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Microencapsulation Of Omega-3 Rich Flaxseed And Fish Oils

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Abstract

Omega-3 fatty acids can be widely considered as potential therapeutic agents due to their antioxidant, nutritional, and health aspects. They have unsaturated nature which leads to susceptibility to oxidation conditions. Therefore, to get the maximum health benefit and to minimize or prevent the process of oxidation, omega-3 rich oils must be protected against atmospheric oxygen. To achieve this objective, two strategies were usually carried out: First addition of an antioxidant to the oils, and second, the encapsulation process. Here we review omega-3 fatty acids chemistry, natural sources, health benefits, and antimicrobial activity. This review highlights obstacles to incorporating omega-3 fatty acids in foods, particularly concerning oxidation. The importance of incorporating natural polyphenols especially curcumin as well as using different wall materials (sodium alginate, chitosan, and natural clays) in microencapsulating fish and flaxseed oils were also discussed. Different techniques of encapsulation were highlighted as well.

Keywords : Fish oil; flaxseed oil; Health benefits; Microencapsulation; Clay

1. Introduction

Omega-3 fatty acids are very essential for normal growth and have also positive impacts on the brain, heart, eyes, skin, joints as well as mood and behavior **[1]**. Besides, omega-3 fatty acids are involved in the prevention of coronary artery diseases, hypertension, diabetes, arthritis, autoimmune disorders, and cancer **[2]**. They possess numerous biological activities, such as anti-inflammatory **[3]**, antioxidant **[1]**, antimicrobial **[4]**, and neuroprotective **[5]** activities. Nevertheless, their unsaturated character, omega-3 fatty acids are unstable chemically and liable to oxidation, leading to produce free radicals and unpleasant tastes and off-flavors, which affect negatively the shelf-life, sensory properties as well as on the general acceptability of the food products.

Microencapsulation can be deemed as a main step to coat sensitive constituents (e.g. omega-3 rich oils) inside package matrix produced from different wall coatings and enhanced delivery systems. Microencapsulation technology has been also used as an applicable method to develop and improve the biological and functional characteristics of the oils **[1, 6]**.

The addition of antioxidants to oil systems is one of the most effective methods to protect the oil from oxidation conditions. However, the concern related to the possible adverse effects of synthetic antioxidants is increasing. Therefore, there is an increasing need for using natural antioxidants for better health **[7]**. A polyphenolic compound, Curcumin (Cur), is widely applied due to its pharmacological effects, (e.g. anti-inflammatory, antioxidant and anticancer) **[8]**. Cur can also be used in oil systems (bulk or emulsion) to reduce the oxidation process **[9]**.

So, this review aimed to highlight the efforts of how to protect omega-3 rich oils from oxidation and to enhance its delivery through fortification with

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effective natural antioxidants such as curcumin parallel with microencapsulation technique.

1. Chemistry of omega-3 fatty acids

Fatty acids (FAs) are the basic structural components of fats and oils. It can be categorized as either saturated or unsaturated based on its chemical structures **(Figure 1)**. Saturated fatty acids with a single carbon to carbon (C–C) bond in their chemical structure are frequently solid at room temperature (r.t.), whereas it is liquid in the case of unsaturated fatty acids which have one or more double bonds.

The unsaturated FAs can be divided into monounsaturated FAs with one C=C double bond and polyunsaturated fatty acids (PUFAs) with two or more C=C double bonds **[10]**. The relation between the arrangements of hydrogen atoms and the double bonds, two configurations for unsaturated fatty acids can also be categorized. When the hydrogen atoms on the opposite direction of the double bond are called trans configuration, On the other hand, the cis configuration has hydrogen atoms on the same side.

Two fatty acids have been known as essential in the human diet namely linoleic acid (LA, 18:2 n-6, omega-6 FAs) and alpha-linolenic acid (ALA, 18:3n-3, omega-3 FAs). These fatty acids are deemed essential because they cannot be synthesized by the human body due to the lack of enzymes that can form double bonds beyond the Δ9 carbon **[11]**. The essential fatty acids can be turned into longer-chained and more unsaturated fatty acids through desaturation and elongation after consumption in the human body, which their precursors are less bioactive than it **[12]**. Arachidonic acid (AA, 20:4n-6) is the most common derivative of LA. ALA could be converted to eicosapentaenoic acid (EPA, 20:5n-3), which is further elongated to docosahexaenoic acid (DHA, 22:6n-3). Unfortunately, this conversion is very limited **[12]**. So, EPA and DHA should be supplemented from the diet to increase their levels **[13]**.

2. Omega-3 fatty acids natural sources

Fish and land plants are some of the nutritional sources of omega-3 FAs [14]. The type and amount of omega-3 FAs differ between sources. Fish is the most prevalent source of omega-3 FAs and the amount of DHA and EPA differs between fish species, the fish's diet, time of year, and geography. Coldwater, pelagic fish frequently contain the highest levels of DHA and EPA. DHA is found in mammals such as seals, whales, and algal species. EPA existed in fatty fish (e.g herring and mackerel), liver of lean white fish such as cod and halibut, blubber of marine. In general, oily fish contain the highest amount of omega-3s per serving. Land plant sources of omega-3 FAs include dark green leafy vegetables, flaxseed, soy, chia, canola, perilla, kiwifruit, and walnuts fundamentally in the form of ALA. Increased consumption of omega-3 FAs from these sources may have a limited effect in decreasing stroke or cardiovascular disease due to the incompetent conversion of alpha-linolenic acid to eicosapentaenoic acid and docosahexaenoic acid [12].

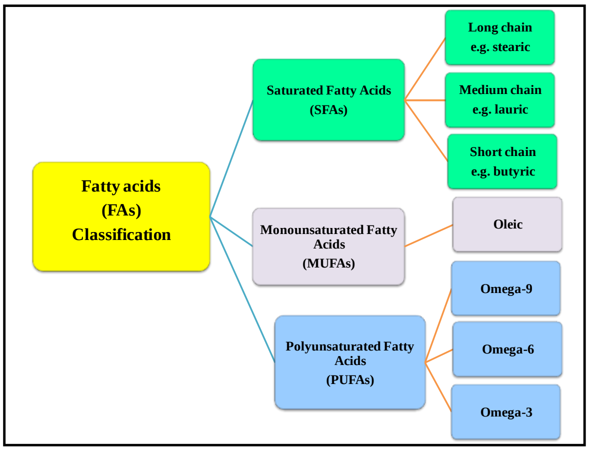

Figure (1): Classification of FAs (SFAs, MUFAs, and PUFAs).

3. Health aspects and antimicrobial activity of omega-3 fatty acids

The beneficial effects of omega-3-PUFAs from fish oil on human health are derived from their role in modulating membrane lipid composition and signal-transduction pathways and affecting metabolism [15]. The cardiovascular health benefits of EPA plus DHA are largely through membrane phospholipids enrichment. Fish oil is identified to increase bleeding time and reduce clotting. DHA is vital for brain growth, development, central nervous system [16]. The three fatty acids (ALA, DHA, and EPA) have been revealed to reduce cardiovascular disease risk [1, 17].

ALA comprises about 60% of total fatty acids in flax making it the richest source of ALA. ALA from flaxseed applies a favorable impact on blood lipids. It was stated that flaxseed oil or its blends supported the cholesterol reduction in hypercholesterolemic rats as compared to diets formulated with hard fats. Ground flaxseed is high in omega-3 fatty acids which have been exposed to reduce hypertension, cholesterol, and triglyceride level. Oikarinen et al., 2005 informed that flaxseed oil may prevent colon carcinogenesis in multiple intestinal neoplasia (Min) mice [18]. Dwivedi et al., 2005 revealed that flaxseed oil blocked the increase of colon tumors in rats [19]. Flaxseed lignan may prevent the production of oxygen radicals, thus effectively reducing atherosclerosis and may give the flaxseed anticancer activity [20]. Due to their anticarcinogenic, antihypercholesterolemic, and glucose metabolism controlling effects, these components may prevent or decrease the risk of several main diseases (e.g. diabetes, lupus nephritis, arteriosclerosis, and hormone) reliant on cancer types [21].

Due to their vast antagonistic effects against pathogenic growth [22, 23], omega-3 FAs can be used in consumable food to preserve and confirm the supply of required antimicrobial concentrations. The incorporation of omega-3 FAs in products (e.g. drinks, dentifrice, and milk toothpaste) may display the demands of antimicrobial for treating and preventing oral diseases [24].

It was reported that the incorporation of DHA and EPA into food preservatives may inhibit bacterial growth (Bacillus subtilis, S. aureus, Listeria monocytogenes, Escherichia coli, Enterobacter aerogenes, Salmonella enteritidis, Pseudomonas aeruginosa, and Salmonella typhimurium) and making them potential agents to develop food safety [25]. Products like polypropylene meshes that are utilized in hernia repair are treated with a mixture of esterified omega-3 FAs to suppress microbial colonization and inflammatory reaction [23]. Moreover, DHA and EPA are stated to induce the Plasmodium species death, viral replication inhibition, exert anti-hepatitis C virus action, and display fungicidal and bactericidal effects. Therefore, omega-3FAs have functioned as endogenous antimicrobial agents [26].

The oligosaccharides extracted from the flaxseed has antibacterial and fungistatic effects [27], which can resist the growth of the pathogen affecting the agricultural sector [28], such as Alternia alternata, Alternia solani, and the human pathogen e.g. Candida albicans; it can also control the deterioration of the foodstuff by Penicillium chrysogenum, Aspergillusflavusa, and Fusarium graminearum.

4. Challenges of incorporating omega-3 fatty acids into foodstuff

Several obstacles must be overcome before omega-3 fortified nanoemulsions can be successfully integrated into commercial food products [29], such as their susceptibility to lipid oxidation as well as enhancing its nutritional aspects and bioavailable.

4.1. Oxidation

Several problems caused by lipid oxidation impact shelf-life, nutritional value, safety, and flavor of food products [30]. It is readily observed by consumers due to undesirable sensory attributes in food products at very low levels [29]. Oxidation is the reaction process between oxygen and unsaturated FAs free radicals which happen in initiation/induction, propagation, and termination stages [30].

Lipid oxidation is promoted by contact of unsaturated lipids to air, heat, light and irradiation [30]. An emulsion-based delivery system is susceptible to oxidation depending on many factors including the composition, structure and organization of the oil, water and interfacial phases, and the kind, amount, and any antioxidants location present [31]. Nanoemulsions are particularly susceptible to lipidoxidation for a number of reasons: high surface area ofexposed lipidsand greater light and air penetration [31]. Lipid oxidation limits the utilization of these oils in processed foods and as nutritional supplements in fortified food.

Therefore, to get the maximum health benefit and to minimize the oxidation process, omega-3 rich oils must be protected against atmospheric oxygen. To achieve this objective, two strategies were planned: First addition of an antioxidant to the oils [32] and second, the encapsulation process of the oil [1, 6].

5. Polyphenols

Phenolics are naturally occurring substances that have aromatic rings (one or more) comprising hydroxyl groups (one or more). Phenolics are vastly found in the plant kingdom and are the most plentiful group of plant metabolites. Nowadays, phenolic structures of more than 8,000 are familiar. Such phenolics may be ranged from simple molecules such as phenolic acids to tannins with a very high polymerized structure such as tannic acid. Whole grains, vegetables, fruits as well as beverages like tea, and chocolate are rich polyphenol sources. Classification of polyphenols may be done according to chemical structure, their source of origin, and their biological role [33]. Flavonoids comprise the highest category of polyphenols in our diet. Flavan nucleus (C6-C3-C6), with its three rings labeled as A, B and C is the basic backbone of flavonoid structure [34].

Flavanones, flavones, isoflavones, flavonols, flavonols, and anthocyanins are six subgroups of flavonoids. In each group, the structure varies partly due to the methoxylation, degree and hydroxylation pattern, glycosylation, or prenylation.

In recent years only, nutritionists have an attention to the health impacts of dietary polyphenols through their wide distribution. Phenolic compounds have become recently the focus of many researchers and food manufacturers for their potentials as antioxidants, and their amazing effects in the prevention of a lot of oxidative stress attached diseases [35].

The daily intake of polyphenols can reach 800 mg/day, with a mean intake of 23 mg/day in western countries [35]. Numerous epidemiological data and preclinical research suggest that plant polyphenols can slow the expansion of particular cancers, neurodegenerative diseases, decrease cardiovascular disease risks, diabetes, or osteoporosis [36]. Moreover, polyphenols were found to modify the activity of a broad range of enzymes and receptors of the cell. So, polyphenolics are not only have antioxidant properties but also have versatile other specific biological actions in fighting and/or recovery of several diseases. Furthermore, phenolics (e.g flavonoids, anthocyanins) have more antioxidant activity than vitamin-C, vitamin-E, and β-carotene.

5.1. Curcumin

Curcumin (Cur) is a yellow-colored polyphenolic compound extracted from the turmeric rhizome (Curcumin longa) which is an Indian spice and also a coloring agent used in a variety of Asian foods. According to the origin and the soil conditions where turmeric is grown, it contains 2%– 9 % curcuminoids. The curcuminoid refers to curcumin, cyclic curcumin, demethoxy curcumin and bis-demethoxycurcumin compounds [37]. Curcumin is the main component, whilecyclic curcuminrepresentsthe minor component. It has anti-inflammatory, antioxidant, and anti-cancer activity [37]. It has been found that free Cur induces apoptosis in many tumor cell lines derived from breast, colorectal, lung, and prostate carcinoma. Cur is also found to inhibit antiapoptotic, proliferative, and metastatic proteins in the cell lines of breast cancer [38]. Additionally, Cur possesses the potential to modulate multidrug resistance (MDR) in cancer [39].

The IUPAC name of curcumin (diferuloylmethane) is (1E, 6E)-1,7-bis (4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione, with chemical formula C21H20O6 (MW 368.38). The symmetric structure of curcumin consists of seven carbon linkers containing α, β-unsaturated β-diketone moiety attached to two aromatic ring units having o-methoxy phenolic units [40]. The diketo group displays keto-enol tautomerism, which can occur in different kinds of conformers relying on the environment [40]. In the state of crystal, it happens in a cis-enol configuration, where it is stabilized by resonance supported hydrogen bonding and the structure contains three substituted planar groups interconnected through two double bonds. The enol form is commonly higher stabilized than the keto form by 5 to 8 k cals/mol depending on the solvent nature in most of the non-polar and moderately polar solvents. It is nearly insoluble in water and easily soluble in polar solvents (Dimethyl sulfoxide (DMSO), acetonitrile, methanol, ethanol, ethyl acetate, chloroform, etc.) It is moderately soluble in hydrocarbon solvents (cyclohexane and hexane).

6. Microencapsulation

An alternative approach to keep it from deterioration is to microencapsulate omega-3 oils. With the use of microencapsulation, the oil is protected from harsh processing environments during processing.

Microencapsulation is a process in which small particles of the sensitive and/or active component (e.g. pure fatty acids) recognized as the active core materials, are packaged within a more inert coat or shell material [41]. This technology has been utilized as an applicable method to improve and develop the biological functions of the oils [42]. It can also partially prevent the omega-3 fatty acids oxidation and extends their shelf life as well as displaying a practical solution for their stabilization and enhanced delivery of food products.

6.1. Core materials

The functional long-chain omega-3 fatty acids (DHA and EPA) are found mainly in oily fish, such as tuna, salmon, sardines, and mackerel, and seaweeds, and marine algae [43]. The shorter-chain omega-3 fatty acid (ALA) can be found in many plant sources such as flaxseed, hemp, canola, perilla, and some vegetables such as beans, spinach, and green peas.

6.1.1. Fish Oil

Fish is rich food for poor people and supplies quality vitamins, proteins, fats, and minerals. There are two sorts of fish oil: fish liver oil generally comes from the cod, halibut, or shark liver) and fish body oil is usually derived from the flesh of the herring, sardine, or anchovy). Both oils are a good source of omega-3 long-chain polyunsaturated fatty acids (LCPUFAs, EPA, and DHA) and also possess a large number of vitamins D and A. In recent years seafood products have been developed significantly supported by the fish image as a healthy diet component. Fish products and fish are considered functional marine nutraceuticals [6].

6.1.2. Flaxseed oil

Flax (Linum usitatissimum) annually species of the Linaceae family is a blue flowering rabi crop, which is cultivated for the seed, textile fiber, and oil production. Suitable moisture and relatively cool temperatures, mainly during the flowering to maturity period, appear to support oil content and quality together. The seed is oval and flat with a pointed tip. Its surface is glossy and smooth. The flaxseed texture is chewy and crisp having an attractive nutty taste. It differs in color from yellow to dark brown. Flaxseed varieties (yellow and brown) are nearly the same in nutrient content [44]. The color of coated seed is identified by the pigment amount that exists, a feature that can be altered through the breeding practices for the normal plant.

Flaxseed is one of the major oil plants, especially in China and Canada. Flaxseed, also known as flaxseed or linseed, contains 20–40 % oil [45]. It has become well-known as a functional food due to its nutritional composition. This oil has the lowest levels of nutritionally unfavorable saturated fatty acids. Flaxseed is well known as a high source of polyunsaturated fatty acids, elevated quality proteins, and dissolvable fiber [46].

However, because of their unsaturated nature, omega-3 -rich oils are chemically unstable and are easily oxidized to free radicals and unpleasant tastes, which are impacted negatively on food products (shelf life and total acceptability). Therefore, microencapsulation technology is utilized as an applicable method to improve the functional and biological characteristics of the oils, to furthermore improve food products functionalized with omega fatty acids (e.g. yogurt, fortified milk, and baked products).

6.2. Wall materials

Most of the delivery systems developed for pharmaceutical applications use synthetic components that cannot be applied to food products due to their potential negative effects upon chronic consumption [47]. Dima et al., 2015 stated that delivery systems should be designed to be biocompatible, bio-based ingredients, and non-toxic with food products [48]. However, some drawbacks of using bio-based food components are the variations in their properties due to the isolation conditions, quality, and initial source composition [49]. Besides, encapsulating materials should have good film formation capacity, low viscosity, neutral odor, taste and barrier, and gelling properties.

Due to biodegradability; biocompatibility and non-toxicity of lipids, proteins, and polysaccharides are applied as encapsulating matrices. Polysaccharides are the most applied biopolymers in nutraceutical encapsulation for food applications. They can be utilized in the delivery system formation with various functions, for example as a coating material in spray drying microcapsules or as structured layered o/w interfaces in emulsions. Hydrogen bonds, van der Waals forces, hydrophobic and ionic interactions are the main interactions established between polysaccharides and nutraceuticals.

Nutraceutical release depends mostly on the hydrolysis of the glycosidic linkages of the polysaccharides [50]. When polysaccharides (alginate, chitosan....etc) are exposed to environmental changes such as ionic strength, temperature, pH, or solvent composition, they undergo a transition to various aggregation states and different modifications.

6.2.1. Sodium alginate

Sodium alginate is a linear heteropolysaccharide, naturally derived from various species of algae, and composed of β-D-mannuronic (M) and α-L-guluronic (G) acids. The effective properties of alginate varied depending on the source of the polymer. Alginate microcapsules are the most generally applied in encapsulation because of their simplicity, biocompatibility, and non-toxicity. These microcapsules are produced in the divalent cations usually calcium ions in the form of calcium chloride (CaCl2) solution through ionotropic gelation [51]. The model of egg-box was formed from coordination between Ca+2 and carboxyl and hydroxyl groups of four α-L-guluronate (G) monomers from two adjacent chains on the polymer (Figure 2) [52].

Despite the previously mentioned advantages of using alginate as an encapsulating agent, some disadvantages are endorsed to the use of alginate due to its properties; alginate microcapsules have a less efficient encapsulation due to their porous network in its structure **[51]**. However, these drawbacks can be efficiently overcome by mixing alginate with other polymers or coating polymer layers on an alginate microcapsule **[53]**. For example, several studies reported that blending alginate with starch **[54]**, whey protein **[55]**, skim milk **[56],** or coating with chitosan **[57].** Covering alginate beads with chitosan has been reported to enhance the physical stability and mucoadhesive properties of alginate microcapsules in the colon.

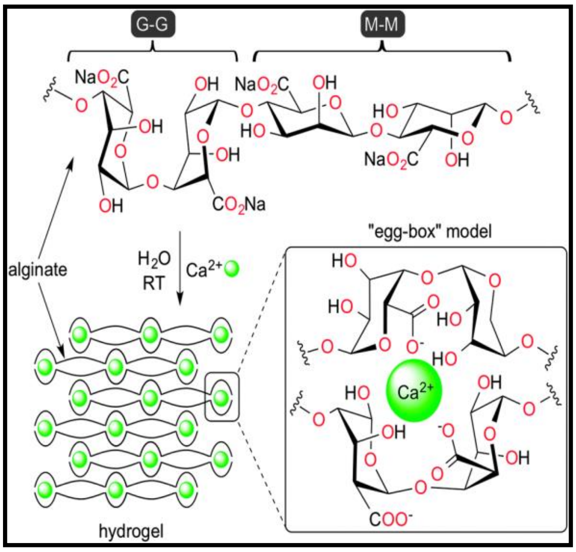

Figure (2): Structure of the repeating units of sodium alginate and formation of the egg-box model **[52].**

6.2.2. Chitosan

Chitin is an abundant natural polymer and is found in the shell wall of crustaceans like crabs and shrimp and biological materials as the cell walls of fungi). Chitosan is a linear polysaccharide positively charged consists of glucosamine units formed by chitin deacetylation in an alkaline media. Chitosan is a copolymer consisting of β-(1–4)-2-acetamido-D-glucose and β-(1–4)-2-amino-D-glucose units with the latter usually exceeding 60%**.** Chitosan and cellulose have the same structure except that an acetamide group replaced the secondary hydroxyl on the second carbon of the hexose repeat unit. At below pH 6, Cs is water soluble like alginate and produces a gel via ionotropic gelation **[58]**. It is preferred to be used in low concentration as a coat but not as a capsule because chitosan as polycations binds to the cells and inhibits their growth **[59]**.

Chitosan is defined in terms of average molecular weight and deacetylation degree. Its antimicrobial activity is very important due to its cationic nature and film-forming features. The films of Chitosan possess good mechanical properties and selective permeability to gasses (CO_2 and O_2) so it is an excellent film formulating material **[60]**. The antimicrobial activity of chitosan is supposed to be produced from its polycationic nature **[61]**. The antimicrobial properties of chitosan may be supposed by the electrostatic forces between its amino group (NH_2) and the negative residues. at cell surfaces. The number of protonated amino groups (NH_2) existing in chitosan rises with increased deacetylation degrees (DD) which impacts the antimicrobial activity. **Liu *et al.* (2004)** explained that the bactericidal effect is produced through the electrostatic interaction between the phosphoryl groups ($P^+O_3^{2-}$) on the cell membrane and the NH^{3+} group in chitosan **[62]**.

6.2.3. Clay minerals

Clay is a naturally occurring material consisted mainly of fine-grained minerals and has a plastic behavior at convenient water contents. The concern and challenge in improving nanocomposites are to discover methods to make macroscopic substances that benefit from the unique physical and mechanical properties of their very tiny objects. The increasing demand for nanocomposites from emerging districts of the world is also expected to share the growth of the polymer nanocomposites market **[63, 64]**.

A wide range of nanocomposites with high performance is from nanoclay as a new field of treated clay. The clay minerals are usually silicates less than 2 µm (1 millionth of a meter) in dimension, about the same dimension as a virus. Clays are quite abundant at the surface of the earth; they compose rocks known as shales and are a main component in roughly all sedimentary rocks. The small size of the particles and their crystal structures afford clay materials particular properties, including cation exchange capabilities, the behavior of swelling, low permeability, and catalytic capacity.

The great interest in the utilize of nanoclays for the amendment of polymeric material for many applications may be pointed from the increased commercial interest **[65]**, and consumption of clay nanocomposites that was almost about 25% in 2005 of the total nanocomposite consumed **[66]**. Uddin, 2008 estimated the sharing of the nanoclay composites in the market to be more than 45%. Depending on the chemical and morphology structure of nanoclay, several classes such as bentonite, montmorillonite, halloysite, kaolinite, illite, hectorite, and chlorite can be specified **[67]**.

The use of kaolin (China clay) is dated to the 3rd century BC in China. It is a mixture of minerals commonly including kaolinite, illite, quartz, mica, feldspar, and montmorillonite. Montmorillonite is the main raw material in nanoclay.

The structural nature of clay minerals as fine-grained is the common feature between them with sheet-like geometry. Phyllosilicates are generally the sheet silicates a hydrous. The diameter of unique particles of natural clay is < 0.004 mm. While, the diameter of mica, feldspar, quartz, iron, and aluminum oxides is in the range of 0.002 to 0.001 mm. On the other hand, the diameter of colloidal clay particles is finer and less than 0.001 mm and is found in silicates layered.

Kaolinite, smectite (montmorillonite), illite, and chlorite are four major groups of clay minerals that varied in the layered structure. Montmorillonite, talc, nontronite, pyrophyllite, and saponite are a few members of the bigger smectite clay group. The chemical structure of this group has the general formula (Ca, Na, H) $(Al, Mg, Fe, Zn)_2$ $(Si, Al)_4$ O_{10} $(OH)_2$. XH_2O. The important difference among the members of this group is seen in the chemical characteristics. The structural layer comprises silicate layers sandwiching an aluminum oxide/hydroxide layer $(Al_2 (OH)_4)$.

Each layer of clay particles consists of two types of structural sheets (tetrahedral and octahedral. The sheet of tetrahedral is composed of silicon-oxygen tetrahedra producing a hexagonal system by linked to adjacent tetrahedra and sharing three corners. The fourth angle of every tetrahedral is formed a portion of neighboring sheet octahedral. The sheet of octahedral is generally contained magnesium/aluminum in six-fold coordinate with the oxygen of tetrahedral sheet and hydroxyl. A layer formed from both two sheets and a clay crystallite may be produced from several layers by the force of Vander Waals, electrostatic, interlayer cations, or by hydrogen bonding. **Nanocor, (2006) [68]** produced the formula theoretically and structure, as shown in

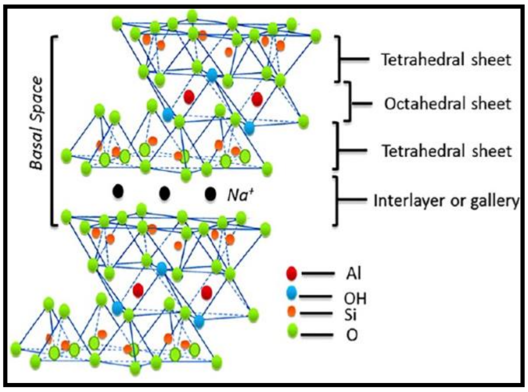

Figure 3.

Figure (3): Structure of montmorillonite **[69]**.

6.3. Omega-3 rich oils microencapsulation techniques

The microencapsulation of vegetable and marine oils is commonly done using emulsification, extrusion; spray drying, freeze-drying, and coacervation techniques **[58] (Table 1 and 2)**.

*6.3.1.*Emulsification

The main step in the microencapsulation of oils is the emulsification process. In the extrusion process, emulsion droplets can be incorporated into the matrix and also, can be used as templates in coacervation processing. While microencapsulation in spray and freeze-drying, the core and wall materials could be used by emulsion techniques before the final drying. An emulsion consists of at least two immiscible liquids (oil and water) with one of them are dispersed as small droplets in the other. Generally, three categories of emulsions are most probable to be prepared depending on the composition: oil-in-water (O/W) emulsion in which the droplets of oil are dispersed in the aqueous phase. Emulsion of water-in-oil (W/O) in which the water droplets are dispersed in the oil continuous phase. Inter-dispersed micro-domains of oil and water are used to prepare bi-continuous and multiple emulsions. In the three categories of emulsion, a suitable combination of surfactants and/or co-surfactants is used to stabilize the interface **[70]**. The coarse emulsions are prepared using a homogenizer (high shear mixer, sonicator, high-pressure homogenizer) for homogenizing oil, water, and emulsifier together. The advantages of this method are relative ease of preparation and low cost but have the drawbacks of physical instability when exposed to heating, freezing, chilling, pH extremes, drying, and high mineral concentrations **[71]**. Mainly vitamins, minerals, enzymes, and microorganisms have been encapsulated using emulsification.

***6.3.2. Extrusion*:**

This technique is based on the gel formation of polysaccharide that immobilizes the core just in touch with a multivalent ion. Extrusion encompasses mixing the core in a solution of sodium alginate, then the mixture dropwise extruded with the aid of a caliber pipette or a reduced syringe into calcium chloride as a hardening solution **[1]**. The main benefit of this process is the prolonged shelf life of flavor compounds due to the provision of a practically impermeable barrier against oxygen. One of the disadvantages of this method is to some extent large particles produced by extrusion (typically 500-1000mm), which limit the usage in applications where mouth-feel is an essential factor. Furthermore, the encapsulation of extrusion has a very limited range of wall materials **[72]**.

***6.3.3. Spray drying*:**

In spray, drying microencapsulation is usually utilized for the fragrances, oils, and flavors coating. Core materials are dispersed into the polymer mixture then sprayed into droplets in a hot chamber. This technique is used on a large scale and is generally applied in the food industry **[73]**. However, the high temperature used in this technique may negatively affect the encapsulated materials due to its accompanied high temperature **[58]**. This drawback could be overcome by adding thermo protectants like granular starch and soluble fibers to the mixture before the drying process **[53]**.

6.3.4. Freeze-drying:

According to **[74]**, the main concept of freeze-drying microencapsulation is that the cold air injection for solidification of particles. Microparticles are formed from a mixture having the core and wall material in droplets. This mixture is nebulized by an atomizer and at low temperature enters a chamber wherein air flows. This temperature can be used to encapsulate core material by reduction of the wall material due to solidification. This technology is seen as the cheapest encapsulation process by using lower temperatures. However, microcapsules can show some drawbacks, including low encapsulation efficiency and the core expulsion during storage. **Heinzelmann *et al*., (2000)** reported that the powders of fish oil microcapsules using freeze-drying have highly porous structures and a short shelf-life **[75]**. Various vitamins and minerals can be encapsulated using freeze-drying **[58]**.

6.3.5. Coacervation:

This method included that polymer deposition around the core by changing the physicochemical features of the medium, (temperature, ionic strength, polarity, and pH). It is termed simple coacervation when only a single macro-molecule has existed. In omega-3 rich oils microencapsulation, the oil droplets are usually dispersed in gelatin mixture, and the pH is modified to coacervate of gelatin that forms a coating over oil droplets. The next cooling step hardens the coating and encapsulates the oil. When two or more opposite charges molecules are found the process is called complex coacervation **[76]**. The protection of omega-3 rich oils can be achieved by this microencapsulation method **[77]**. The coacervation process does not need organic solvents or high temperatures so it is low-cost and relatively simple. On the other hand, the coacervation occurs within limited ranges of pH, the concentration of colloid, and/or electrolyte **[78]**. **Jun-Xia *et al.* 2011** protected sweet orange oil by encapsulation used soybean protein isolate using the coacervation method **[79]**.

6.4. Reasons for encapsulation

1. It is mostly utilized to increase the stability and life of the product.

2. To control the rate at which the core leaves the microcapsule, as in the controlled release.

3. Microencapsulation has been used to support the core materials protection against surrounding environmental conditions (e.g., oxygen, temperature, pH, light, and humidity).
4. Retarding evaporation of a volatile substance, isolating a reactive core from chemical attack, improving the treatment properties of viscous material.
5. Masking the unpleasant flavor and taste of the core material, transforming liquid compounds into solids for easy handling, and diluting the core material when only very small amounts are required **[116-118]**.

6.5. Factors affecting the microencapsulation effectiveness

Various factors influence the encapsulation effectiveness including:

I. The encapsulating coat material and the technique used for microencapsulation influence the microcapsule stability and the encapsulation efficiency **[119, 120]**.

II. Capsule size should be enough for protecting the entrapped cells from adverse environmental conditions but without causing a gritty mouthfeel **[121]**.

III. The type and severity of the environmental condition **[122-124]**.

IV. **Figure 4** summarizes the factors affecting the microencapsulation efficacy.

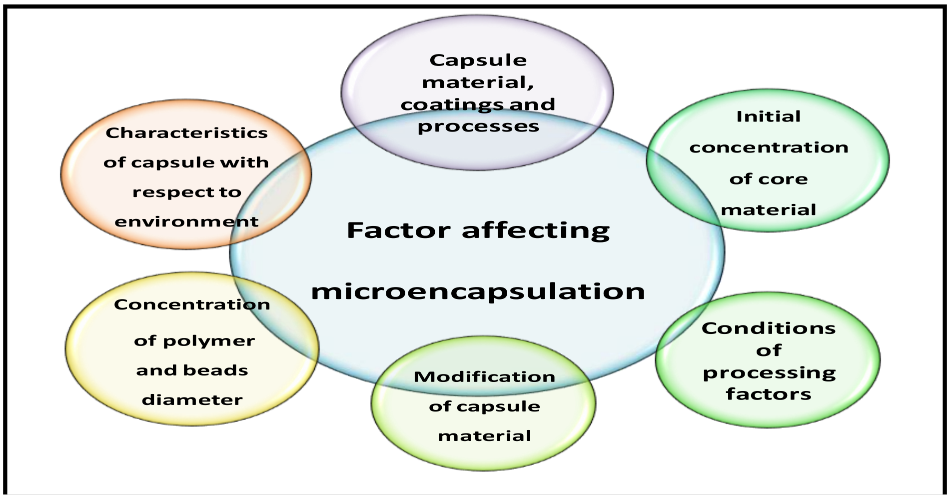

Figure (4): Factors affecting the microencapsulation efficacy**.**

Future perspectives

Future studies must be pointed towards the applying of microencapsulation technology to encapsulate a mixture of various oils by differing techniques. This technology can improve the quality, safety, and nutritional value of food products. Besides, more than one technique of microencapsulation can be used in the process. Other future suggestions comprise to be eco-friendly by purification and use of agro-industrial waste as a wall material, thereby decreasing the economical cost of the encapsulation process. Shortly, for food products, it can be applied as coatings containing microencapsulated oil that prolong the shelf life of these products, thus also decreasing the economic losses. For medical products, it can be applied in adhesive bandages to control the occurrence of infections and in wheelchair patients to avoid skin infections.

Conclusion

Omega fatty acids-rich oils (e.g., fish oil and flaxseed oil) are being used in the preparation of safe products with a positive impact on consumer health. Deliver omega-e fatty acids into food systems can be achieved using the nanoemulsion method due to enhancement bioavailability and mask unwanted off-flavors. Microencapsulation is well-established for oil protection from oxidation. Several materials can be used as wall coatings, the most common being polysaccharides and some proteins, due to their higher affinity with various types of materials to be encapsulated (omega-3 fatty acids). There are various techniques of the microencapsulation process. The most commonly used techniques for oil microencapsulation are spray- drying and coacervation oils. The incorporation of functional omega-3 fatty acids in foods is needed to improve the health benefits and marketability of foods.

Table 1: Microencapsulation of fish oil using different wall materials and techniques

Flaxseed oil	Wall material	Technique	References
Flaxseed oil	WPI	Spray drying	**[101]**
Flaxseed oil	GA and lecithin	Spray drying	**[102]**
Flaxseed oil	Gelatin and GA	Complex coacervation and freeze-drying	**[77]**
Flaxseed oil	Zein	Spray drying	**[103]**
Flaxseed oil	Gum arabic, WPC & a modified starch	Spray drying	**[104]**
Flaxseed oil	MD/GA, (25% &30%)	Spray drying	**[105]**
Flaxseed oil	MD, WPC, GA, and two chemically modified starches: tapioca starch and waxy maize	Spray drying	**[106]**
Flaxseed oil	Modified starches(Hi-Cap 100TM) /AG/WPC	Spray drying	**[107]**
Flaxseed oil	GA, MD, methylcellulose (MC) and WPI	Spray drying	**[108]**
Flaxseed oil	Chickpea (CPI) orlentil protein isolate (LPI & MD)	Freeze-drying	**[109]**
Flaxseed oil	Modified starch	Spray drying	**[110]**
Flaxseed oil	Soya proteins– GA	Complex coacervation	**[111]**
Flaxseed oil	Flaxseed protein isolate (FPI) and flaxseed gum (FG)	Complex coacervates	**[112]**
Flaxseed oil	Legume Proteins in Combination with Soluble Fiber or Trehalose	Spray drying	**[113]**
Flaxseed oil	Soy protein isolate and modified starch	Spray drying	**[114]**
Flaxseed oil	Polyphenol-adducted flaxseed protein isolate-flaxseed gum	Complex coacervates	**[115]**

Table 2: Microencapsulation of flaxseed oil using different wall materials and techniques

Fish oil	Wall material	Techniques	References
Fish oil	Sodium caseinate (SC), carbohydrate	Freeze-drying	**[75]**
Fish oil	Highly branched cyclic dextrin and sodium caseinate	Spray drying	**[80]**
Fish oil	Methylcellulose Hydroxypropylmethylcellulose (HPMC)	Spray drying	**[81]**
Fish oil	GA	Spray drying	**[82]**
Fish oil	Sodium caseinate, glucose, glucose syrup	Spray drying	**[83]**
Fish oil	Methylcellulose Hydroxypropyl	Spray drying	**[84]**
Fish oil	Sugar beet pectin and glucose syrup	Spray drying	**[85]**
Fish oil	Alginate & starch	Spray drying	**[86]**
Fish oil	Barley protein	Spray drying	**[87]**
Fish oil	Skim milk powder (SMP)	Spray drying	**[88]**
Fish oil	SMP, Whey protein concentrate (WPC), whey protein isolate (WPI)	Spray drying	**[89]**
Fish oil	Gelatin, acacia gum (AG)	Complex coacervation	[**90]**
Fish oil	Gelatin: sodium carboxymethylcellulose (CMC)	Spray drying	**[91]**
Fish oil	Inulin (IN)	Spray drying	**[92])**
Fish oil	Cashew gum, Arabic gum, and starch	Spray drying	**[93]**
Fish oil	Porous silica particles	Spray drying	**[94]**
Fish oil	Alginate	Extrusion	**[95]**
Fish oil	Thiol-modified β-lactoglobulin fibrils/chitosan complex	Spray drying	**[96]**
Fish oil	Casein-pectin, maltodextrin, and gum arabic	Spray-drying and complex coacervation and spray-drying	**[97]**
Fish oil	Hydroxypropyl methylcellulose	Spray drying	**[98]**
Fish oil	β-lactoglobulin (β-LG) fibril variants, chitosan and MD.	Spray-drying	**[99]**
Fish oil	Gelatin	Freeze-drying	**[100]**

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