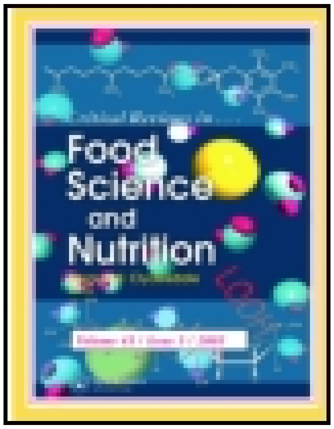

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A Review: Supplementation of Foods with Essential Fatty Acids - Can It Turn a Breeze without Further Ado?

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A Review: Supplementation of Foods with Essential Fatty acids – Can it turn a breeze without further ado?

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Abstract

This article focuses on the critical aspects of supplementation of foods with essential fatty acids (EFAs), the need, health benefits of supplementation and the constraints of the process. Current trend of supplementation of foods with EFAs has been gaining momentum and more research pioneers due to the health benefits in par with the direct intake of EFA supplements. Technologies including encapsulation, nanotechnology, molecular complexing, genetic engineering and more emerging means, hold promise to food supplementation with EFAs. Food trials with adoption of various technologies, studies of bioavailability and health benefits are still underway and crucial before EFA supplementation in foods can hit the market on a global scale.

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Keywords: Essential fatty acids, supplementation, foods, technologies, health benefits

Abbreviations

EFA – Essential fatty acids

n-3 – Omega-3

n-6 – Omega-6

ALA – Alpha (α)-linolenic acid

EPA - Eicosapentaenoic acid

DHA - Docosahexaenoic acid

LA - Linoleic acid

AA - Arachidonic acid

DPA - Docosapentaenoic acid

GLA – Gamma (γ)-linolenic acid

SDA – Stearidonic acid

1. INTRODUCTION

a. Importance of supplementation in foods

Human nourishment, survival and health revolve around a single, essential commodity: food. ôFoodö is defined by items that are intended for human consumption for taste or nutritional value, available in liquid, concentrated, solid, frozen, dried or dehydrated forms; however, excluding alcoholic beverages, tobacco and dietary supplements (The Mayatech Corporation 2010). Foods help sustain life by providing the energy for vital processes in the body and also help manage the quality of life. The term ôdietö was coined to collectively group the distinct selection of foods for regular consumption. With civilization, ôfoodö has seen different trends, origins, discoveries and significance. The relationship between foods and health/ wellness has been gaining popularity in the last few decades and highly portrayed by the top trends in the food industry (Leatherhead food research 2012; Innovaös top 10 trends 2012). ôBalanced nutritionö, ôeating rightö and ôaging well or healthy agingö are messages indicated and advocated by health professionals and hence by todayös food industries around the world.

Apart from energy, one of the major reasons why food is deemed indispensible is because of the nutrients provided by diets. To some extent, the human body can synthesize certain major nutrients required for the physiological functions. However, few nutrients are deemed *essential* because they cannot be synthesized in the body due to the absence of the necessary pathways and lack of precursors for the synthesis. A paucity of essential nutrients can lead to devastating and debilitating consequences, collectively termed as ôdeficiency diseasesö (WHO 1992). Furthermore, the nutritional contents of foods vary due to the geography of cultivation, genetics, environmental factors and growth conditions. The diversity in nature is prominent in the different proportions of macro- and micro-nutrients inherent in a specific food. Thus an essential nutrient predominant in one food may be lacking in another, or found only in exotic foods that cater to a local population. Few ways to address nutrient deficiencies are by interventions such as dietary diversification (choosing a variety of foods), and food fortification or supplementation with the essential nutrients (WHO 1992).

Though diet composed of diverse foods supplying the essential characteristics is always an option, the world is witnessing a radical change in lifestyles and work habits of people. With urbanization, a demand for convenient, ready-to-eat and healthful foods is on the rise (Leatherhead food research 2012). To keep pace with the growing trend and also prevent an unbalanced intake of food and dietary components, supplementation of foods with essential nutrients is an undisputable strategy.

b. Essential fatty acids

Long chain polyunsaturated fatty acids are crucial for normal cellular and physiological functioning, from conception through pregnancy, infancy and the entire lifespan (Connor, 2000). These fatty acids require supplementation by diet and hence referred to as œssential fatty acidsô or EFAs. Two major kinds of EFAs are the omega-3 (n-3) and omega-6 (n-6) fatty acids. The past two decades have witnessed an exploding interest in the EFAs due to their potential impact on health and preventable diseases.

Structures of essential fatty acids

The n-3 and n-6 EFAs differ in the position of the double bonds in their structure. The n-3 and n-6 fatty acids contain a double bond that is 3- and 6-carbons away from the methyl end of the molecule respectively. The different n-3 and n-6 EFAs commonly known have been presented in Table 1. The major n-3 EFAs are Ŭ-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), while n-6 EFAs are linoleic acid (LA) and arachidonic acid (AA). Apart from the above mentioned, other important n-3 EFAs are stearidonic acid (SDA), eicosatetraenoic acid (ETA), and docosapentaenoic acid (DPA) and n-6 EFAs are gamma-linolenic acid (GLA), and docosatetraenoic acid (DTA).

Sources of essential fatty acids

An inefficient enzymatic conversion of ALA to EPA or DHA can occur within the human body using n-3 desaturase in 3 consecutive steps (conversion to 1. EPA; 2. DPA and; 3. DHA), but the rate of conversion is less than 1% (Covington, 2004; Singh, 2005). In a similar fashion, LA can be converted to AA by desaturation with an intermediate production of GLA. However, the initial requirement for ALA or LA has to be met from external dietary sources.

The most common and natural sources of the n-3 EFAs are fish and fish oil. Both EPA and DHA are rich in fatty fish, shellfish, sea mammals and algae. These are found in minute quantities or almost absent in land animals and plants (Connor, 2000). About 2.0-4.5 oz servings of most common fish like salmon and tuna can provide approximately 1g of EPA+DHA per day (Kris-Etherton et al., 2002). Such fatty acids are synthesized by the phytoplanktons that later form foods for rest of the marine population. Alpha linolenic acid is commonly present in seeds and oils, green leafy vegetables, nuts (such as walnuts) and beans (such as soybeans) (Kris Etherton et al., 2000).

Dietary needs of n-6 fatty acids can be met with vegetable oils (from sunflower, safflower, sesame, palmolein and corn) and also occur as invisible fat in cereals, pulses, tubers, legumes and vegetables (Singh, 2005). About 85-90% of the dietary n-6 EFAs is linoleic acid (Franzen-Castle and Ritter-Gooder, 2010), whose common sources include seeds, meat and grains.

Physiological/ Nutraceutical roles of essential fatty acids

Essential fatty acids such as AA and EPA form important components of the mammalian cell membranes and are precursors of eicosanoids including prostaglandins, thromboxanes and leukotrienes, that are vital components of the immune system. The biological effectors thus formed aid in inflammatory responses, regulating blood pressure (antiarrhythmic, vasodilatory), blood clotting (antithrombotic) and cell signaling (Qi et al., 2004, Covington, 2004). The EFAs can reduce levels of thromboxanes and increase prostacyclins that can help in vasodilation, better tissue perfusion, and oxygen delivery to cells. Consumption of fish and fish oils has been associated with changes in circulating triglyceride levels, eicosanoids, cytokines, properties of cell membranes and their functions such as hormone binding, ion channels and enzymatic activities (Garg et al., 2006).

Docosahexaenoic acid (DHA) is the most common fatty acid found in the human brain, distributed in the cerebral cortex, neuronal membranes, membranes of synaptic communication centers, mitochondria and retinal photoreceptors (Haag, 2003). The fatty acid also increases the levels of serotonin and acetylcholine which enhance good feeling and memory, and helps scavenge free radicals generated (Singh, 2005). The EFAs AA, EPA and DHA with vitamins (B, C, E), minerals (iodine, iron, zinc, copper) and aminoacids (taurine, choline) are required for the brain development, maintaining the brain cell integrity keeping the membranes pliable, proper functioning and reducing the cellular and vascular inflammation (Singh, 2003).

Both classes of EFAs are metabolically and functionally different and not interconvertible. The main differentiating factor between n-3 and n-6 fatty acids is that n-6 are proinflammatory agents (AA is most potent) that promote platelet aggregation, stimulate the production of glutamate and oxygen free radicals in the brain while n-3 are anti-inflammatory (Singh, 2005).

The well known benefits of EFAs have been highly researched and reviewed. As a collective effort, these nutraceutical potentials that stem from the physiological roles of EFAs, have been consolidated in Table 2. The EFAs, especially n-3 fatty acids have showed protective effects against coronary heart diseases, stroke and prevention of cardiac arrests, certain types of cancer, inflammatory diseases, arthritis, diabetes, multiple sclerosis and clinical depression (Ruxton 2004). A list of diseases compiled by the supplement issue of American Journal of Nutrition (2000) included EFA deficiency in infancy (retinal and brain development), autoimmune disorders (such as lupus and nephropathy), Crohn disease, several cancers (breast, colon, prostate), mild hypertension and rheumatoid arthritis.

About 72000-96000 preventable deaths in the U.S. occur annually as a result of n-3 fatty acid deficiencies, claiming status as the sixth leading cause of preventable deaths in the country

(Danaei et al., 2009). The physiological roles and the nutraceutical properties of the EFAs emphasize the requirement for the n-3 and n-6 fatty acids at or above the recommended dosages to have a positive impact on health and life quality.

2. Why essential fatty acid supplementation in <u>foods</u> is necessary?

Hippocrates (460-370 BC) pointed out that food could be a medicine and vice versa. Each food carried a purpose of providing the basic nutrients to the consumer but some scooted beyond the nutritional value to providing added health benefits. The following are some of the reasons for direct EFA supplementation in foods:

(a) Balance of EFAs: A balance between n-3 and n-6 EFAs is mandatory for healthy growth and development. A larger amount of n-6 fatty acid (LA), can lead to more production of AA and higher eicosanoids, tempering from prothrombotic to proaggregatory conditions (Simpoulos 2008). Prehistoric folk consumed n-3 and n-6 fatty acids in the ratio of 1:1 and today, it ranges between 1:15 to 1:16.7 (McManus et al., 2011). This imbalance in n-3 and n-6 fatty acids consumption predominant is the result of dietary changes, with a higher preference for plant-seed oils and products and farm-raised fish that have less n-3 fatty acid content (Kris-Etherton et al., 2000; Qi et al., 2004).

(b) Food selection and sources: The major food constituents include vegetables, fruits, meat and poultry which have significantly lower amounts of n-3 EFAs. Cultural, religious and societal reasons are often influencing factors for the intake of EFAs. An instance is vegetarian and vegan diets that totally lack or contain little n-3 fatty acids EPA and DHA, and low in ALA, which leads to relatively less production of EPA and DHA in the body (Davis and Kris-Etherton, 2003).

Clinical evidences have proved that tissue levels of n-3 fatty acids are lower in vegetarians and hence their requirements for vegetarians exceed that of non-vegetarians (Davis and Kris-Etherton, 2003). For vegetarians, vegans and people who do not consume seafood, ALA remains the only source of n-3 fatty acids.

(c) Food processing: In many circumstances, a major reason for the decreased levels of EFAs in foods is commercial processing that often eliminates fatty acids (including essential) in the food to improve the productös shelf life. Unsaturated fatty acids are prone to oxidation, and lower the product quality and shelf life characteristics and hence removed during processing.

(d) Toxins in fish: Presence of methyl mercury, dichloro-diphenyl-trichloroethane (DDT), parachlorobenzoic acid and dioxins in seafood has raised concerns in their consumption (Mahaffey, 2004; Melanson et al., 2005). An alternative source or sustainable supply of n-3 fatty acids such as EPA and DHA other than marine sources, and also ways to incorporate them into foods to cater benefits to the public may be required.

(e) Recommended dose levels: Western diet does not include oily fish in the recommended dose level (2-3 servings/ week) (Kris-Etherton et al., 2000; Meyer et al., 2003). The fatty acid recommendation (adequate intake) for avoiding nutritional deficiencies and reduced risk of chronic diseases is 0.6-1.2% of energy (1.6 g/d for men and 1.1 g/d for women aged 19-50 years (IOM, 2002). However, to observe the nutraceutical benefits of EFAs, it is vital to meet the higher demand for EFA levels than needed to maintain a normal health. Even a modest increase in the intake of bioactive EFAs can significantly impact health and provide beneficial health outcomes (Gebauer et al., 2006).

All the above reasons echo the need for enrichment of food with EFAs and throw light on why the trend is becoming increasingly popular.

3. Constraints of supplementation of essential fatty acids in foods

Essential fatty acids, especially n-3 fatty acids have a shorter shelf life than n-6, monounsaturated and saturated fatty acids. All EFAs are more susceptible to oxidation due to their unsaturated nature (double bonds in their fatty acid chains) and can contribute to rancid off flavors and unpleasant taste in the food product (Nawar, 1996; Watkins and German, 1998). The oxidation process is initiated by the presence of free radicals, reacting with oxygen to create peroxyl radicals and hydroperoxides and the breakdown of the n-3 or n-6 fatty acid chains to form secondary oxidation products (aldehydes and ketones). The latter are responsible for the off-flavor of the products (Zhu and Taneja, 2006). The shelf life of n-3 fatty acids is only about 6 months when stored at 4°C in closed containers under nitrogen. Fish aroma and taste often linger in n-3 oil products even after processing and refining that can be offsetting to some people. Sensory evaluation studies conducted with fish oil/ powder-enriched products have shown a change in attributes such as odor and taste of foods and suggested enrichment with EFA at sensory acceptable levels (Kolanowski et al., 1999; 2007).

Many a time, preferred mode of supplementation of bioactive lipids is in an aqueous medium so that they can be palatable in beverages or foods (McClements et al., 2007). The direct addition of lipids to an aqueous medium or liquid food product can result in a thermodynamically unstable emulsion, influenced by the other components of the medium. Furthermore, the lipid oxidation in foods supplemented or rich in EFAs is more due to the presence of multiple phases (as lipids exist in the foods as oil-in-water or water-in-oil emulsions) and can be promoted by metal ions such as iron in the products. Apart from metals, the other factors that can contribute to the oxidative stability of the EFAs in the products are the different components in the emulsion (proteins and polysaccharides), presence of antioxidants and oxygen (Taneja and Singh, 2012).

4. Confronting limitations of supplementation of essential fatty acids in foods

The following are some of the methods to overcome the challenges posed by EFA supplementation in foods and have been explicitly addressed in Table 3:

a. **Refining and deodorizing fish oils**

Fish oils undergo refining to remove non-triglyceride substances, insoluble impurities, free fatty acids and the volatile compounds that contribute to the fishy odor (Bimbo, 2011). Four basic processes in refining of the oils include degumming, neutralization, bleaching and deodorization, of which deodorization that commonly employs steam distillation, forms the final step in preparation of the bland tasting marine oil. Undesirable volatile compounds (free fatty acids, mono- and di-glycerides, aldehydes, ketones, chlorinated hydrocarbons, and pigment decomposition products) are removed in the step, leading to a product with a better quality and stability for addition to foods (Fournier et al., 2006). On the downside, refined fish oil may still contain non-volatile oxidation products (core aldehydes) that may not be removed by steam distillation and can be toxic and act as proxidants (Decker et al., 2012). Better refining methods to remove the non-volatile components in the oils can go a long way in improving the stability of the fish oils.

b. **Production and use of EFA concentrates**

Though fish oil is a source of EFA, the use as functional ingredients may require concentration of the oil into a form with stability and absorbability (Rubio-Rodriguez et al., 2010). Concentrates of fish oils in methyl and ethyl ester forms have been developed from concentration as such, as modified triacylglycerols, free fatty acids or alkyl esters (Shahidi and Wanasundara, 1998). Pilot scale production of EFA concentrates include methods such as adsorption chromatography, fractional or molecular distillation, enzymatic splitting, low-temperature crystallization, supercritical fluid extraction and urea complexation, of which urea complexation is the most common for free fatty acid/ simple ester forms of EFA concentrates (Shahidi and Wanasundara, 1998).

c. **Use of natural and synthetic antioxidants**

Antioxidants can preserve the quality of foods supplemented with EFAs and are more often, the primary choice of processors. Though synthetic antioxidants like butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT) and tertiarybutyl hydroxyquinone (TBHQ) are cheap, there is a growing market demand for natural preservatives. As a result, Vitamin C, E, plant extracts such as rosemary, grape seed, green tea, fenugreek extract, plant-derived phenolic acids, polyphenols, flavonoids and mixtures of antioxidants are being tested in products for efficacies and increasingly favored (Jacobsen et al., 2008; Hettiarachchy et al., 1996; Perumalla and Hettiarachchy, 2011; Maqsood et al., 2013) to help maintain and prolong product stability.

d. **Use of delivery systems**

Proper delivery systems are essential to encapsulating n-3 and n-6 fatty acids, compatible with target beverage or food to which it will be added, protecting the fatty acids from degradation during processing and controlling release of the lipid into the medium (McClements et al., 2007;

Sagalowicz and Leser, 2010). More of these desirable characteristics have been listed in Figure 1.

➔ ***Colloidal carrier systems:*** Emulsions consist of atleast two immiscible liquids, one dispersed as spherical droplets (dispersed phase) in the other (continuous phase). Conventional emulsions, multiple emulsions, multilayer emulsions, solid lipid particles, filled hydrogel particles are some of the delivery systems based on the emulsion technology and their production, applications, merits and demerits have been elaborately reviewed by McClements et al. (2007). Low viscosity, isotropic dispersions of oil in water, stabilized by surfactants, with sizes 5-100 nm have been termed ómicroemulsionsô and researched for use as delivery systems (Flanagan and Singh, 2006). Modification of interfacial characteristics in emulsions has been a great achievement in delivery of EFAs. Use of positively charged emulsifiers such as dodecyltrimethylammonium bromide and uncharged emulsifier such as Brij 35 demonstrated slower oxidation rates in emulsions and can be adapted for EFA-in-water emulsions (Mei et al., 1998). As some surfactants could carry toxicity issues (Flanagan and Singh, 2006), better food-grade surfactants that are natural, non-toxic, but do not compromise the emulsion stability and dispersibility, have been explored. Apart from low molecular weight emulsifiers, proteins such as whey protein isolate, and casein are potential surfactant candidates and have also been used to stabilize fish oil-in-water emulsions, due to their tendency to inhibit lipid oxidation and chelate metal ions (Hu et al., 2003; Faraji et al., 2004; Singh, 2011).

Nanoemulsions are more finely dispersed droplets produced by high-pressure value homogenizers, of sizes 100-500 nm (McClements, 2005). The ability of nanoemulsions to encapsulate functional food ingredients such as EFAs and deliver them in food systems is a promising avenue (Rashidi and Khosravi-Darani, 2011).

➔ ***Microencapsulation:*** This is a process in which droplets of the bioactive component can be surrounded by a coating or embedded in a homogenous or heterogenous matrix (Wegmuller et al., 2006). Materials used for microencapsulation include proteins, carbohydrates, lipids, gums, polysaccharide and cellulose materials (Sanguansri and Augustin, 2007). The aims of microencapsulation are to improve the stability of EFAs before incorporation into food; to be compatible with the food matrix and readily degrade in the body upon consumption (Taneja and Singh, 2012). In this technology, fatty acids can be enveloped by a coating and these microcapsules range from 1-1000 µm in size. Commonly employed methods include spray drying, complex coacervation, and gravity flow dry blending (Barrow et al., 2007), each method having the share of advantages and disadvantages. With microencapsulated powders, the properties and storage stability can be influenced by any free oil particles on the surface, which may lead to oxidation and rancidity (Drusch and Berg, 2008; Taneja and Singh, 2012).

Liposomes are a type of microencapsulation formed when phospholipids are hydrated, and can serve as carrier for n-3 fatty acids. A lamellar phase (bilayer) is formed initially as a result of surfactant mix with water and later dispersed to form vesicles. Depending on the formation, number of bilayers and vesicles, liposomes can adopt one of the three kinds: a single bilayer forming unilamellar vesicles; concentric bilayers forming multilamellar vesicles; and non-concentric bilayers forming multivesicular vesicles (Sagalowicz and Leser, 2010). The net properties, such as permeability, charge density and steric hindrance of the constituting phospholipids contribute to the physical and chemical properties of a liposome (Malam et al., 2009). While biocompatibility, biodegradability, and encapsulating efficacies of liposomes form positive aspects as delivery systems, there can be problems with batch-to-batch variation, stability and controlling size of the vesicles (Gomez-Hens and Fernandez-Romero, 2006). Cansell et al. (2003) investigated an extract of marine lipids to produce liposomes, that could deliver n-3 fatty acids and observed to improve their bioavailability and absorption upon ingestion.

➔ ***Nano-laminated coating or nanoencapsulation and solid lipid nanoparticles:*** These are also a kind of emulsion-based delivery technology. When droplets of EFAs are encapsulated by nano-laminated biopolymer coatings (10-100 nm diameter), they can be used economically and safely in food formulations and beverages and their bioavailability controlled in the gastrointestinal (GI) tract. Conventional food emulsifiers and homogenization techniques have limited the functional aspects of emulsion-based delivery systems. Hence, to improve the properties of such systems, strategies of nano-laminated coatings in which oil-in-water emulsions can be surrounded by multi-component nano-laminated interfacial coatings with food-grade emulsifiers (surfactants, phospholipids) and/ or biopolymers (proteins, polysaccharides) have been researched (McClements, 2010).

The limitations of emulsion-based delivery systems, including thermodynamic instability, can be overcome with the latest generation of nanoscalar colloidal carrier systems, the solid lipid nanoparticles and has been extensively reviewed by Weiss et al. (2008). Comprising a core of lipid matrix in which lipophilic bioactives such as EFAs can be dispersed, the particles are stabilized by one or more surfactants (Jenning et al., 2000). The advantages include the absence of organic solvents for pilot scale manufacture, the encapsulation and delivery of high

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concentrations of the desired component without danger of disintegration (Weiss et al., 2008) and can be a potential strategy for delivering EFAs.

➔ ***Molecular complexes:*** Physical complexing with molecules such as cyclodextrins that contain a lipophilic cavity to host EFAs can be used as an aqueous delivery system in foods (Davis and Brewster, 2004; Sagalowicz and Leser, 2010). The sizes of these complexes range from 10-600 nm and apart from cyclodextrins, proteins or protein aggregates being amphiphilic, can also be employed. Both ϐ-lactoglobulin and ϐ-lactoglobulin complexed with pectin were used to contain n-3 fatty acids and found effective (Zimet and Livney, 2009).

➔ ***Others delivery systems:*** Apart from the above listed delivery systems, few more include simple solutions, association colloids, biopolymer matrices and powders (McClements et al., 2009).

d. Genetic engineering

Apart from relying on fish and algal oils for EFAs, biotechnology has made the possibility to engineer several oilseed crops and transgenic plants with EFAs (Venegas-Caleron et al., 2010). Oilseed crops such as soy, canola, palm, peanut, sunflower provide oils rich in n-6 fatty acids and contribute to an imbalance in the n-3: n-6 profile. Genetic engineering of these plants has led to a manipulation of their fatty acid profiles by blocking steps or introducing enzymes in fatty acid desaturation and lipid metabolism (Damude and Kinney, 2007). Ursin (2003) has reported the possibility of producing SDA from transgenic canola seeds (~23% of the oil weight), which is a metabolic intermediate between ALA and EPA and canola could offer promise of a sustainable source for generating n-3 EFAs.

5. Diet supplementation vs essential fatty acid dietary supplements

Fish oil capsules with EPA and DHA form one of the top five dietary supplements consumed around the world (Ocean-nutrition) and the market will continue to increase over the years. However, the current trends in the functional food market and consumer surveys showed that people preferred supplementation of foods with EFAs (4 in 10 US adults) and 45% of UK consumers indicated more likeliness to purchase a product rich in n-3 fatty acids. Further, evidence suggests the contrast in the recommended dosage levels and the actual intake levels of EFAs by people. With encapsulation and delivery technologies of EFAs in diet, studies have proven the effectiveness of the EFAs similar to that obtained from the daily intake of fish oil gelatin capsules (Wallace et al., 2000).

6. How far are we in the trend towards direct supplementation with EFAs?

Refining of marine oils can remove the compounds contributing to the fishy aroma and is most commonly adopted in the preparation of fish oil supplements and fish oil for supplementation to foods. Currently EPA and DHA depend mainly on marine sources (Beindorff and Zuidam, 2010), with genetic engineering on plants mostly at research level and low availability in other plant oils.

Many food companies have begun incorporating EFAs in new functional food products such as bread and bakery products, milk and dairy products, meat and poultry products, juices and sauces and the trend has increased with health claims on such products with EFAs (Sanguansri and Augustin, 2010; Barrow et al., 2007; Kolanowski and Laufenberg, 2006). Stabilization of fish oils or EFAs in microencapsulation and powder form has enabled their use in functional foods. Microencapsulation by spray drying EFAs has been used in different foods such as infant formulas and bread mixes (Andersen, 1995) and the shelf life improved to more than 2 years with emulsion spray drying (Schrooyen et al., 2001; Andersen, 1995). Microencapsulated EPA powder was used in instant powdered-milk-based protein-carbohydrate formulas with and without artificial flavors. Novomega is a n-3 fatty acid encapsulated product, designed for use in bakery products. Other examples of marketed fish oil powders include Marinol™ Omega-3 HS, Marinol DHA HS, Nordic Naturalsô Omega-3 Fortify and MEG-3 in U.S. and Canada (Sathivel and Kramer, 2011). The features of these microencapsulated products include food- and water solubility, lacking odor, with neutral flavor and delivering a certain quantity of n-3 per serving (Eg: Omega Fortify formula delivers ~500 mg/ serv). The low diffusion coefficient of oxygen into microcapsules helps to increase the shelf life to several years (Gouin, 2004; Augustin and Hemar, 2009). Hummus-based dip product containing n-3 fatty acids was developed using micro-emulsification technique and examined for the bioavailability of the fatty acids after consumption and alteration of the plasma lipid profile (Garg et al., 2007).

Nanotechnology has boomed as a promising and revolutinizing strategy to deliver functional foods and micronutrients with targeted and sustained release properties (Rashidi and Khosravi-Darani, 2011). Exploration with nanocapsules and nanocarriers could offer successful scope of supplementing foods with EFAs. Apart from microencapsulated products, other emulsion-based delivery systems are finding applications in food industries, however, not as much popular. There are growing interests in understanding and controlling the stability, digestibility and release of EFAs in the GI tract (McClements and Li, 2010) and overcoming some of the major hurdles with colloidal carrier systems including design and fabrication, compatibility, stabilization and proper understanding of the formulation and functionality may be targets (Velikov and Pelan, 2008). Several studies currently also focus on the bioavailability and health benefits from consumption of foods enriched with EFA (Kolanowski and Laufenberg, 2006).

Concluding remarks

The knowledge of EFAs, and the overall awareness of their health attributes is rapidly growing. These have stemmed the need and pursuit of different encapsulation, and delivery technologies to provide the recommended dosage levels of EFAs in foods and also genetic engineering strategies to design alternative and sustainable sources of EFAs for diet supplementation. Results from different studies with delivery systems have suggested a significant progress and applicability for delivering EFAs in food systems. However, several challenges such as method efficacy, bioavailability, cost effectiveness and delivering the desired levels and balanced ratio of n-3 and n-6 fatty acids still require exploration. For successful application of certain delivery systems for EFAs in foods, knowledge of the interactions and compatibility of EFAs with the components; and the use of biodegradable and sustainable materials, are prerequisites. As incorporation of EFA into the product will contribute to a hike in food processing costs, the benefit of cost versus performance of the adopted technologies needs to be surveyed in detail before application. However, with the market for EFAs especially n-3 fatty acids depending on convenient, palatable and odorless n-3 fatty acid fortified or rich foods, the scale up of technologies from lab to commercial, may not be far off. The overall effort and aim to deliver more or the recommended levels of the fatty acids to elicit the clinical and biological effects for the consumers and the booming functional food market can keep the technologies, innovations, advances and adaptation afloat and rampant. The answer to the question: Can it turn a breeze without further ado? With better technologies, research and solutions entering this age, it is more than just an optimistic view that foods with n-3 EFAs (similar to micronutrients that are already present in the ófortificationô list), and having the proper balance between n-3 and n-6 may not be far from the table to significantly improve life quality.

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References

1) Alessandri, J-M., Guesnet, P., Vancassel, S., Astorg, P., Denis, I., Langelier, B., Aïd, S., Poumès-Ballihaut, C., Champeil-Potokar, G., and Lavialle, M. (2004). Polyunsaturated fatty acids in the central nervous system: evolution of concepts and nutritional implications throughout life. *Reproduction Nutrition Development* **44** : 509-538.

2) Andersen, S. (1995). Microencapsulated omega-3 fatty acids from marine sources. *Lipid Technology* **7** : 81-85.

3) Appel, L.J., Miller, E.R., Seidler, A.J., and Whelton, P.K. (1993). Does supplementation of diet with ófish oilô reduce blood pressure? A meta-analysis of controlled clinical trials. *Archives of Internal Medicine* **153** : 1429-1438.

4) Augustin, M.A., and Hemar, Y. (2009). Nano- and micro-structured assemblies for encapsulation of food ingredients. *Chemical society reviews* **38** : 902-912.

5) Barrow, C.J., Nolan, C., and Jin, Y. (2007). Stabilization of highly unsaturated fatty acids and delivery into foods. *Lipid technology* **19** : 108-111.

6) Beindorff, C.M., and Zuidam, N.J. (2010). Microencapsulation of fish oil. **In** : Encapsulation technologies for active food ingredients and food processing, pp. 161-185. Zuidam, N.J., and Nedovic,V.A., Eds., Springer, New York.

7) Bimbo, A.P. (2011). The production and processing of marine oils. Available at URL: http://lipidlibrary.aocs.org/processing/marine/index.htm.

8) Cansell, M., Nacka, F., and Combe, N. (2003). Marine lipid-based liposomes increase *in vivo* FA bioavailability. *Lipids* **38** : 551-559.

9) Connor, W.E. (1994). n-3 fatty acids and heart disease. **In** : Nutrition and disease update: heart disease, pp. 7-42. D. Kritchevsky, and K.K. Carroll, Eds., American Oil Chemistsô society, Illinois.

10) Connor, W.E. (2000). Importance of n-3 fatty acids in health and disease. *American Journal of Clinical Nutrition* **71**(suppl) : 171S-5S.

11) Covington, M.B. (2004). Omega-3 fatty acids. *American Family Physician* **70** : 133-140.

12) Damude, H.G., and Kinney, A.J. (2007). Engineering oilseed plants for a sustainable, land-based source of long chain polyunsaturated fatty acids. *Lipids* **42** : 179-185.

13) Danaei, G., Ding, E.L., Mozaffarian, D., Taylor, B., Rehm, J., Murray, C.J.L., and Ezzati, M. (2009). The preventable causes of death in the United States: Comparative risk assessment of dietary, lifestyle, and metabolic factors. *Public Library of Science (PLOS) Medicine Journal* **6** : e1000058.

14) Das, U.N. (2008). Folic acid and polyunsaturated fatty acids improve cognitive function and prevent depression, dementia, and Alzheimer's disease ï but how and why? *Prostaglandins Leukot. Essent. Fatty Acids* **78** : 11-19.

15) Davis, M.E., and Brewster, M.E. (2004). Cyclodextrin-based pharmaceutics: past, present and future. *Nature Reviews in Drug Discovery* **3** : 1023-1035.

16) Davis, B.C., and Kris-Etherton, P.M. (2003). Achieving optimal essential fatty acid status in vegetarians: current knowledge and practical implications. *The American Journal of Clinical Nutrition* **78(suppl)** : 640S-646S.

17) Decker, E.A., Akoh, C.C., and Wilkes, R.S. (2012). Incorporation of (n-3) fatty acids in foods: challenges and opportunities. *The Journal of Nutrition* doi: 10.3945/jn.111.149328.

18) Drusch, S., and Berg, S. (2008). Extractable oil in microcapsules prepared by spray-drying: localization, determination and impact on oxidative stability. *Food Chemistry* **109** : 17-24.

19) Faraji, H., McClements, D.J., and Decker, E.A. (2004). Role of continuous phase protein on the oxidative stability of fish oil-in-water emulsions. *Journal of Agricultural Food Chemistry* **52** : 4558-4564.

20) Flanagan, J., and Singh, H. (2006). Microemulsions: A potential delivery system for bioactives in food. *Critical reviews in food science and nutrition* **46** : 221-237.

21) Fournier, V., Destaillats, F., Juaneda, P., Dionisi, F., Lambelet, P., Sebedio, J-L., and Berdeaux, O. (2006). Thermal degradation of long-chain polyunsaturated fatty acids during deodorization of fish oil. *European Journal of Lipid Science and Technology* **108** : 33-42.

22) Fox, P.L., and DiCorleto, P.E. (1988). Fish oils inhibit endothelial cell production of platelet-derived growth factor-like protein. *Science* **241** : 453-456.

23) Franzen-Castle, L.D., and Ritter-Gooder, P. (2010). Omega 3 and omega 6 fatty acids. Nebguide. Available at URL: http://elkhorn.unl.edu/epublic/live/g2032/build/g2032.pdf

24) Garg, M.L., Wood, L.G., Singh, H., and Moughan, P.J. (2006). Means of delivering recommended levels of long chain n-3 polyunsaturated fatty acids in human diets. *Journal of Food Science* **71** : R66-R71.

25) Garg, M.L., Blake, R.J., Clayton, E., Munro, I.A., MacDonald-Wicks, L., Singh, H., and Moughan, P.J. (2007). Consumption of an n-3 polyunsaturated fatty acid-enriched dip modulates plasma lipid profile in subjects with diabetes type II. *European Journal of Clinical Nutrition* **61** : 1312-1317.

26) Gebauer, S.K., Psota, T.L., Harris, W.S., and Kris-Etherton, P.M. (2006). N-3 fatty acid dietary recommendations and food sources to achieve essentiality and cardiovascular benefits. *The American Journal of Clinical Nutrition* **83(suppl)** : 1526S-1535S.

27) Gomez-Hens, A., and Fernandez-Romero, J.M. (2006). Analytical methods for the control of liposomal delivery systems. *Trends in Analytical chemistry* **25** : 167-178.

28) Gouin, S. (2004). Microencapsulation: industrial appraisal of existing technologies and trends. *Trends in Food science and Technology* **15** : 330-347.

29) Haag, M. (2003). Essential fatty acids and the brain. *Canadian Journal of Psychiatry* **48** : 195-203.

30) Harris, W.S. (1997). n-3 fatty acids and serum lipoproteins: human studies. *American Journal of Clinical Nutrition* **65** : 1645S-1654S.

31) Hettiarachchy, N.S., Glenn, K.C., Gnanasambandam, R., and Johnson, M.G. (1996). Natural antioxidant extract from fenugreek (Trigonella foenumgraecum) for ground beef patties. *Journal of Food science* **61** : 516-519.

32) Hu, M., McClements, D.J., and Drecker, E.A. (2003). Impact of whey protein emulsifiers on the oxidative stability of salmon oil-in-water emulsions. *Journal of Agricultural Food Chemistry* **51** : 1435-1439.

33) IOM. Dietary reference intakes: energy, carbohydrates, fiber, fat, fatty acids, cholesterol, protein and amino acids. Washington, DC: National Academic Press, 2002.

34) Jacobsen, C., Let, M.B., Nielsen, N.S., and Meyer, A.S. (2008). Antioxidant strategies for preventing oxidative flavor deterioration of foods enriched with n-3 polyunsaturated lipids: a comparative evaluation. *Trends in Food Science and Technology* **19** : 76-93.

35) James, M.J., and Cleland, L.G. (1997). Dietary n-3 fatty acids and therapy for rheumatoid arthritis. *Seminar on Arthritis Rheumatoid* **27** : 85-97.

36) Jenning, V., Mader, K., and Gohla, S.H. (2000). Solid lipid nanoparticles (SLN^{TM}) based on binary mixtures of liquid and solid lipids: a ^{1}H-NMR study. *Int. J. Pharm.* **205** : 15–21.

37) Kang, J.X., and Leaf, A. (1996). Antiarrhythmic effects of polyunsaturated fatty acids. *Circulation* **94** : 1774-1780.

38) Kolanowski, W., Swiderski, F., and Berger, S. (1999). Possibilities of fish oil application for food products enrichment with omega-3 PUFA. *Int. J. Food Sci. Nutr.* **50** : 39-49.

39) Kolanowski, W., and Laufenberg, G. (2006). Enrichment of food products with polyunsaturated fatty acids by fish oil addition. *Eur. Food Res. Technol.* **222** : 472-477.

40) Kolanowski, W., Jaworska, D., Laufenberg, G., and Weibrodt, J. (2007). Evaluation of sensory quality of instant foods fortified with omega-3 PUFA by addition of fish oil powder. *Eur. Food Res. Technol.* **225** : 715-721.

41) Kris-Etherton, P.M., Taylor, D.S., Y-Poth, S., Huth, P., Moriarty, K., Fishell, V., Hargrove, R.L., Zhao, G., and Etherton, T.D. (2000). Polyunsaturated fatty acids in the food chain in the United States. *American Journal of Clinical Nutrition* **71** : 179S-8S.

42) Kris-Etherton, P.M., Harris, W.S., and Appel, L.J. (2002). Fish consumption, fish oil, omega-3 fatty acids, and cardiovascular disease. *Circulation* **106** : 2753.

43) Malam, Y., Loizidou, M., and Seifalian, A.M. (2009). Liposomes and nanoparticles: nanosized vehicles for drug delivery in cancer. *Trends in Pharmacological sciences* **30** : 592-599.

44) Maqsood, S., Benjakul, S., and Shahidi, F. (2013). Emerging role of phenolic compounds as natural food additives in fish and fish products. *Critical reviews in food science and nutrition* **53** : 162-179.

45) McManus, A., Merga, M., and Newton, W. (2011). Omega-3 fatty acids. What consumers need to know. *Appetite* **57** : 80ï 83.

46) McClements, D.J., and Li, Y. (2010). Review of in vitro digestion models for rapid screening of emulsion-based systems. *Food and Function* **1** : 32-59.

47) McClements, D.J. (2010). Design of nano-laminated coatings to control bioavailability of lipophilic food components. *Journal of Food Science* **75** : R30-R42.

48) McClements, D.J. (2011). Edible nanoemulsions: fabrication, properties, and functional performance. *Soft Matter* **7** : 2297-2316.

49) McClements, D.J., Decker, E.A., Park, Y., and Weiss, J. (2009). Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. *Critical reviews in Food science and nutrition* **49** : 577-606.

50) McClements, D.J., Decker, E.A., and Weiss, J. (2007). Emulsion-based delivery systems for lipophilic bioactive components. *Journal of Food Science* **72** : R109-R124.

51) McClements, D. J. (2005). Food Emulsions: Principles, Practice and Techniques, 2nd Ed, . p. 609. CRC Press, Florida

52) Mei, L., McClements, D.J., Wu, J., and Decker, E.A. (1998). Iron-catalyzed lipid oxidation in emulsion as affected by surfactant, pH and NaCl. *Food chemistry* **61** : 307-312.

53) Meyer, B.J., Mann, N.J., Lewis, J.L., Milligan, G.C., Sinclair, A.J., and Howe, P.R.C. (2003). Dietary intakes and food sources of omega-3 and omega-6 polyunsaturated fatty acids. *Lipids* **38** : 391-398.

54) Ocean nutrition. http://www.ocean-nutrition.com/omega3/market_opportunities/trends. Accessed on 28th October 2012.

55) Perumalla, A.V.S., and Hettiarachchy, N.S. (2011). Green tea and grape seed extracts ï Potential applications in food safety and quality. *Food research International* **44** : 827-839.

56) Qi, B., Fraser, T., Mugford, S., Dobson, G., Sayanova, O., Butler, J., Napier, J.A., Stobart, A.K., and Lazarus, C.M. (2004). Production of very long chain polyunsaturated omega-3 and omega-6 fatty acids in plants. *Nature biotechnology* **22** : 739-745.

57) Rashidi, L., and Khosravi-Darani, K. (2011). The applications of nanotechnology in food industry. *Critical reviews in Food science and nutrition* **51** : 723-730.

58) Rubio-Rodriguez, N., Beltran, S., Jaime, I., de Diego, S.M., Sanz, M.T., and Carballido, J.R. (2010). Production of omega-3 polyunsaturated fatty acid concentrates: A review. *Innovative Food science and Emerging technologies* **11** : 1-12.

59) Ruxton, C. (2004). Health benefits of omega-3 fatty acids. *Nurs. Stand* **18** : 38-42.

60) Sagalowicz, L., and Leser, M.E. (2010). Delivery systems for liquid food products. *Current opinion in colloid and interface science* **15** : 61-67.

61) Sanguansri, L., and Augustin, M.A. (2006). Microencapsulation and delivery of omega-3 fatty acids. **In** : Functional food ingredients and nutraceuticals, pp. 298-320. Shi, J., Ed., CRC Press, Florida.

62) Sanguansri, L., and Augustin, M.A. (2010). Microencapsulation in functional food product development. **In** : Functional food product development, pp. 1-12. Smith, J., and Carter, E., Eds., Wiley Blackwell, Oxford, UK.

63) Sathivel, S., and Kramer, D. (2011). Microencapsulation, nanoencapsulation, edible film, and coating applications in seafood processing. **In** : Handbook of seafood quality, safety and health applications, pp. 416-417. Alasalvar, C., Miyashita, K., Shahidi, F., and Wanasundara, U., Eds., Wiley Blackwell, Oxford, UK.

64) Schrooyen, P.M.M., van der Meer, R., and De Kruif, C.G. (2001). Microencapsulation: its application in nutrition. *Proceedings of the Nutrition society* **60** : 475-479.

65) Shahidi, F., and Wanasundara, U.N. (1998). Omega-3 fatty acid concentrates: nutritional aspects and production technologies. *Trends in Food Science & Technology* **9** : 230-240.

66) Simopoulos, A.P. (2008). The importance of the omega-6/omega-3 fatty acid ratio in cardiovascular disease and other chronic diseases. *Experimental Biology and Medicine* **233** : 674ï 688.

67) Singh, M. (2003). Nutrition, brain and environment. How to have smarter babies? *Indian Journal of Pediatrics* **40** : 213-220.

68) Singh, M. (2005). Essential fatty acids, DHA and human brain. *Indian Journal of Pediatrics* **72** : 239-242.

69) Singh, H. (2011). Aspects of milk-protein-stabilized emulsions. *Food hydrocolloids* **25** : 1938-1944.

70) Taneja, A., and Singh, H. (2012). Challenges for the delivery of long chain n-3 fatty acids in functional foods. *Annual reviews in Food science and technology* **3** : 105-123.

71) The Mayatech Corporation. (2010). Bridging the Gap Program (www.impacteen.org/data.htm). Available at URL: http://www.impacteen.org/statetaxdata/Food%20Definitions%202009_for_web_020110.pdf; Accessed on 18 October 2012.

72) Ursin, V.M. (2003). Modification of plant lipids for human health: Development of functional land-based Omega-3 fatty acids. *Journal of Nutrition* **133** : 4271-4274.

73) Velikov, K.P., and Pelan, E. (2008). Colloidal delivery systems for micronutrients and nutraceuticals. *Soft matter* **4** : 1964-1980.

74) Venegas-Caleron, M., Sayanova, O., and Napier, J.A. (2010). An alternative to fish oils: Metabolic engineering of oil-seed crops to produce omega-3 long chain polyunsaturated fatty acids. *Progress in lipid research* **49** : 108-119.

75) Wanasundara, U.N., Wanasundara, J., and Shahidi, F. (2002). Omega-3 fatty acid concentrates: a review of production technologies. **In** : Seafoods ï Quality, technology and nutraceutical applications pp. 157-173. Alasalvar, C., and Taylor, T., Eds., Springer, New York.

76) Wegmuller, R., Zimmermann, M.B., Buhr, V.G., Windhab, E.J., and Hurrell, R.F. (2006). Development, stability, and sensory testing of microcapsules containing iron, iodine, and vitamin A for use in food fortification. *Journal of Food Science* **71** : S181-187.

77) Weiss, J., Decker, E.A., McClements, D., Kristbergsson, K., Helgason, T., and Awad, T. (2008). Solid lipid nanoparticles as delivery systems for bioactive food components. *Food biophysics* **3** : 146-154.

78) WHO. 1992. Major issues for nutrition strategies: Summary. International conference on nutrition. Available at URL: http://apps.who.int/iris/bitstream/10665/61054/1/a34309.pdf

79) Zimet, P., and Livney, Y.D. (2009). Beta-lactoglobulin and its nanocomplexes with pectin as vehicles for omega-3 polyunsaturated fatty acids. *Food hydrocolloids* **23** : 1120-1126.

80) Zhu, X., and Taneja, A. (2006). The trouble with omega-3 oils. *Functional foods and nutraceuticals* 26-28.

Table 1: Common essential fatty acids with their scientific names and structures

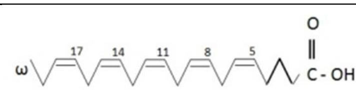
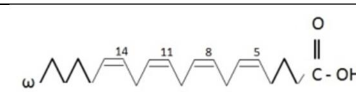
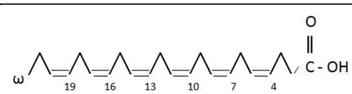
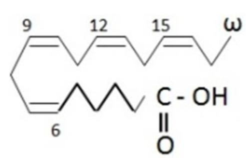
Omega-3 fatty acids			Omega-6 fatty acids		
Alpha-linolenic acid (ALA)	9,12,15-octadecatrienoic acid (18:3)		Linoleic acid (LA)	9,12-octadecadienoic acid (18:2)	
Eicosapentaenoic acid (EPA)	5,8,11,14,17-eicosapentaenoic acid (20:5)		Arachidonic acid (AA)	5,8,11,14-eicosatetraenoic acid (20:4)	
Docosahexaenoic acid (DHA)	4,7,10,13,16,19-docosahexaenoic acid (22:6)				
Stearidonic acid (SDA	6,9,12,15-octadecatetraenoic acid				

Table 2: Essential fatty acids as nutraceutical agents

Organ system/ Disorder	Specific/ Broad function played by EFA	n-3/ n-6	Amount of intake	References
Heart disease	Prevent arrhythmias Prostaglandin and leukotriene precursors Anti-inflammatory (inhibit cytokine and mitogen production) Antithrombotic Inhibit atherosclerosis	n-3	1 g/ day (500 mg/ day or 900 mg/ day of combined DHA and EPA for regular/ CHD patients	Connor (1994) Connor (2005) Kang and Leaf (1996) Gebauer et al. (2006)
Alzheimerôs disease	Upregulate genes for neurogenesis, neurotransmission and connectivity Suppress production of proinflammatory cytokines Precursors for anti-inflammatory compounds that protect neurons from cytotoxicity	n-3 n-6	-	Das (2008)
Hyperlipidemia	Lower plasma triacylglycerols Inhibit VLDL and triglyceride synthesis in liver	n-3	2-4 g/ day	Harris (1997)
Central nervous system (CNS)	Regulates gene transcription, controlling apoptosis, proliferation, differentiation, immune and inflammatory functions in the CNS Precursors for anti-inflammatory compounds	n-3 n-6	-	Alessandri et al. (2004)
Rheumatoid arthritis	Reduce inflammatory mediators	n-3	3 g/ day	James and Cleland (1997)
Atherosclerosis	Reduces plaque formation by reduction in platelet-derived growth factor Reduces blood pressure	n-3	5.6 g/ day	Fox and DiCorleto (1988) Appel et al. (1993)

VLDL ï very low density lipoprotein

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Table 3: Confronting the limitations of supplementation of essential fatty acids in foods

Technology/ Technique	Positive outcomes	Pitfalls and limitations	References
Refining and deodorizing oils	Removes ófishô aroma and other unpleasant off-flavors	Thermal degradation (polymerization and isomerization) of fatty acids at high deodorization temperatures Core aldehydes may not be removed, leading to oxidation	Fournier et al. (2006) Decker et al. (2012)
Production and use of concentrates	Better absorption Better oxidative stability	Amount of EFA/ recovery in concentrate can vary with enrichment conditions and method adopted	Rubio-Rodriguez et al. (2010) Wanasundara et al. (2002)
Use of natural and synthetic antioxidants	Reduces lipid oxidation	Efficacy of antioxidants depends on factors such as pH, temperature, polarity and concentration of antioxidants and the physical properties of food system	Chen and Ho (1997) Frankel et al. (1994) Huang et al. (1994)
Microencapsulation	Reduces lipid oxidation and improves stability Increases bioavailability Ease of handling Water solubility Surface oil can be reduced depending on the method of microencapsulation	Storage stability at high humidity can be reduced	Anderson (1995) Taneja and Singh (2012) Barrow et al. (2007)

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Colloidal carrier/ Emulsion-based delivery system	Easy to disperse in water-based foods Made from food-grade materials Can be dehydrated and powdered for easy handling and storage	Sensitive to changes in pH, metal concentrations and environmental stresses Thermodynamically unstable and can disintegrate with dilutions or phase separate over time	Taneja and Singh (2012) Djordjevic et al. (2004) Weiss et al. (2008)
Nano-laminated coating or nanoencapsulation	Properties of coating can be controlled for different kinds of functionality Bioavailability and targeted release Improved physical stability	Need for suitable food grade ingredients to prepare coatings Need for suitable processing operations for pilot scale translation	McClements (2010, 2011)
Molecular complexing	Aid in molecular solubilization, increase bioavailability, biodispersibility and bioefficacy Reduce smell and taste	Moderate and limited loading capacity of cyclodextrins	Davis and Brewster (2004) Sagalowicz and Leser (2010)
Liposomes	Biodegradable Non-toxic	Expensive (high cost of pure lecithins for liposomes) Low encapsulation efficiency Complex fabrication equipment	Sagalowicz and Leser (2010)
Genetic engineering	Sustainable source of EFAs for diet	Correct balance of n-3: n-6 fatty acid ratio is yet to be attained Regulations for transgenic crops Acceptance	Damude and Kinney (2007)

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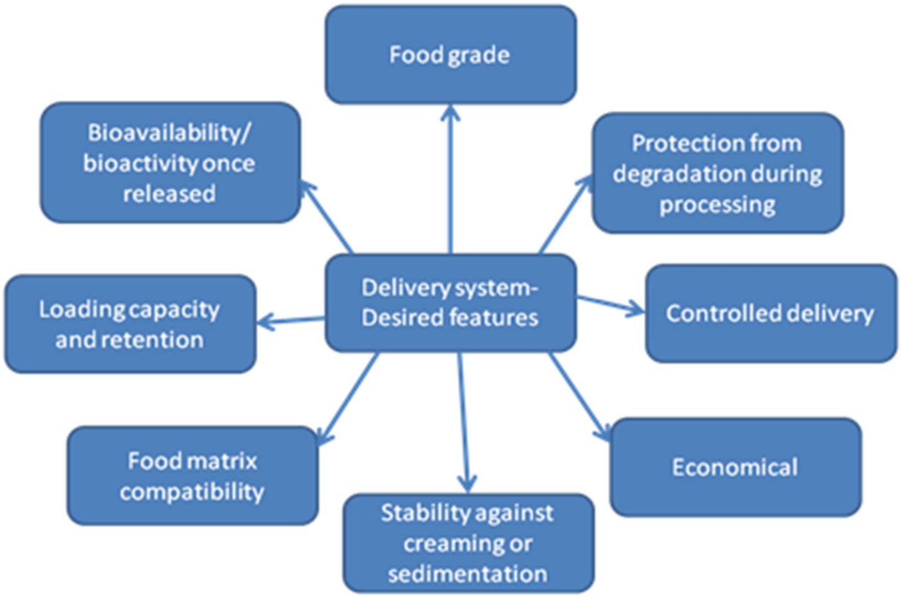

Figure 1: Desired characteristics of delivery systems