step, external energy, such as light, acts on unsaturated lipid molecules or fatty acids, in the presence of catalysts such as transition metal, to generate a free radical by losing a hydrogen atom. During the propagation step, the alkyl of the unsaturated lipid (R·) reacts very fast with molecular oxygen to form peroxide radicals. This step is always much faster than the following which involves a hydrogen transfer reaction with unsaturated lipids to form hydroperoxides. At this stage, lipid peroxyl radicals (ROO·) and hydroperoxides (ROOH) are the primary oxidation products. Lipid hydroperoxides are tasteless, but they further decompose to aldehydes, ketones, alcohols, hydrocarbons, volatile organic acids and epoxy compounds known as secondary oxidation products, which are responsible for the off-flavour and off-odour of the oil. Primary oxidation products and secondary oxidation products, together with free radicals, constitute the basis for measuring the oxidative deterioration of food lipids (Shahidi & Zhong, 2005). In the termination step, the produced radicals from the propagation step can be terminated by self-interactions to form non-radical species, such as oxidized polar/ non-polar dimers or trimers of lipids.

In emulsions formed from oil and water, lipid oxidation reactions are generally initiated at the interface between the oil and water, where pro-oxidants (transition metals) in the continuous phase are able to come into close contact with the hydroperoxides located at the droplet surface (McClements & Decker, 2000). Lipid oxidation in mayonnaise leads to the development of potentially toxic reaction products (Coupland & McClements, 1996), undesirable off-flavours and consequently decreases the shelf life of mayonnaise (Alemán et al., 2015). In order to tackle the problem of lipid oxidation, different strategies such as eliminating factors promoting lipid oxidation and using antioxidants are necessary. One of the common ways of retarding lipid oxidation is the use of antioxidants. The efficacy of an antioxidant is influenced by different factors such as its interaction with other ingredients and its ability to be located at the interface, where oxidation takes place (Coupland & McClements, 1996). Synthetic antioxidants such as butylated hydroxy toluene (BHT), butylated hydroxy anisole (BHA) and ethylene diamine tetraacetic acid (EDTA) (commercial antioxidants) are widely used in mayonnaise to prevent rancidity. However, these products suffer from a negative impression for their toxic and carcinogenic effects in high concentrations (Martínez-Tomé et al., 2001). In addition, there is a growing demand from customers for products such as mayonnaise to replace chemical ingredients with natural ingredients. Incorporation of natural antioxidants into food products has great potential for improving oxidative stability of food products and will appeal to a wider group of consumers. In addition, these compounds could also have health-promoting benefits which would enable mayonnaise producers to hit two desirable targets: health and natural (Hermund et al., 2015).

Low pH and high fat content of mayonnaise makes it resistant to microbial spoilage (Depree & Savage, 2001). Therefore, the objective of the present paper is to review current understanding of factors affecting lipid oxidation and antioxidative strategies to retard lipid oxidation in mayonnaise with a particular focus on current knowledge on the efficacy of natural antioxidants in retarding lipid oxidation in mayonnaise. The aim is to provide important information based on available literature reports concerning lipid oxidation in mayonnaise to control lipid oxidation and facilitate the replacement of synthetic antioxidants with natural ones.

Factors affecting lipid oxidation in mayonnaise

Lipid oxidation in a complex food system such as mayonnaise, is not simple, so the mechanism of lipid oxidation in mayonnaise is more complex than in bulk oil systems. Although the basic oxidation reactions of lipids in mayonnaise are the same as those of lipids in bulk oil systems, factors affecting lipid oxidation are significantly different in mayonnaise and bulk oil systems (Jacobsen, Let, Nielsen, & Meyer, 2008). In this section, data from previous studies of factors influencing lipid oxidation in mayonnaise, from intrinsic to extrinsic, will be presented in order to highlight not only the most important factors affecting lipid oxidation in mayonnaise, but also to provide a general view of ways to lessen these factors and control lipid oxidation in mayonnaise.

Metals

The presence of even small amounts of transition metals in mayonnaise can accelerate oxidation by decreasing the induction period of the oil and making it more susceptible to oxidation. Iron and copper are known initiators of lipid oxidation. Mayonnaise is an acidic product; during manufacturing and packaging, it contacts utensils and machinery. The acid of mayonnaise dissolves out the iron from a tin-lined tank and may become contaminated with metals, which accelerate rancidity and shorten the shelf life of the finished product (Epstein, 1929b; Reynolds, 1927). Epstein (1929a) pointed out that the presence of metals in mayonnaise products not only causes rancidity but also it decreases nutritional value of ingredients present in the product. However, with proper care and precautions it is possible to lessen the risk of contamination of products, for instance, using aluminium utensils.

Temperature

We know from lipid oxidation theory that high temperature increases lipid oxidation (Frankel, 1998). Findings from experiments with mayonnaise have shown the increase in oxidation at higher temperatures which are in agreement with lipid oxidation theory. A study investigating the effect of temperature on the oxidation of fish oil mayonnaise, showed that fish oil mayonnaise is more stable at refrigerator temperatures (2 °C) than at higher temperatures (30 °C) (Hsieh & Regenstein, 1991). In addition, a study on the oxidative stability of cholesterol in commercial mayonnaise demonstrated that temperature and time are important factors in oxidation of cholesterol in mayonnaise. They proposed that total formation of cholesterol oxides during 165 days was 20.3 µg/g at 4 °C and 30.2 µg/g at 25 °C. Hence, decreasing storage temperature could be a good way of supressing the oxidation of cholesterol in mayonnaise (Morales-Aizpurúa & Tenuta-Filho, 2005). Based on another study, light mayonnaise (40% oil), even those without fish oil, cannot be stored at 20 °C for 4 months because of significant lipid oxidation (Sørensen, Nielsen, Hyldig, & Jacobsen, 2010). Consistent with previous studies, higher totox values and peroxide values were recorded for mayonnaises stored at 25 °C compared with samples stored at 4 °C (Li et al., 2014).

Light

Lipid oxidation caused by light exposure can be due to either photolytic auto-oxidation or photosensitized oxidation. Photolytic auto-oxidation occurs when lipids are exposed to ultraviolet radiation and consequently, free radicals are produced. On the other hand, in the presence of photosensitisers and visible light, unsaturated fatty acids undergo photosensitised oxidation. Natural pigments present in foods, such as riboflavin and chlorophylls, are known to be efficient photosensitisers due to their conjugated double-bond system (Bradley & Min, 1992). Light, with a wavelength of 365 nm, promotes the oxidation of unsaturated fats due to photosynthesised oxidation but light of wavelengths above 470 nm has no effect. Hence, it is important to protect mayonnaise from wavelengths shorter than 470 nm (Lennersten &

Lingnert, 2000). The visible light in the blue range also increases oxidation in mayonnaise. Considering lights used in supermarkets (significant source of light at 365 nm and in the 410-450 nm range) avoiding intensive lighting can help preserving the fresh taste of mayonnaise (Lagunes - Galvez, Cuvelier, Odonnaud, & Berset, 2002).

Packaging

In addition to processing, mayonnaise quality during storage depends on the chosen packaging material. Some substances used in these materials may migrate to the food matrices and cause off-flavours. In some cases, gas may permeate the packaging material and cause oxidation of mayonnaise. Producers choose packaging materials based on several factors (e.g. the costs of material, shelf life of the product and the convenience to the user). Usually manufacturers use glass or polyethylene plastics. Glass is a greater barrier against oxygen than many plastics, so it can provide better protection against oxidation of the mayonnaise (Buquet, 1979). Polyester materials such as PET (polyethylene terephtalate) and PEN (polyethylene naphtalate) are also popular in mayonnaise packaging. They have the benefits of glass like lightness, breakability and transparency. However, producers should consider light transmission properties of packaging material in choosing the right packaging material. The polyester materials (PET, PEN and PET/PEN) filter out the ultraviolet radiation to different degrees (PEN and PET/PEN > PET) and thereby protect mayonnaise against lipid oxidation, but not against colour changes (Lennersten & Lingnert, 2000). The incorporation of Amosorb as an oxygen scavenger in PET greatly improves the oxidative stability of mayonnaise (Sensidoni, Leonardi, Possamai, Tamagnone, & Peressini, 2004). Other types of packaging, such as Tetra Brik, reduce mayonnaise oxidation and extend shelf life of mayonnaise by protecting it from air and light (Berasategui, 2001). In addition to packaging materials, other factors like type and size of packaging may affect shelf life of mayonnaise. Studies showed that type of package (jar or pouch) do not have an effect on changes during storage time while package size influence aroma of mayonnaise (Martinez, Mucci, Cruz, Hough, & Sanchez, 1998). Reducing oxygen concentration (minimizing headspace in the container or packaging under vacuum or nitrogen) can reduce the oxidation rate in mayonnaise (Hsieh, 1990; Hsieh & Regenstein, 1991).

pH

The pH of mayonnaise ranges from 3.6 to 4.0 (Krishnamurthy & Witte, 1996). The highest viscoelasticity and stability of mayonnaise is achieved when the pH is close to the isoelectric point of the egg yolk because of the minimum charge on the proteins (Depree & Savage, 2001). However, decreasing pH from neutral to around four can have a strong pro-oxidant effect on mayonnaise by breaking bridges between the egg yolk proteins (low-density lipoproteins, lipovitellin, and phosvitin) and iron. Subsequently, iron releases from the egg yolk and becomes more accessible as oxidation initiator (Jacobsen, Adler-Nissen, & Meyer, 1999; Jacobsen, Timm, & Meyer, 2001). In addition to having pro-oxidant activity, the distribution of the volatile compounds (secondary products of oxidation) is dependent on pH. For example at pH 4, carbonyl compounds (propanal) can easily migrate from the liquid phase to gas phase because of weak interactions between the proteineous emulsifier under acidic conditions, so the stability of the mayonnaise flavour could be totally different from oxidative stability (Takai, Endo, Okuzaki, & Fujimoto, 2003).

Chemical structure of lipids

Susceptibility of a lipid molecule to oxidation is determined by its chemical structure, in particular, the number and location of the double bonds (McClements & Decker, 2000). Saturated lipids are more stable to lipid oxidation than unsaturated lipids. One of the ways of retarding oxidation could be to use saturated lipids but in practice, it is not possible because different types of lipid in mayonnaise can provide special physical and sensory characteristics that cannot be obtained using saturated lipids. Incorporating lipids that contain polyunsaturated fatty acids into mayonnaise can improve consumers' health, but these are less stable because of their double bonds. Surprisingly, from the studies on fish oil enriched mayonnaise, we can see that this mayonnaise does not oxidise faster or more than mayonnaises without fish oil. However, development of unpleasant off-odours and off-flavours in fish oil enriched mayonnaise is much faster than for mayonnaise without fish oil (Bragadóttir, Þorkelsdóttir, Klonowski, & Gunnlaugsdóttir, 2006; Jacobsen, Hartvigsen, et al., 1999). Off-flavour in fish oil enriched mayonnaise may be caused by specific volatile compounds with low sensory threshold values that stem from the oxidation of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Sørensen, Nielsen, Hyldig, et al., 2010).

Recently the interest in using structured lipids for nutritional applications has increased. Three different lipids based on sunflower oil such as: traditional sun flower oil (SO), specific structured lipid from sunflower oil and caprylic acid (SL), and chemically randomized lipid (RL) were used in mayonnaise and their oxidative stability was studied (Jacobsen, Xu, Skall Nielsen, & Timm-Heinrich, 2003). Mayonnaise produced with SL had the least oxidative stability among the three. The low oxidative stability of mayonnaise based on SL could be due to several factors, but the most influential were the structure of the lipid, the lower tocopherol content and the higher initial levels of lipid hydroperoxides and secondary volatile oxidation compounds in the SL itself compared with the RL and traditional sunflower oil employed. Although the oxidative stability of mayonnaise was totally dependent on the lipid type, the rheological properties of the mayonnaise was influenced by the structure of the lipid (Jacobsen et al., 2003). Taken together, obtaining a good quality mayonnaise enriched with SL, the process of purifying and producing SL based on sunflower oil should be improved. In addition, structured lipids based on fish oil were incorporated in mayonnaise and their oxidative stability was studied (Timm-Heinrich, Xu, Nielsen, & Jacobsen, 2004). The oxidative stability of mayonnaise was significantly dependant on lipid type. The mayonnaise based on specific structured lipid showed the least oxidative stability and these results were in good agreement with a previous study on structured lipid based on sunflower oil (Jacobsen et al., 2003).

Using two different types of oil in mayonnaise can change the oxidative stability of mayonnaise. For instance, mayonnaise made with mixed saturated medium triglyceride and unsaturated linseed oil was less prone to oxidation than mayonnaise made with unsaturated linseed oil (Raudsepp, Brüggemann, Lenferink, Otto, & Andersen, 2014). It can be assumed that mixed unsaturated medium triglyceride decreased the oxidation of unsaturated linseed oil droplets but the oxidative stabilization of mixed oil mayonnaise was not just due to diluting unsaturated triglycerides with saturated triglycerides. Further studies are needed in order to identify these effects.

Oil concentration

The food industry is trying to develop healthier products such as low fat formulations in response to advice from consumers. Low fat mayonnaise is expected to have a lower rate of oxidation than whole mayonnaise (Abu-Salem & Abou-Arab, 2008) but there are some contradicting results about the effect of reduced fat content on lipid oxidation of mayonnaise. In a study on mayonnaise with 63% oil and mayonnaise based salad with lower amount of oil (24%), it was found that the mayonnaise with more oil was more oxidatively stable than mayonnaise with less oil (Sørensen, Nielsen, & Jacobsen, 2010). Moreover, fish oil enriched mayonnaise used in this study had a greater oxidative stability compared to other fish oil enriched mayonnaises in other studies. Sørensen et al. (2010) referred this higher oxidative stability to a combination of lower total oil content (63%), lower fish oil content (6.3%) and low storage temperature (2 °C). In another study, light mayonnaise (40%) oxidized at the same rate as a full fat mayonnaise (80%) but faster than (63%) mayonnaise (Sørensen, Nielsen, Hyldig, et al., 2010). Therefore, it is likely that factors other than the oil content affect the oxidation rate in light mayonnaises, and further investigations should be done to resolve this issue.

Type of emulsifier

In mayonnaise, oil droplets are surrounded by a membrane of emulsifier molecules that provides physical stability of the emulsion and oxidative stability by acting as a barrier against pro-oxidants such as metals and free radicals. Hence, the effect of emulsifier on the oxidative stability of mayonnaise is important.

Mayonnaise is traditionally made from egg yolk, which plays the role of emulsifying agent. Besides egg yolk, several emulsifiers have been used in mayonnaise and their oxidative stability has been studied. Lecithin from different oil sources (sunflower, corn germ and soybean) as well as their modified forms (lecithin-soybean protein isolate and alcohol soluble fraction) were used in low calorie mayonnaise (Magda, Mostafa, El-Deep, & Kishk, 2003). Mayonnaise made with whole egg was the most sensitive to oxidation while soluble lecithin fractions were the best emulsifiers during storage period. It can be concluded that the use of modified lecithins can improve the oxidative stability of low calorie mayonnaise (Magda et al., 2003). On the other hand, a study on oxidative stability of mayonnaise-like emulsions containing salmon oil emulsified with soy milk and whole egg showed that the emulsion prepared with whole egg was more stable to oxidation than the mayonnaise made with soymilk (Takai et al., 2003). Soymilk and whole egg have a variety of proteins so the protein structures in the emulsion might influence the form and size of lipid droplets. Additionally, electric charge differs between whole egg and soymilk. Moreover, phospholipids might act as antioxidants and increase oxidative stability of emulsions containing whole egg. Some studies on fish oil enriched mayonnaise suggested the pro-oxidant effect of iron from egg yolk used as emulsifier at low pH (Jacobsen, Timm, et al., 2001). Based on these findings Sørensen et al. (2010) decided to investigate the influence of substituting egg yolk as an emulsifier with an emulsifier with a lower iron content such as milk protein on oxidative stability of fish oil enriched mayonnaise. Surprisingly replacing egg yolk with a lower iron-containing emulsifier did not enhance the oxidative stability of fish oil enriched mayonnaises. Even though the mayonnaise with milk protein as emulsifier was more viscous and probably had a multilayer or a cationic surface around the oil, the peroxide value of it was 100-fold higher than the peroxide value of mayonnaise with egg yolk. From the results of this study, Sørensen et al. (2010) suggested that the initial quality of emulsifier is even more important than its iron content.

The influence of ingredients

Mayonnaise is composed of an array of components in the aqueous phase and at the oil-water interface, such as NaCl, sugar, lemon juice and vinegar, that can affect lipid oxidation processes. Some of these ingredients contain low concentrations of Fe and Cu (Jacobsen, Hartvigsen, et al., 2000) but egg yolk, a traditional emulsifier in mayonnaise, is a major source of iron and contains >720 µM iron, but only ~17 µM copper. The iron in the egg yolk is bound to the protein phosvitin (Causeret, Matringe, & Lorient, 1991). Mayonnaise has a low pH and at this pH, the iron bridges between phosvitin, lipovitelin and low-density lipoprotein (LDL) break and cause the release of iron. Ascorbic acid is able to reduce Fe^{3+} to Fe^{2+}, which is more active as an oxidation catalyst than Fe^{3+} (Jacobsen, Adler-Nissen, et al., 1999; Jacobsen, Timm, et al., 2001). This phenomenon can happen even when Fe^{3+} is bound to phosvitin as indicated in Figure 1 (equilibrium 3).

Accessible iron either at the oil/water interface (as with low pH) or in the aqueous phase (as with the presence of ascorbic acid) catalyses the breakdown of hydroperoxides (LOOH) to secondary oxidation products ($LOOH + Fe^{2+} \rightarrow LO^{\cdot} + OH^{-} + Fe^{3+}$) that make rancid and fishy off-flavours. Lemon juice in the aqueous phase of mayonnaise promotes radical formation. This could be because of the presence of ascorbic acid in lemon juice. As mentioned above ascorbic acid in mayonnaise acts as a pro-oxidant because it can form a complex between iron and ascorbate, which breaks lipid hydroperoxides at the oil-water interface (Hsieh, 1990; Jacobsen, Adler-Nissen, et al., 1999). Vinegar is one of the mayonnaise ingredients that act as pro-oxidant because of its ability to reduce the pH and subsequently increase the release of iron from egg yolk (Thomsen, Jacobsen, & Skibsted, 2000). Salt has an important role to play. It contributes to the flavour of mayonnaise and can promote the stability of emulsion. In addition, salt can influence the rate of auto-oxidation. The effect of three types of salt: NaCl, mineral salt (65% NaCl, 25% KCl and 10% $MgSO_4.6H_2O$) and Morton Lite salt (50% NaCl, 50% KCl) showed that NaCl and mineral salt increased the oxidation of mayonnaise in the absence of antioxidant while Morton Lite salt did not (Lahtinen & Ndabikunze, 1990). However, antioxidant neutralized their effect but 85% NaCl still increased the oxidation level. On the other hand Thomsen et al. (2000) indicated that neither NaCl nor sugar induce the formation of radicals in freshly produced mayonnaise. Ostrich eggs are a good source of protein, total lipids, carbohydrates, calcium, phosphorus, potassium, sodium and zinc. Interestingly, a study showed that mayonnaise made from ostrich eggs was more oxidatively stable than that made from chicken eggs (Abu-Salem & Abou-Arab, 2008). Also, in that study they found out that by pasteurization of mayonnaise made either with ostrich eggs or with chicken eggs, we can increase oxidative stability of mayonnaise. Pasteurization is likely to stabilise the egg by inactivating pro-oxidation and oxidation factors and oxidation mediating enzymes.

Physical structure of mayonnaise

Contact between iron and oil in water emulsion droplet surface promotes metal catalysed oxidation. Therefore, it could be assumed that the size of the total oil droplet surface area influences the rate of oxidation. For this reason, a study investigated the influence of oil droplet size on oxidative stability of mayonnaise (Jacobsen, Hartvigsen, et al., 2000). They found out that kinetics of the initiation and propagation of oxidation process in mayonnaise is greatly affected by oil droplet size. Mayonnaise with larger droplets developed fishy and rancid off-flavour slower and later than mayonnaise with smaller droplets in the initial stage of the storage period. These findings show that the initial oxidation of mayonnaise is dependent on interfacial area and support the hypothesis that lipid oxidation is initiated at the oil/water interface. However, the propagation of oxidation is less dependent on interfacial area. Moreover, the droplet size also influences the rheological properties of mayonnaise. It has been proposed that one way of retarding oxidation in oil in water emulsion could be reducing the diffusion rate of oxidation by increasing the viscosity of the aqueous phase (Sims, Fioriti, & Trumbetas, 1979). Although higher viscosity generally decreases the rate of oxidation by reducing the diffusion rate of pro-oxidants, in the case of mayonnaise, higher viscosity increased the oxidation rate due to a smaller average particle size. Therefore, it seems that particle size plays a greater role than viscosity in oxidation processes in mayonnaise. Mayonnaise with small droplet size is more physically stable. In order to meet the needs of food manufacturers for having both physically and oxidative stable mayonnaise, optimal combination of processing conditions and emulsifiers should be adopted (Jacobsen, Hartvigsen, et al., 2000).

Retarding lipid oxidation in mayonnaise

Eliminating possible factors, which will reduce the induction period and hasten rancidity, can increase the shelf life of mayonnaise. Some of the means of retarding lipid oxidation is reducing oxygen concentration in food (by packing under vacuum or nitrogen and using packaging materials with good oxygen barrier properties) (Coupland & McClements, 1996) and lowering the storage temperature. For example, exclusion of oxygen by using nitrogen can retard lipid oxidation more than addition of Tertbutyl hydroquinone (TBHQ) (0.02%) to mayonnaise produced with fish oil (70%) (Hsieh & Regenstein, 1991). However, exclusion of oxygen in a used food product is difficult so one of the most effective means of retarding lipid oxidation in mayonnaise is to incorporate antioxidants. Several studies have been carried out on the effect of synthetic and natural antioxidants in mayonnaise. Table 1 presents collated summary on the use of natural and synthetic antioxidants in mayonnaise.

Synthetic antioxidants used in mayonnaise

According to the codex standard for mayonnaise, utilizing of some chemical antioxidants at defined concentration is permitted. Synthetic antioxidants such as BHT, BHA, TBHQ and EDTA have been used in food industry to prevent the oxidation of fat in food. Although these products are more economical than natural antioxidants, they get a negative impression for being a synthetic product. Among the synthetic antioxidants, BHA and BHT are widely used in food industry (Sanhueza, Nieto, & Valenzuela, 2000).

TBHQ

Tert-butylhydroquinon **(**TBHQ) is a popular synthetic antioxidant. It is a phenolic compound and a polar antioxidant (Belitz, Grosch, & Schieberle, 2009). The maximum level of allowed TBHQ in the finished product is 120 mg/kg according to Codex Alimentarius. It was a successful antioxidant for deodorized and stabilized fish oil mayonnaise stored at 2 °C for 14 weeks (Hsieh, 1990; Hsieh & Regenstein, 1991). In addition, TBHQ was effective at early storage times in lengthening the period before oxidation was initiated (Hsieh & Regenstein, 1992).

EDTA

Ethylene diaminotetraacetic acid (EDTA) is a synthetic antioxidant. It was the first widely used chelating agent. EDTA, together with ascorbic acid, propyl gallate, and citric acid, efficiently inhibited off-odor development in mayonnaise based on 100% fish oil (Jafar, Hultin, Bimbo, Crowther, & Barlow, 1994). EDTA can chelate free iron as well as phosvitin-bound iron in egg yolk at the oil-water interface (Thomsen, Jacobsen, et al., 2000). Therefore, iron ions are unable to catalyse lipid hydroperoxide decomposition to products that may develop oxidation or probably decompose further to off-flavour volatiles. EDTA has been found to prevent peroxide formation (Thomsen, Jacobsen, et al., 2000) also it has the ability to inhibit formation of heptadienal better than hexanal (Jacobsen, Hartvigsen, Thomsen, et al., 2001) and it can efficiently prevent off-flavours in mayonnaise. From all studies on the effect of EDTA on oxidation in mayonnaise we can conclude that it is an efficient antioxidant in mayonnaise (Jacobsen, Hartvigsen, Thomsen, et al., 2001; Jacobsen et al., 2003; Nielsen, Petersen, Meyer, Timm-Heinrich, & Jacobsen, 2004; Thomsen, Jacobsen, et al., 2000; Thomsen, Kristensen, & Skibsted, 2000).

As mentioned above EDTA prevented formation of heptadienal better than hexanal, this difference is due to the different origin of these volatiles (Jacobsen et al., 2008). Heptadienal is formed from n-3 fatty acids (n-3 peroxides) and are more polar than hexanal that is formed from n-6 fatty acids (n-6 peroxides). Therefore, n-3 peroxides may be present more in the aqueous phase or the oil/water interface than n-6 peroxides where EDTA is present. Therefore, co-localisation of EDTA and n-3 peroxides could be a reason of EDTA's efficiency on prevention of formation of n-3 peroxides. Other reason could be, more sensitivity of n-3 PUFA peroxides (because of having more high number of double bonds) to metal catalysed degradation (Jacobsen et al., 2008).

When EDTA was added to fish oil mayonnaise the droplet size, decreased but EDTA strongly inhibited oxidation. This result indicated that only when oxidation is catalysed by iron stemming from egg yolk compounds (phosvitin) at the oil water interface the droplet size is important otherwise a decrease in the oil droplet size did not promote oxidation rate (Jacobsen, Hartvigsen, Thomsen, et al., 2001).

Propyl gallate

Propyl gallate is an ester of gallic acid. Due to its alkyl chain, it is less polar than gallic acid. It is widely used as antioxidant in food industry. Previous studies suggested that propyl gallate was one of the two best phenolic antioxidants in mackerel muscle system (Kelleher, Silva, Hultin, & Wilhelm, 1992). Jafar et al. (1994) decided to use propyl gallate in fish oil mayonnaise as the free radical scavenger (propagation inhibitor) in the oil phase. They used the mixture of citric acid or sodium citrate and propyl gallate in the oil phase, and EDTA and ascorbic acid in the aqueous phase and suggested that this mixture could increase the shelf life of fish oil mayonnaise without antioxidant, from 1 day to an average of 49 days at room temperature as judged by sensory evaluation. In another study, Jacobsen, Hartvigsen, Lund, Meyer, Adler-Nissen, Holstborg, and Hølmer (1999) employed two different types of commercial propyl gallate mixtures (oil soluble (Grindox 370) and water dispersible (Grindox 413)) in fish oil mayonnaise. Propyl gallate not only increased the fishy and rancid off-flavour but also affected rheological characteristics of mayonnaise. Mayonnaise containing propyl gallate was less viscous, had bigger droplets and a lower gel strength. In addition, propyl gallate slightly increased the peroxide value of mayonnaise so it could be concluded that propyl gallate had a pro-oxidant effect in mayonnaise. Pro-oxidative property of propyl gallate (polar antioxidant) could be due to its presence at the interface where it can interact with metal ions (Fe^{3+}) in the egg yolk and its ability to alter the structural properties of the system (Jacobsen, Schwarz, et al., 1999). In order to confirm that if propyl gallate was a pro-oxidant in mayonnaise and omit the effect of type of oil Jacobsen et al. (2003) decided to use propyl gallate in mayonnaise with specific structured lipid (SL) from sunflower oil and caprylic acid . The results from this study were in good accordance with previous studies on fish oil mayonnaise. Mayonnaises had higher amounts of secondary oxidation products and volatile compounds. Therefore, it can be concluded that propyl gallate was a pro-oxidant.

Natural antioxidants used in mayonnaise

Because of synthetic antioxidants' chemical stability, low cost and availability they are universally applicable. However, some studies questioned their safety due to their potential risk. Nowadays consumers are more concerned about the safety of preservatives and additives. Therefore, there is a growing trend in consumer preferences toward clean labelling. All of these motivated food industries to explore natural sources of antioxidants.

Gallic acid

Gallic acid is a plant phenolic acid. Antioxidant activity of phenolic acids is generally by trapping free radicals. Mayonnaise is a hetrophasic food system, in such a system antioxidants may partition into different phases. In mayonnaise, 80% of gallic acid –a polar antioxidant- is partitioned in the aqueous phase but 20% of it is distributed in the interface (Jacobsen, Schwarz, Stöckmann, Meyer, & Adler-Nissen, 1999). In a study on fish oil mayonnaise, addition of gallic acid, caused the increase in the intensity of fishy, rancid and metallic off-flavour due to a faster decomposition of hydroperoxides (Jacobsen, Hartvigsen, Thomsen, et al., 2001). It is hypothesised that 20% of gallic acid was located at the oil-water interface (Jacobsen, Schwarz, et al., 1999) and gallic acid can reduce metal ions and therefore it may interact with metal ions from phosvitin at the oil-water interface. Nevertheless, gallic acid slightly decreased droplet size that could increase the rate of lipid peroxide decompositions in mayonnaise. In conclusion, gallic acid showed a pro-oxidant activity in mayonnaise because of its ability to reduce metal ions to their more active form e.g. Fe^{3+} to Fe^{2+} (Jacobsen, Hartvigsen, Thomsen, et al., 2001; Jacobsen, Horn, Sørensen, Farvin, & Nielsen, 2014).

Ascorbic acid

Ascorbic acid is a natural water-soluble antioxidant. It mainly exerts its antioxidative effect by terminating chain radical reactions via electron transfer (Gülçin, 2012) but may also act as an O_2 scavenger (Pongracz & Kläui, 1981). Ascorbic acid is considered as a pro-oxidant because it can catalyse the breakdown of already existing lipid hydroperoxides (LOOH) via reduction of Fe^{3+} to Fe^{2+} (Frankel, 2005). As already mentioned in previous section on propyl gallate, Jafar et al. (1994) employed a mixture of antioxidants (citric acid or sodium citrate and propyl gallate in the oil phase and EDTA and ascorbic acid in the aqueous phase) which increased the shelf life of mayonnaise without antioxidant, from 1 day to an average of 49 days at room temperature. In this mixture of antioxidants, ascorbic acid functioned as the free radical acceptor and perhaps as reducing agent. However, addition of ascorbic acid to fish oil mayonnaise developed the formation of strong metallic, fishy and rancid off-flavours in fish oil mayonnaise and acted as a pro-oxidant. The intensity of off-flavours was dependent on ascorbic acid concentration (Hsieh & Regenstein, 1991; Jacobsen, Adler-Nissen, et al., 1999; Jacobsen, Timm, et al., 2001). When ascorbic acid is added to the aqueous phase of mayonnaise, it can reduce Fe^{3+} to Fe^{2+}, which is more active as an oxidation catalyst. This may happen even at high pH (Fe^{3+} is bound to phosvitin) or at low pH (iron ions are more accessible, Fe^{2+}, are liberated from egg yolk). Hence, ascorbic acid accelerates and promotes oxidation in fish oil mayonnaise (Jacobsen, Timm, et al., 2001).

Tocopherol

Tocopherols are the best known and most widely used antioxidants (Pokorny, 1987). They have four isomers (α, β, γ and δ). Tocopherols act as primary antioxidants by donating the hydrogen of the hydroxyl group to the lipid peroxyl radical. Also they are efficient singlet O_2 scavengers (Burton & Ingold, 1981). They can react with hydroperoxyl radicals and alkoxyl free radicals formed by the metal-catalysed decomposition of hydroperoxides (Burton & Ingold, 1981; Huang, Frankel, & German, 1994). In mayonnaise, antioxidative effect of tocopherols was dependent on whether it was water (Grindox 1032) or oil (Toco 70) soluble complex and also on its concentration (Jacobsen, Adler-Nissen, et al., 2000). Water soluble tocopherol resulted in the highest antioxidative effect against both peroxides and volatiles formation, reduced the formation of rancid and fishy off-flavours and increased oil droplet sizes and gel strength compared to oil soluble tocopherol in fish oil mayonnaise. However, oil soluble tocopherol (Toco 70) at high concentrations showed pro-oxidative effects on fishy odour and flavour. The antioxidative properties of water-soluble tocopherol may be due to its ability to decrease the total interfacial area and higher gel strength (Jacobsen, Adler-Nissen, et al., 2000). To get a better insight into the effect of tocopherol on oxidation in mayonnaise Jacobsen, Hartvigsen, Lund, et al. (2001) studied the effect of tocopherol concentration on oxidation. Surprisingly their results were in contrast to their previous study. They found out that Grindox 1032 showed pro-oxidative effect in high concentrations (more than 700 mg/kg, corresponding to 140 mg/kg tocopherol) and in low concentration, showed a week antioxidative effect. They indicated that the different effects of low concentration of Grindox 1032 and Toco 70 on the formation of volatiles could not be due to differences in droplet size. They suggested that the droplet size could be influenced by parameters other than antioxidant addition e.g., small differences in processing conditions. A significant pro-oxidant effect of Grindox 1032 was seen when more than 700 mg/kg Grindox (corresponding to 140 mg/kg tocopherol) was added to mayonnaise. Therefore, it could be concluded that addition of more than 740 mg/kg total tocopherol had pro-oxidative effect. To sum up addition of tocopherol to fish oil mayonnaise is not a good choice of antioxidant. That may be because of it lacks the ability to prevent the metal catalysed decomposition of peroxides.

Rosemary

Recently a lot of attention has been employed on using natural antioxidants of plant extracts. Phenolic compounds that act as natural antioxidants are widely distributed in plant tissues like rosemary. The most effective antioxidant constituents of rosemary are phenolic diterpenes carnosic acid and carnosol. Carnosic acid has several times more antioxidative activity than phenolic synthetic antioxidants like BHT and BHA (Richheimer, Bernart, King, Kent, & Beiley, 1996). Carnosic acid and carnosol can chelate iron and scavenge peroxyl radical in lipid-based systems (Aruoma, Halliwell, Aeschbach, & Löligers, 1992). However, few studies have been carried out on utilising rosemary as an antioxidant in mayonnaise. Addition of rosemary extract to sunflower oil mayonnaise decreased the level of volatile compounds formed from photooxidation in the headspace (Lagunes-Galvez et al., 2002). Rosemary extracts could have a chelating effect in sunflower oil mayonnaise. Also, the antioxidative effect of dried rosemary at a concentration of 1% was studied in fish oil enriched tuna salad (Sørensen, Nielsen, & Jacobsen, 2010). Although rosemary inhibited formation of peroxide and showed antioxidative effect, the taste introduced to the product might be undesirable in tuna salad (Sørensen, Nielsen, & Jacobsen, 2010).

Lactoferrin

Lactoferrin is a milk glycoprotein occurring naturally in numerous bodily secretions, including milk, tears, mucus, blood, and saliva. Lactoferrin is also the main iron-bearing protein in cow's milk, and it is able to bind two Fe^{3+} in cooperation with two HCO^{3-} ions when fully saturated (Nielsen et al., 2004). Synthetic chelating agents like EDTA could be replaced by lactoferrin, which is a natural compound with a metal chelating property. So studies have been done on the possibility of using lactoferrin in mayonnaise as a chelating agent (Jacobsen et al., 2003; Nielsen et al., 2004). In a study on structured lipid (SL) from sunflower oil mayonnaise, 10 µm of lactoferrin was used as an antioxidant. This study showed that lactoferrin at this concentration did not show any antioxidative effect (Jacobsen et al., 2003). Jacobson et al. (2003) suggested that the protein may become denatured at the low pH (pH of mayonnaise was 4.0) and lose its ability to chelate iron. However, only one concentration of lactoferrin was tested in SL mayonnaise and other concentrations should be tested. Therefore, in another study the antioxidative effect of lactoferrin (8-32 µM) in fish oil mayonnaise (16% fish oil, 64% rapeseed oil) was studied (Nielsen et al., 2004). Lactoferrin exhibited a concentration dependent protective effect. It worked optimally as an antioxidant at a concentration of 8 µm while it appeared to have pro-oxidative effect at high concentrations. The pro-oxidant effect of lactoferrin at high concentrations has been speculated to be a result of a change in conformation of lactoferrin when it is at the oil/water interface so metal ions are bound at other sites than its metal chelating sites. This binding brings the metal ions in contact with the lipid and results in pro-oxidant effect of lactoferrin (Nagasako, Saito, Tamura, Shimamura, & Tomita, 1993; Nielsen et al., 2004). In conclusion, lactoferrin appeared to have a slightly antioxidative effect in concentrations of 8-12 µm and was a pro-oxidant at higher concentrations.

Phytic acid

Natural metal chelating substances are present in foods, especially in plant materials. Phytic acid is in the group of natural chelating agents. Food industry and consumers prefer to use natural compounds instead of synthetic ones so in a study Nielsen et al. (2004) tried to use phytic acid in fish oil mayonnaise (16% fish oil, 64% rapeseed oil). However, they found no antioxidative effect of phytic acid in mayonnaise. Lacking antioxidative effect of phytic acid could be due to several reasons: 1. the low pH of mayonnaise that may affect the ability of the phosphoric groups in phytic acid to bind the positively charged Fe ions and 2. a very low formation of the Fe-phytic acid complex. From the available data on phytic acid as an antioxidant in mayonnaise, the efficacy of phytic acid as an antioxidant cannot be concluded so further investigation is needed.

Mustard

Mustard is a nutritious food compound (Fahey, Zalcmann, & Talalay, 2001). The characteristic flavour of mayonnaise is principally based on mustard (Depree & Savage, 2001). The flavour of mustard derives from a group of isothiocyanates especially allyl isothiocynate that are volatile sulphur compounds (Fenwick, Heaney, Mullin, & VanEtten, 1982). They are soluble in oil and slightly soluble in water. In mayonnaise, flavour molecules based on their solubility, partition between oil and aqueous phases. Mustard can act as an emulsifying agent in mayonnaise and stabilise the emulsion (Harrison & Cunningham, 1985). The mustard seed contains natural antioxidants. The antioxidant activity of mustard seed in oil/water emulsions has been studied (McCarthy, Kerry, Kerry, Lynch, & Buckley, 2001; Shahidi, Wanasundara, & Amarowicz, 1994). As meeting the need of using natural antioxidant is important, researchers decided to study the efficacy of mustard as an antioxidant in mayonnaise (Lagunes-Galvez et al., 2002; Milani, Mizani, Ghavami, & Eshratabadi, 2013). In a study on Dijon mayonnaise made with sunflower oil and mustard paste, mayonnaises could be stored for 10 months in closed jars while in mayonnaises without mustard, the oxidation rate was higher and more conjugated dienes were produced. So the protective role of mustard against oxidation in mayonnaise can be concluded from this study (Lagunes-Galvez et al., 2002). Also in another study the effect of different concentrations of yellow powder and paste mustard on rancidity and sensory properties of mayonnaise has been studied (Milani et al., 2013). To eliminate the adverse properties of mustard on mayonnaise such as changes in colour and flavour and also to improve sensory properties of mayonnaise they compared the use of mustard paste, which is made by heating treatments, and inactivation of myrosine enzyme to powder mustard. Yellow mustard paste and powder showed antioxidative effect and their antioxidative activity was concentration dependent. Using mustard paste improved sensory properties of mayonnaise by decreasing the pungent flavour also; it made the use of high concentrations of mustard paste (0.75%-1.5%) possible.

Fenugreek extract

Fenugreek (*Trigonella foenumgraecum*), is a food ingredient that is used traditionally in the Far East. It is recognised as a possible source of natural antioxidant. The effectiveness of fenugreek extracts in inhibiting/minimizing lipid oxidation in comparison with synthetic antioxidant (TBHQ and BHT) has been studied in mayonnaise (Mostafa, 2003). This study stated that fenugreek extracts at 500 mg/kg in mayonnaise showed the same antioxidant effect as TBHQ (200 mg/kg) but was more effective than BHT (200 mg/kg). Although high concentration of fenugreek (1500 mg/kg) was more effective than synthetic antioxidants, it had a diverse effect on sensory characteristics of mayonnaise. So based on this study fenugreek at 500 mg/kg can be used as a natural antioxidant in mayonnaise but further studies on fenugreek are essential.

Black glutinous rice

Black glutinous rice is generally used as an ingredient in snacks and desserts. It contains high amounts of phenolic compounds especially anthocyanins in pericarp that has the antioxidant ability and radical scavenging (Hu, Zawistowski, Ling, & Kitts, 2003; Ichikawa et al., 2001). Optimum condition of solvent extraction of black glutinous rice crude extract and its application in fish oil mayonnaise was studied (Tananuwong & Tewaruth, 2010). The highest antioxidant activity was obtained when extracted twice with 70:30 acetone-water mixture (v/v) at pH 6.8 for 4 hours of total extraction times. 1000 mg/kg crude extract could efficiently increase oxidative stability of mayonnaises. Phenolic compounds in black glutinous rice can retard oxidation with three mechanisms: 1. chain breaking, 2. hydroperoxide destroying and 3. metal chelating. In spite of good antioxidative ability of high concentrations of crude extract, greater colour deterioration could be seen. The reasons for the colour changes in mayonnaise might be a result of: 1. maillard reaction and 2. oxidative degradation of anthocyanin to undesirable brown-coloured products.

Lycopene

Lycopene is a natural food colorant. It is incorporated in dairy beverages, powdered beverages, dairy foods, surimi, confectionery, bakery, breakfast cereals, nutritional bars, soups, meal replacement, sauces, salsas, pastas, chips, snacks, dips and spreads. Lycopene crystals from tomato waste skin (50 mg/kg) were used in mayonnaise and its effect on oxidative stability of mayonnaise was studied during storage for four months (Kaur, Wani, Singh, & Sogi, 2011). Lycopene slowed down the development of off-flavour, off-odours, and colour changes and acted as an antioxidant by interrupting the chain of free radicals involved in auto-oxidation. Also, sensory analysis showed that lycopene-treated mayonnaises had good consumer acceptability.

Ginger powder

Ginger contains polyphenol compounds (6-gingerol and its derivatives), which have a high antioxidant activity (Chen, Kuo, Wu, & Ho, 1986) like TBHQ, BHA and BHT. Water ginger extract is a strong radical scavenger (Y. F. Kishk & El Sheshetawy, 2010). The role of ginger powder on oxidative stability of mayonnaise has been investigated (Y. Kishk & Elsheshetawy, 2013). This study showed that ginger powder at concentrations of 1.0% and 1.25% reduced the production of primary and secondary oxidation products (measured by anisidine value) and subsequently retarded oxidation process during storage for 20 weeks. The rheological properties of mayonnaise were not influenced by ginger powder at concentrations mentioned above. Interestingly, ginger powder improved the taste, flavour, mouth feel, and overall acceptability of mayonnaise at zero time, and after 20 weeks the overall acceptability of mayonnaise samples at concentration of 1.0% and 1.25% was improved.

Grape seed extract

Grape seed is a by-product from wine production that contains catechin and proanthocyanidins. It has radical scavenging and antioxidative properties. The potential use of grape seed extract on the oxidative stability and sensory properties of mayonnaise during storage for 8 weeks has been studied (Altunkaya et al., 2013). High concentrations of grape seed extract (0.15%) showed a very good antioxidative activity. However, mayonnaises without grape seed extract had a higher sensorial acceptability. On the other hand high concentrations of grape seed, extracts increase toxicological risk. Therefore, 0.50 mg/ml did not establish toxicological health and improved oxidative stability with acceptable sensory properties.

Essential oils extracted from Zenyan

Carum copticum is an annual herbaceous plant that grows in the east of India, Iran and Egypt. Its fruits (generally known as "Zenyan" in Iran) have been used extensively in Iranian folk and traditional medicine (Goudarzi, Saharkhiz, Sattari, & Zomorodian, 2010). The potential antioxidative ability of essential oils from Zenyan in mayonnaise has been studied. Also the differences between the antioxidative activity of two different extraction methods (ohmic assisted hydro distillation and conventional hydro distillation) were compared (Mazaheri Tehrani, 2013). The results from this study showed that the antioxidant activity of Zenyan essential oils was independent on extraction methods. However, they suggested ohmic assisted hydro distillation method for extraction of essential oils was more efficient than traditional hydro distillation method as in this method more time and energy will be saved. All concentration of essential oils (0.015%, 0.03% and 0.045%) showed antioxidant activity, against DPPH free radicals, in mayonnaise. They proposed that BHA and BHT (synthetic antioxidants used in mayonnaise) could be replaced by high concentration of Zenyan essential oils. Antioxidative property of Zenyan essential oils mainly is dependent on its thymol content. Thymol is a main component of essential oils and acts as a primary antioxidant by delaying or preventing the initiation and propagation step (Hashemi, Niakousari, & Saharkhiz, 2011). The colour of mayonnaises was not influenced by addition of Zenyan essential oils. However, the odour of mayonnaises with and without Zenyan was significantly different. Whereas, in the case of preference test there were no differences between all represented samples (Mazaheri Tehrani, 2013).

Chitosan

The antioxidant activity of chitosan derivatives has been reported in several studies but few studies have been done on real foodstuff. Antioxidant activity of chitosan with different molecular weighs was evaluated in mayonnaise (García, Silva, & Casariego, 2014). This study indicated that addition of chitosan not only retarded lipid oxidation of mayonnaises during 63 days of accelerated storage but also improved organoleptic properties (odour and taste). Mayonnaises treated with chitosan with the bigger molecular weight showed better stability during accelerated storage at all temperatures.

Tansy extracts

Tansy (Tanacetum vulgare L., Asteraceae) is an aromatic plant spread mainly in the northern hemisphere in Europe, Asia and North America. Its anti-inflammatory, antibactericidal, antifungicidal, insects' repellent and antioxidative activities is reported. Tansy acetone extract at higher concentrations could inhibit oxidation in rapeseed oil (Pukalskas & Venskutonis, 2000). The oxidative stability of mayonnaise treated with tenacy extract was studied. This study showed that all tansy extracts improved oxidative stability of mayonnaise (Baranauskienė, Kazernavičiūtė, Pukalskienė, Maždžierienė, & Venskutonis, 2014).

Clove

Cloves (Syzygium aromaticum Linn) are aromatic dried flower buds of the family Myrtaceae. Generally, clove extracts are used as biopreservatives in preventing food spoilage by pathogenic contaminants. The potential application of eugenol-lean fraction of clove buds as a flavouring agent (replacing mustard in the classic formulation) and as a natural antioxidant in mayonnaise was studied (Chatterjee & Bhattacharjee, 2014). Mayonnaise incorporated with eugenol-lean clove extract was found to be oxidative stable beyond 6 months. Also had better physical properties such as higher colour intensity, lower thermal and nonthermal creaming, homogenous and compact microstructure and higher consistency index. Organoleptically, addition of eugenol-lean clove extract did not cause any significant changes in body and consistency of all the mayonnaise samples.

Anthocyanin extracted from purple corn husk

Purple corn cobs, purple sweet potatoes and blueberries are usually the main source of anthocyanins employed as food colorant in commercial production (Kähkönen, Hopia, & Heinonen, 2001). Anthocyanins possess strong antioxidant capacity because they have free radical scavenging (Espin, Soler-Rivas, Wichers, & García-Viguera, 2000) and metal-chelating properties (Nam et al., 2006). Purple corn husk has 10 times more anthocyanins than other plant sources of anthocyanins (Li et al., 2008). The feasibility of the use of anthocyanins extracted from purple corn husk extract (PCHE) as a natural antioxidant in comparison with the synthetic antioxidants (BHT and EDTA) was studied (Li et al., 2014). Addition of PCHE reduced the amount of both primary and secondary oxidation products. The antioxidative activity of PCHE was concentration dependent and the mayonnaise containing 0.4 g/kg PCHE showed the strongest antioxidative performance during storage. This study proposed that PCHE could be used as a natural antioxidant in mayonnaise instead of synthetic antioxidants like BHT and EDTA. This study considered the colour difference (mayonnaises with PCHE had purplish colour) as a positive point and related it to the sign of natural antioxidant in consumers' food (Figure 2).

Seaweed

Plants and marine algae can be used as a source of natural antioxidants. Not only these antioxidants show potential for improving oxidative stability of food but also they have a broad array of health-promoting benefits (Hata, et al., 2001; Kim et al., 2009). Seaweed contains different tocopherols, amino acids, sulphated polysaccharides, mono- and polyphenols, and bioactive compounds (Honold et al., 2015). Seaweed extracts from *Fucus vesiculosus* as a potential antioxidant was used in mayonnaise (Hermund et al., 2015; Honold et al., 2015). *Fucus vesiculosus* is rich in polyphenols that can act as free radical scavengers and metal chelators. Hermund et al. (2015) evaluated the antioxidant properties of water extract (WE) and an ethyl acetate fraction (EAF) of *Fucus vesiculosus* and studied their efficacy to inhibit lipid oxidation in fish oil mayonnaise. 2 g/kg of WE was more efficient in lowering the formation of primary oxidation products and secondary oxidation products however, EAF was more efficient in decreasing the degradation of the n-3 PUFA. The effectiveness of EAF and WE was concentration dependant. It was shown that the antioxidant effectiveness of EAF and WE was related to high-total phenolic content, high-radical scavenging activity, moderate- or high-metal chelating ability and high-carotenoid content in the extract. In another study, the antioxidant properties of four extracts (ethanol (EtE), acetone (AcE), and water extracts (WE)) from *Fucus vesiculosus* in fish oil mayonnaise was studied (Honold et al., 2015). Ethanol and acetone extracts had higher antioxidant efficacy compared to water extracts. In this study, the concentration dependency of antioxidant efficacy was observed too. Same as Hermund et al. (2015) study, Honold et al. (2015) indicated the relation between the high-total phenolic content and high-radical scavenging activity with antioxidant efficacy but also they pointed out the location of phenolic compounds at the interface of oil droplets and water in mayonnaise.

Glucose oxidase (GOX)

Glucose oxidase is an enzyme that acts as a natural antioxidant in food products. Glucose oxidase can be isolated and purified from the mould *Aspergillus niger* (Whitaker, 1993). It is tightly bound to the mycelium so it is difficult to separate it from enzyme catalase (CAT) (Crueger & Crueger, 1990). Hence, in food grade preparation of glucose oxidase it is usually coupled with catalyse. GOX/CAT has the ability to scavenge molecular oxygen by catalysing the reaction of converting two moles of glucose and one mole of molecular oxygen to two moles of δ-gluconolactone which spontaneously hydrolyses to gluconic acid and hydrogen peroxide that can be removed by catalase (Crueger & Crueger, 1990; Frankel, 2005). Glucose oxidase has been utilised as an antioxidant in different mayonnaise systems. In mayonnaise containing 790 g/kg soy oil, 450 U/Kg of GOX could retard off-flavour, off-odour and rancid taste in dark at 20 °C (Skrede, RØtbotten, & Baardseth, 1991). In fish oil mayonnaise GOX/CAT system acted as an oxygen scavenger and prolonged the shelf life of the product at refrigerator temperature but at room temperature the mayonnaise with and without glucose oxidase showed no detectable differences (Jafar et al., 1994). To see if the enzyme system was active at room and refrigerator temperature and to get a better understanding of GOX/CAT activity in mayonnaise Isaksen and Adler-Nissen (1997) investigated the effect of GOX/CAT system in fish oil mayonnaise and soybean oil mayonnaise. They found that GOX/CAT system retarded lipid oxidation at 5 °C and 25 °C. As they expected GOX/CAT scavenged oxygen in the packages under the consumption of glucose. Although GOX/CAT could retard lipid oxidation, using it as antioxidant in mayonnaise cannot be practical because of formation of off-flavour in both mayonnaises at 5 °C and 25 °C. So in order to solve this problem further investigation is needed.

Factors affecting the activity of antioxidants

Polar paradox and cut off theory

The effectiveness of an antioxidant in oil/water emulsion is highly affected by its partitioning properties and its ability to be located in the environment where lipid oxidation takes place that could be at the interface between the oil and water phases (Coupland & McClements, 1996). Mayonnaise is a heterophasic food system, antioxidants may partition into at least three different phases, the aqueous phase, the oil phase and the interface between oil and water phase (Jacobsen, Schwarz, et al., 1999). In mayonnaise lipophilic antioxidants like tocopherol are located in the oil phase while the more polar antioxidants such as gallic acid (80% of gallic acid) are concentrated in the aqueous phase but a significant proportion of them distributed into interface (20% of gallic acid) (Jacobsen, Schwarz, et al., 1999). The relationship between antioxidant partitioning and antioxidant efficacy is also called “the polar paradox” (Figure 3) (Frankel, Huang, Kanner, & German, 1994; Laguerre et al., 2013). According to the so-called “polar paradox” theory, polar antioxidants would be more effective than their nonpolar analogues in bulk oil, whereas nonpolar antioxidants would be more effective in oil in water emulsion than their polar counterparts would. Gallic acid which is a polar antioxidant was added in mayonnaise (Jacobsen, Hartvigsen, Thomsen, et al., 2001). Gallic acid showed a poor antioxidative effect and these results were in accordance with the theory of polar paradox that the efficacy of polar antioxidants in oil in water emulsion is poor (Jacobsen, Hartvigsen, Thomsen, et al., 2001). To get more insights into the efficacy of the polar paradox theory in mayonnaise researchers tried two pairs of homologue antioxidants (ascorbic acid/ascorbyl palmitate and gallic acid/propyl gallate) in fish oil enriched mayonnaise (Jacobsen, Hartvigsen, et al., 1999; Jacobsen, Hartvigsen, Thomsen, et al., 2001; Jacobsen et al., 2008). In these studies, surprisingly all employed compounds acted as pro-oxidants and the antioxidant activity did not improve with increased lipophilicity.

From these reports authors concluded that in much more complex systems like mayonnaise, in which iron stemming from the egg yolk catalyses lipid oxidation and many different molecules can affect antioxidant activity polar paradox theory cannot predict the antioxidant efficacy.

Moreover there is another theory called “cut off” that shows the nonlinear influence of hydrophobicity on antioxidant capacity (Laguerre et al., 2013). Lipophilization of antioxidants can improve antioxidant efficacy. However, there are not many studies on their effectiveness in real food systems such as mayonnaise. Alemán et al. (2015) investigated the antioxidant effect of caffeic and its esters (caffeates C1-C18) in fish oil mayonnaise. Both caffeic acid and caffeates had antioxidative effect in fish oil mayonnaise. The caffeates with short to medium alkyl chain (butyl, octyl and dodecyl) were the most effective antioxidants. Whereas, the increase in alkyl chain caused a collapse in the antioxidant capacity of esterified phenolic compounds. This phenomenon can be explained by the cut off theory. The caffeates retarded the formation of both primary and secondary oxidation products in fish oil mayonnaise.

Conclusion and future perspectives

This review has highlighted the important factors affecting lipid oxidation in mayonnaise. A general conclusion is that we can reduce oxidation in mayonnaise by cutting of the factors that reduce the induction period and accelerate rancidity such as lowering the storage temperature, reducing oxygen concentration in food, avoiding intensive lighting, manipulating chemical structure of the oil and physical properties of mayonnaise. In addition, one of the promising ways of retarding oxidation in mayonnaise could be using antioxidants. As people are more concerned about their health there is a worldwide trend toward using natural antioxidants in food products. After reviewing the literature about using natural antioxidants in mayonnaise, it can be concluded that it could be possible to design a mayonnaise with greater oxidative stability, by replacing synthetic antioxidants with natural ones. However, as mayonnaise contains a variety of different components still there is a scarcity of knowledge on the influence of these components on the efficacy of natural antioxidant activity. Further elucidation of the mechanism of oxidation in mayonnaise and a better understanding of antioxidant efficacy would have a great technological importance. The importance of interfacial characteristic of oil droplets has been already demonstrated but using new strategies for retarding lipid oxidation by manipulating the interfacial properties of oil droplet in mayonnaise is missing. The challenge in using natural antioxidants in mayonnaise is to obtain a product with good sensory properties and satisfactory shelf-life hence further studies of the influence of natural antioxidant on the sensory properties of mayonnaise are required. After gathering information on using natural antioxidants in mayonnaise we came to a conclusion that in future more studies should be done on issues like: elucidating the mechanism of oxidation in mayonnaise in order to find the best antioxidant, more studies on the factors affecting antioxidant efficacy in mayonnaise like systems, manipulating interfacial area of oil in water emulsion droplets to decrease rate of oxidation, finding more sources of natural antioxidants and finally working on how to obtain the best sensory properties with using natural antioxidants. In our laboratory we currently are working on elucidating process of oxidation in mayonnaise stored at different temperatures and finding new sources of natural antioxidants as a potential alternatives of synthetic antioxidant.

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Table 1. Summary of the use of natural and synthetic antioxidants in mayonnaise

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (70%)	TBHQ (0.02%)	There were few signs of oxidation in the deodorized and stabilized fish oil mayonnaise at 2 °C and 14 weeks of storage.	(Y.-T. L. Hsieh, 1990)
Fish oil mayonnaise (70%)	TBHQ (0.08%) Ascorbic Acid (0.5%)	TBHQ was a successful antioxidant for fish oil mayonnaise while ascorbic acid had pro-oxidant effect in fish oil mayonnaise	(Y. T. Hsieh & Regenstein, 1991)
Soy oil mayonnaise (790 g/kg soy oil)	Glucose oxidase (GOX) (450 units per kg (U/kg), 200 U/kg)	450 U/Kg of GOX could retard rancid taste, off-flavour and off-odour developments in mayonnaise stored in dark at 20 °C for 8 months, whereas 200 U/Kg of GOX could not prevent deterioration of the organoleptic quality.	(Skrede et al., 1991)
Fish oil mayonnaise Soy oil mayonnaise Corn oil mayonnaise	TBHQ (0.08%)	In fish oil mayonnaise TBHQ was effective at early storage times in lengthening the period before oxidation was initiated.	(Y.-T. L. Hsieh & Regenstein, 1992)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (menhaden and capelin oils, 100% fish oil)	Propyl gallate, citric acid, EDTA, BHT, BHA, ascorbic acid, carboxymethylcellulose, sodium tripolyphosphate, lecithin, superoxide dismutase, catalase, and GOX/CAT.	GOX/CAT had a significant effect on reduction of the development of off-odour when mayonnaise was stored at refrigerator temperature, but at room temperature, the enzymes were not effective. Citric acid or sodium citrate and propyl gallate in the oil phase and EDTA and ascorbic acid in the aqueous phase increased the shelf-life to an average of 49 days at room temperature	(Jafar et al., 1994)
Fish oil mayonnaise (16% fish oil)	Antioxidant system: ascorbic acid, lecithin and gamma tocopherol (A/L/T) (4 g/kg mayonnaise)	Addition of A/L/T system resulted in strong fishy and rancid off-flavours of mayonnaise despite low peroxide and anisidine values.	(Meyer & Jacobsen, 1996)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (0, 0.25 and 0.50 of the vegetable oil was substituted by fish oil corresponding to contents of 0, 200 and 400 g/kg) Soybean oil mayonnaise	Glucose oxidase/catalase (GOX/CAT) (0, 400 and 800 units/kg)	The enzyme system of GOX/CAT could reduce lipid oxidation in mayonnaise both sored at 25 °C and 5 °C in soybean oil and fish oil mayonnaise.	(Isaksen & Adler-Nissen, 1997)
Fish oil mayonnaise (16% fish oil)	Propyl gallate, oil soluble (Grindox 370) and Propyl gallate, water dispersible (Grindox 413)	propyl gallate was a weak pro-oxidant.	(Jacobsen, Hartvigsen, et al., 1999)
Fish oil mayonnaise (16% fish oil)	ascorbic acid (0-800 mg/kg)	Ascorbic acid increased the formation of fishy off-flavours in fresh mayonnaise.	(Jacobsen, Adler-Nissen, et al., 1999)
Fish oil mayonnaise (16% fish oil)	α-, *β*-, and *γ*-tocopherol and six polar antioxidants (trolox, ferulic acid, caffeic acid, propyl gallate, gallic acid, and catechin)	Antioxidants partitioned in accordance with their chemical structure and polarity.	(Jacobsen, Schwarz, et al., 1999)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (16% fish oil)	A/L/T, and two commercial mixtures of tocopherol, an oil-soluble (Toco 70) preparation and a water-soluble (Grindox 1032)	Addition of A/L/T system caused the immediate formation of distinct fishy and rancid off-flavours in the fresh mayonnaises Addition of Toco 70 did not affect the sensory perception of mayonnaise nor the development of volatile off-flavour compounds, but the peroxide values were slightly increased as compared to the other mayonnaises. Mayonnaise with Grindox 1032 seemed to have fewer fishy and rancid off-flavours than mayonnaises without antioxidant.	(Jacobsen, Adler-Nissen, et al., 2000)
Fish oil mayonnaise (16% fish oil)	EDTA (0, 50, 75, 125, and 200 mg/g)	EDTA (down to 50 mg/g) efficiently delayed oxidation in fish oil enriched mayonnaise.	(Thomsen, Jacobsen, et al., 2000)
Fish oil mayonnaise (16% fish oil)	EDTA (0 and 75 mg/kg)	A significant antioxidative effect of EDTA for lipid samples from mayonnaise was noted.	Thomsen et al., 2000 (Thomsen, Kristensen, et al., 2000)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (16% fish oil)	Water-dispersible tocopherol preparation, Grindox 1032 (20–280 mg/kg) Oil-soluble tocopherol preparation, Toco 70 (20–280 mg/kg)	Addition of tocopherol to a mayonnaise that already contained tocopherol (600 µg/g) either had no effect or increased oxidation.	(Jacobsen, Hartvigsen, Lund, et al., 2001)
Fish oil mayonnaise (16% fish oil)	Ascorbic acid (0-4000 mg/kg)	Ascorbic acid promoted formation of volatile oxidation compounds and reduced the peroxide value in mayonnaises.	(Jacobsen, Timm, et al., 2001)
Fish oil mayonnaise (16% fish oil)	Gallic acid (200 mg/kg) EDTA (200 mg/kg)	EDTA was an efficient antioxidant in fish oil enriched mayonnaise but gallic acid was a poor antioxidant.	(Jacobsen, Hartvigsen, Thomsen, et al., 2001)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Dijon mayonnaise	EDTA (0.004%) Rosemary extracts (0.03%) Mustard (5%)	Addition of antioxidant (rosemary extract and EDTA) decreased the level of photooxidative volatiles in the headspace. In the absence of mustard, the oxidative degradation was somewhat faster and the amount of conjugated dienes was increased more quickly and to a higher degree than that in the mustard-containing sample.	(Lagunes-Galvez et al., 2002)
Mayonnaise based on specific structured lipid (SL) from sunflower oil and caprylic acid	lactoferrin, (800 mg/kg ~ 10 μM) Propyl gallate, (200 mg/kg) EDTA, (75 mg/kg)	EDTA was a strong antioxidant, while propyl gallate and lactoferrin did not exert any antioxidative effect in the SL mayonnaise	(Jacobsen et al., 2003)
Mayonnaise	TBHQ (200 mg/kg) BHT (200 mg/kg) Fenugreek extract (FE) (500, 1000, 1500 mg/kg)	FE at 500 mg/kg in mayonnaise was as effective in decreasing lipid oxidation as TBHQ and more effective than BHT at their permitted level (200 mg/kg).	(Mostafa, 2003)
Fish oil mayonnaise (16% fish oil, 64% rapeseed oil, 80% fat)	Lactoferrin (8-32 μM), Phytic acid (16-124 μM) EDTA (16-64 μM)	The antioxidative effect of EDTA was much more pronounced than the effect of lactoferrin and, especially, phytic acid in mayonnaise.	(Nielsen et al., 2004)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil-enriched mayonnaise-based salads (shrimp and tuna salads)	Oregano (1%) Rosemary (1%) Thyme (1%)	In fish oil-enriched shrimp salad, asparagus had an anti-oxidative effect and shrimp a pro-oxidative effect. The addition of spices increased the oxidative stability of tuna salad (oregano>rosemary>thyme).	(Sørensen, Nielsen, & Jacobsen, 2010)
Fish oil mayonnaise	Black glutinous rice flour (500 mg/kg and 1000 mg/kg (oil weight basis))	The addition of dried black glutinous rice crude extract at 500 and 1000 mg/kg (oil weight basis) could retard an increase in conjugated diene hydroperoxides and thiobarbituric acid reactive substances (TBARs)	(Tananuwong & Tewaruth, 2010)
Mayonnaise (rapeseed oil, 74% fat)	Lycopene crystals (50 mg/kg)	Lycopene slowed the development of off-flavour, off-odour, and colour changes in lycopene-added butter, ice cream, and mayonnaise during storage as it interrupts the chain of free radicals involved in auto-oxidation	(Kaur et al., 2011)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Mayonnaise and salad dressing (olive oil 50% and 25%)	Natural spices and herbs such as parsley, ground black pepper, basil and hot paprika) and their extracts	Natural spices and herbs were replaced with their extracts. Pure olive oil, mayonnaise and salad dressing containing extracts had better microbiology and oxidative quality. Also sensory properties of mayonnaise with extracts showed that it had the highest score of the degree of liking.	(Slavchev, Nikovska, & Nenov, 2012)
Rice bran oil mayonnaise	Oryzanol Squalene Tocopherols Tocotrienols	Incorporation of Rice bran oil provides oryzanol (0.8g/100g oil), tocopherol, tocotrienol, squalene which enhances the stability along with providing balanced Fatty acid composition to the mayonnaise.	(Das, Bhattacharya, Kar, Ghosh, & Bhattacharyya, 2013)
Mayonnaise (corn oil)	Ginger powder (GP) (0% - 1.25%)	The addition of GP at concentrations 1.0% and 1.25% could improve oxidative stability of mayonnaise. After 20 weeks, the values of peroxide, anisidine, acid and totox for mayonnaise prepared using 1.0% and 1.25% GP were significantly lower compared to the control.	(Y. Kishk & Elsheshetawy, 2013)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Mayonnaise (rapeseed oil)	Grape seed extract (GSE) (0 mg GSE per ml, 0.5 mg GSE per ml (~0.050%), 0.9 mg GSE per ml (~0.10%) and 1.4 mg GSE per ml (~0.15%))	The oxidative stability of the mayonnaises enriched with GSE was slightly improved through storage.	(Altunkaya et al., 2013)
Mayonnaise (corn oil 70%)	Juice of basil leaves (0.5%, 1.0% and 1.5%) BHT (0.01%)	Addition of (1.0% and 1.5%) juice of basil leaves could reduce the oxidation process of mayonnaise during 12 weeks.	(Abou-Zaid, Abdelahafez, & Amer, 2015)
Mayonnaise (sunflower oil, 68% fat)	Essential oils (EOs) (0.015%, 0.03% and 0.045%) extracted from Zenyan by Ohmic assisted hydro distillation and conventional hydro distillation methods BHA BHT	All concentrations of Zenyan EOs were suitable antioxidants but synthetic antioxidants like: BHA and BHT could be replaced by higher concentrations of Zenyan Eos.	(Mazaheri Tehrani, 2013)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Mayonnaise (Soybean oil, 63% fat)	Yellow powder mustard (0%, 0.01%, 0.02%, 0.03%, 0.04%, 0.05% and 1%,) Paste mustard (0%, 0.75%, 1%, 1.25% and 1.5%)	Powder mustard increased oxidative stability but caused undesired changes in colour and flavour of mayonnaise for this reason they substituted powder mustard with paste mustard so undesired changes in colour and flavour of the sauce were removed to some extent.	(Milani et al., 2013)
Mayonnaise	Chitosan with bigger molecular weight (MW=310 kDa and DD=77.7%) (100 mg/kg) Chitosan with smaller molecular weight (MW=123 kDa and DD=83.2%) (100 mg/kg) EDTA (75 mg/kg)	Addition of chitosan slowed down the lipid oxidation process of mayonnaises. Chitosan with bigger molecular weight showed better stability during accelerated storage at all temperatures. It has been observed that addition of chitosan slowed down the lipid oxidation process of mayonnaises during 63 days of accelerated storage.	(García et al., 2014)
Mayonnaise (soy oil)	Tocopherol (450 mg/kg) TBHQ (150 mg/kg)	Tocopherol limited hydroperoxide formation effectively.	(Shahin, Nayebzadeh, Alizadeh, & Mohammadi, 2014)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Mayonnaise	Tansy extracts (1%)	Tansy extracts increased oxidative stability of mayonnaise.	(Baranauskienė et al., 2014)
Mayonnaise (Soybean oil 85% fat)	Anthocyanin-rich purple corn husk extract (PCHE) (anthocyanin concentrations of 0.1, 0.2, and 0.4 g/kg mayonnaise) BHT (0.2 g/kg mayonnaise) EDTA (0.075 g/kg mayonnaise)	The antioxidative effect of the mayonnaise containing PCHE was higher than that of mayonnaise with chemical antioxidants BHT and EDTA as positive control. The strongest antioxidative performance was in mayonnaise containing 0.4 g/kg PCHE.	(Li et al., 2014)

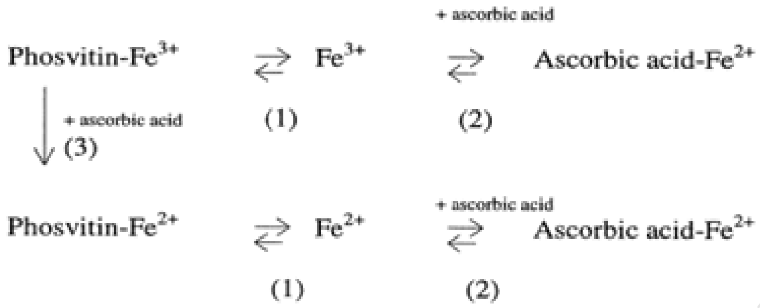
Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Fish oil mayonnaise (16% fish oil)	Caffeic acid and lipophilised derivatives of caffeic acid (caffeates): Methyl caffeate (100µM) Butyl caffeate (100µM) Octyl caffeate (100, 200 µM) Dodecyl caffeate (100µM) Octadecyl caffeate (100µM)	Caffeic acid esterified with fatty alcohols of different chain lengths (C1–C20) were better antioxidants than the original phenolic compound. Fish oil enriched mayonnaise (stored for 4 weeks at 20 °C) with caffeates of medium alkyl chain length (butyl, octyl and dodecyl) added resulted in a better oxidative stability than caffeates with shorter (methyl) or longer (octadecyl) alkyl chains. For peroxide value of mayonnaises the shorter lag phase (3 days) was in samples without antioxidant and octyl caffeate at 200 µM and the longest lag phase (9 days) was seen in samples containing butyl caffeate and octadecyl caffeate	(Alemán et al., 2015)

Product	Antioxidant/pro-oxidant (Concentration)	Results	Reference
Mayonnaise	Sesame sprouts (0.5%, 0.75%, 1.0% and 1.25%) EDTA (0.0075%) BHT (0.02%)	Sesame sprouts powder retarded oxidation during 45 days (at 25±5 °C) in mayonnaise but did not have good sensory perception.	(Shabbir et al., 2015)
Mayonnaise (Soybean oil 74% fat)	Eugenol-lean fraction isolated from clove buds (Syzygium aromaticum Linn) (0.42 %)	Mayonnaise formulated with eugenol-lean clove extract had significantly higher antioxidant activity than mustard mayonnaise. The antioxidant activity and phytochemical properties tend to decrease after 30 days for the reference market sample and after 90 days for the experimental control sample while the mayonnaise formulated with eugenol-lean clove extract was found to be stable beyond 6 months.	(Chatterjee & Bhattacharjee, 2015)

Figure 1. Proposed mechanism for the release of Iron by Ascorbic Acid. Adopted from (Jacobsen, Adler-Nissen, et al., 1999)

Figure 2. Different colours of mayonnaise containing various PCHE contents: (A) PCHE 0.4 g/kg, (B) PCHE 0.3 g/kg, (C) PCHE 0.2 g/kg, and (D) PCHE 0.1 g/kg. Adopted from (Li et al., 2014).

Figure 3. Interfacial phenomena as a possible mechanism of action of the polar paradox in oil-in-water emulsion (a and b) and in bulk oil (c and d). Adopted from (Edwin N Frankel, Huang, Kanner, & German, 1994; Laguerre et al., 2013).



$K_{(1)} = [Phosvitin\text{-}Fe^{3+}]/([Fe^{3+}][Phosvitin])$

Figure 1.

Figure 2.

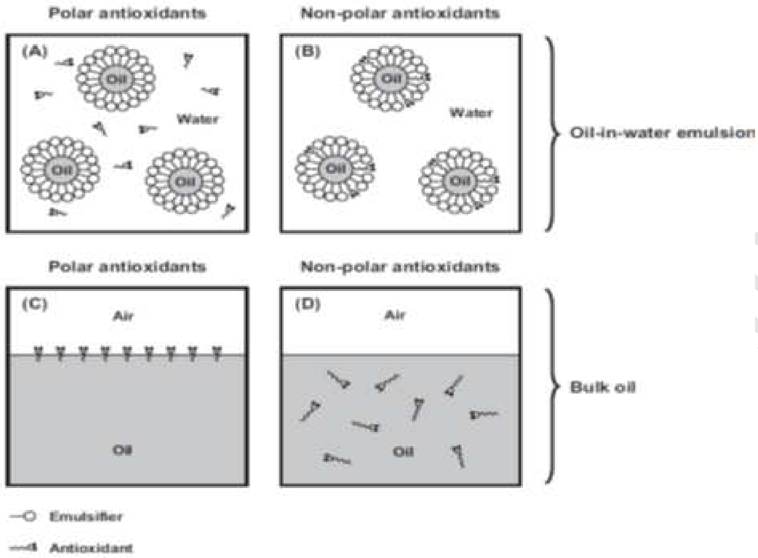

Polar antioxidants
Non-polar antioxidants
(A)
(B)
Oil
Water
Oil-in-water emulsion
(C)
(D)
Air
Oil
Bulk oil
Emulsifier
Antioxidant

Figure 3.

Highlights

- It is possible to increase oxidative stability of mayonnaise by replacing synthetic antioxidants with natural antioxidants
- The most challenging part of using natural antioxidants in mayonnaise is to obtain a product with a good sensory property.
- Factors affecting efficacy of natural antioxidants in mayonnaise are not very well understood.
- Manipulating interfacial layer of oil droplet in mayonnaise to retard lipid oxidation is missing in the literature.