FAT REPLACERS

1. Introduction

Lipids provide a concentrated source of energy (9 kcal/g compared with 4 kcal/g for proteins and carbohydrates) in the diet. The building blocks of lipids are referred to as fatty acids. These can be either saturated, monounsaturated, or polyunsaturated. Dietary fat is found in foods derived from both plants and animals. Foods rich in saturated fats are usually of animal origin. Vegetable fats are generally unsaturated. Lipids supply energy and essential fatty acids. They also serve as carriers for the fat-soluble vitamins A, D, E, and K and aid their absorption in the intestine. Lipids are a source of antioxidants and numerous bioactive compounds. They constitute the building blocks of membranes and play a key regulatory role in numerous biological functions.

Lipids are composed mainly of triacylglycerols (TAGs) and to a lesser extent phospholipids (PL) and glycolipids (GL). The TAGs consist of fatty acids and glycerol. Individual fatty acids have different biological effects ranging from modulating clinical markers of disease risk to regulating many intracellular biological mechanisms due to changes in intracellular signaling and gene expression. Fatty acids modulate lipid metabolism and other physiological systems that affect risk factors for chronic diseases. Whether these effects on health are beneficial or harmful depends on the specific fatty acids and the mix of fatty acids in the diet and the body. Different foods are rich sources of specific fatty acids as mixtures.

Proper nutrition is vital to good health and is essential for the adequate growth and development of children and adolescents. Major causes of morbidity and mortality in the United States are related to poor diet and a sedentary lifestyle. Specific diseases and conditions linked to poor diet include cardiovascular disease, hypertension, diabetes, overweight and obesity, osteoporosis, diverticular disease, iron deficiency anemia, malnutrition, and some cancers, among others. Lack of physical activity has also been associated with similar ailments. Furthermore, muscle strengthening and improving balance can reduce falls and increase functional status among older adults. Together with physical activity, a high quality diet that does not provide excess calories should enhance the health of most individuals.

The 2005 Dietary Guidelines for Americans recommend a total fat intake between 20 and 35% of calories for adults to meet daily energy and nutritional needs (1). A fat intake of 30–35% of calories is recommended for children 2–3 years of age and 25–35% of calories for children and adolescents 4–18 years of age (1). Intake of fat outside of this range is not recommended for most individuals because of potential adverse effects on achieving recommended nutrient intake and on risk factors for chronic diseases. In 2002, The Institute of Medicine (IOM) recommended that the intake of saturated fats be $<10\%$ of calories, cholesterol be <300 mg/day, and trans fatty acid consumption be as low as possible. Consumption of certain fatty acids is encouraged because of their positive health effects. The U.S. Department of Agriculture (USDA) food guidance system, MyPyramid (2), recommends oils from foods eg, vegetable oils, nuts, and some fish, because of their healthful attributes.

To meet the total fat intake of 20–35% of calories, most dietary lipids should come from sources of polyunsaturated and monounsaturated fatty acids. Sources of omega-6 polyunsaturated fatty acids include liquid vegetable oils, eg, those from soybean, corn, and safflower. Plant sources of omega-3 polyunsaturated fatty acids (α-linolenic acid; 18:3n-3) include soybean oil, canola oil, walnuts, and flaxseed, among others. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are omega-3 fatty acids that are present in fish and shellfish. Fatty fish, eg, salmon, trout, and herring, are higher in their content of EPA and DHA than are lean fish (ie, cod, haddock, catfish). Furthermore, commercially grown algae, eg, *Crypthecodinium cohnii* and *Schizochytrium sp*. contain very high concentrations of DHA. Some evidence suggests an association between consumption of omega-3 fatty acids and reduced risks of mortality from cardiovascular disease for the general population. Plant sources that are rich in monounsaturated fatty acids include vegetable oils (eg, canola, olive, high oleic safflower, and sunflower oils) that are liquid at room temperature and oil from nuts, eg, hazelnuts.

According to the Continuing Survey of Food Intakes of Individuals, the median consumption of total fat in the United States ranges from ~32 to 34% of total calories. The main contributors include butter, margarine, vegetable oils, egg yolk, nuts, baked goods, and visible fat on meat, poultry, and fish (Table 1). Saturated fats provide ~11–12% of calories in adult diets, according to the National Health and Nutrition Examination Survey conducted between 1988 and 1994.

1.1. Structure and Functions of Dietary Fat. Lipids consist of fatty acids and glycerol. Nearly all fats in our bodies and in foods are TAGs, being made up of three fatty acid molecules attached to one glycerol molecule. There are ~16 different fatty acids commonly present in foods. The nature of fat depends primarily on its constituent fatty acids.

Fats can be classified as saturated, monounsaturated, or polyunsaturated, depending on the type of chemical bonds present in the fatty acid. If a fatty acid has all the hydrogen atoms it can hold, it is termed saturated. However, if some of the hydrogen atoms are absent and the usual single bond between carbon atoms has been replaced by a double bond, then it is unsaturated. If there is just one double bond, then it is monounsaturated. If there is more than one, then it is polyunsaturated. Most fats contain a proportion of each of these three basic types of fatty acids, but are generally described according to the type predominating. Saturated and monounsaturated fatty acids may be synthesized in the body, but polyunsaturated fatty acids need to be supplied by the diet, hence termed essential.

Saturated fats tend to be of animal origin and are solid at room temperature. Butter, lard, suet, and meat fat are saturated fats. Unsaturated fats are liquid at room temperature. They are usually of plant origin, though fish and algal oils are also high in polyunsaturated fatty acids. Plant oils may be hardened by the addition of hydrogen atoms, converting double bonds to single bonds. This process is known as hydrogenation. Hydrogenated vegetable oils are often present in margarine and other processed foods. As a food ingredient, fat is important in food preparation and consumption because it provides flavor, texture, stability, consistency, mouthfeel, and palatability to foods. It also acts as a heat-transfer medium for cooking and frying of lipid-containing foods.

Lipids play critical roles in the overall functioning of the body, eg, in digestion and energy metabolism. Usually, 95% of the fat in food is digested and absorbed into adipose, or fatty, tissue. Lipids are the body's energy provider and energy reserve, which helps the body maintain a constant temperature. Lipids are also involved in the production and regulation of steroid hormones, which are hydrophobic molecules made from cholesterol in the smooth endoplasmic reticulum, a compartment within a cell in which lipids, hormones, and proteins are made. Steroid hormones are essential in regulating sexuality, reproduction, and development of the human sex organs, as well as in regulating the water balance in the body. Steroid hormones can also freely flow in and out of cells, and they modify the transcription process, which is the first step in protein synthesis, where segments of the cell's deoxyribonucleic acid (DNA), or the genetic code, is copied.

Lipids serve important structural roles in maintaining nerve impulse transmission, memory storage, and tissue structure. Lipids are the major component of cell membranes. The three most common lipids in the membranes of eukaryots, or nucleus-containing cells, are phospholipids, glycolipids, and cholesterol. A phospholipid has two parts: (a) the hydrophilic head, which consists of choline, phosphate, and glycerol; and (b) the hydrophobic fatty acid tail, which consists of carbon and hydrogen. The hydrophilic head is the part of the phospholipids that is in contact with water, since it shares similar chemical properties with water molecules. The hydrophobic tail of the phospholipids faces inward, and therefore is able to avoid any contact with water. In this particular arrangement, the phospholipids arrange themselves in a bilayer alignment in aqueous solution.

Lipids are metabolized primarily in the small intestines because the enzymes present in the stomach cannot break down fat molecules due to their hydrophobicity. In the small intestine, lipid molecules stimulate the release of cholecystokinin, a small-intestine hormone, into the bloodstream. The cholecystokinin in the blood triggers the pancreas to release digestive enzymes that can break down lipids. The gallbladder is also stimulated to secrete bile into the small intestine. Bile acids coat the fat molecules, which results in the formation of small fat globules, known as micelles. The coating prevents the small fat globules from fusing together to form larger fat molecules, and therefore the small fat globules are more easily absorbed. The pancreatic enzymes can also break down TAGs into monoacylglycerols (MAGs) and fatty acids. Once this occurs, the broken-down fat molecules are able to diffuse into the intestinal cells, in which they are converted back to TAGs, and finally into chylomicrons.

Chylomicrons, which are composed of fat and protein, are macromolecules that travel through the bloodstream into the lymphatic capillaries called lacteals. The lymphatic system is a special system of vessels that carries a clear fluid called lymph, in which lost fluid and proteins are returned to the blood. The lacteals absorb the fat molecules and transport them from the digestive tract to the circulatory system, dumping chylomicrons in the bloodstream. The adipose and liver tissues, which release enzymes called lipoprotein lipase, break down chylomicrons into MAGs and fatty acids. These molecules diffuse into the adipose and liver cells, where they are converted back to triacylglycerols, also commonly known as triglycerides, and stored as the body's supply of energy.

1.2. Reducing Dietary Fat. There is an extraordinary consumption of fats in the average western diet, which has led to massive health problems. Poor diet and physical inactivity are the most important factors contributing to the increase in overweight and obesity in North America. Furthermore, overweight and obesity are major risk factors for certain chronic diseases, eg, diabetes. In 1999–2002, an estimated 65% of U.S. adults were overweight (4), an increase from 56% in 1988–1994. Data from 1999 to 2002 also showed that 30% of adults were obese (4), an increase from 23% in an earlier survey (1). Dramatic increases in the prevalence of overweight have occurred in children and adolescents of both sexes, with ~16% of children and adolescents aged 6–19 years considered to be overweight (1999–2002) (4). In order to reverse this trend, many Americans need to consume fewer calories, be more active, and make wiser choices within and among food groups.

There is a growing body of evidence, which demonstrates that following a diet that complies with the Dietary Guidelines may reduce the risk of chronic disease. It was recently reported that dietary patterns consistent with recommended dietary guidance that were associated with a lower risk of mortality among individuals age 45 years and older in the United States (5). The authors of the study estimated that ~16% and 9% of mortality from any cause in men and women, respectively, could be eliminated by the adoption of desirable dietary behaviors. Nutrition professionals encourage people to select diets low in total fat, saturated fat, and cholesterol. National Academy of Sciences, U.S. Surgeon General, American Heart Association, National Cholesterol Education Program, American Cancer Society, American Dietetic Association, National Institutes of Health, USDA, and the Department of Health and Human Services are among the many health and government authorities that advocate a reduction of dietary fat for most consumers. Advice to reduce fat and energy consumption has led to the production of foods with a lower content of fat and to the development of fat replacers.

Due to their high caloric content, lipids are the number one consideration in calorie reduction. Methods to reduce total fat intake include low fat cookery, eg, boiling, broiling, steaming, stewing, baking, and roasting (6). Consumers may also trim visible fat from meat and poultry products and limit fat spreads, dressings, gravies, and other sauces. Another way to achieve lower total fat intake is to replace fat-rich desserts and oily snack foods with fruits and vegetables. Research indicates that individuals who consume a diet that is reduced in fat and calories and includes use of fat-modified products have a better overall nutrient profile than individuals who do not use any fat-modified products (7). A national consumer survey conducted in 2004 by Calorie Control Council, an international association of manufacturers of low calorie, low fat, and diet foods and beverages, indicated that low fat, reduced-fat and fat-free products remained popular among the general public (3). Consumer's most favorite reduced-fat products include milk, cheese, mayonnaise, sauces, salad dressings, margarine, chips and snack foods (Table 2) (3). Another Council survey shows that two-thirds of adults believe there is a need for food ingredients, which can replace the fat in food products.

1.3. Labeling and Nutrition Claims. Many food products in the market include labels that detail their nutritional composition; it is also likely that foods containing fat replacers may carry such information to emphasize their characteristics. Labeling foods for their fat components has received much attention because of the increased consumer demand and modified intake of dietary fats. It is expected that the increased availability of nutrition labels on food products will improve public health and assist consumers in following dietary recommendations. Food labels indicating a reduction in fat are important to both the consumer and the food industry.

The U.S. Nutrition Labeling and Education Act (NLEA) amended the Federal Food, Drug, and Cosmetic Act to require the mandatory nutrition labeling of most foods from May, 1994. The labels on food made with fat replacers must adhere to the NLEA criteria for the use of fat- and calorie-related claims (8). The NLEA requires most foods to bear nutrition labeling and requires food labels that bear certain health and nutrient-content claims to comply with specific requirements. The common and usual name of the fat replacer must be listed on the ingredient statement. Nutrition information must be declared on the "Nutrition Facts" panel and must include information on levels of calories, calories from fat, total fat, saturated fat, cholesterol, sodium, total carbohydrates, dietary fiber, sugars, proteins, vitamin A, vitamin C, and minerals (9). The NLEA permits the use of energy conversion factors to determine the caloric availability of food ingredients. For example, in the case of Caprenin, a low calorie fat, an energy value of 5 kcal/g has been established. Thus, Caprenin should be listed at the appropriate point in the ingredient declaration and accounted for at 5 kcal/g. In 1996, the U.S. Food and Drug Administration (FDA) proposed a rule for the labeling of products containing fat-based fat replacers. The FDA requires that the labels on foods containing fat replacers list the analytical fat amount on the "Nutrition Facts" label with a footnote indicating the amount that is bioavailable. Furthermore, the FDA has proposed to define nutrient-content claims, eg, fat-free, low fat, and reduced fat (Table 3). Products labeled "fat free" and "low fat" must contain <0.5 and <3 g fat/serving, respectively. "Reduced" or "less fat" may be used on the labels of products that contain 25% less fat than full-fat counterpart products. Products labeled "percent fat free" should be based on 100 g, when product meets the definition of low fat or a 100% fat free, claim can be made when products meet the definition of fat free (contains no added fat) (9). However, EU regulations on spreadable fats establish specific requirements with respect to nutrition claims: the claim "reduced fat" is only legitimate if fat content is <62%; and the claims "low fat" and "light" are only legitimate if fat content is <41% (10).

The fat labeling claims do not provide any indication of the caloric content of the food product. However, products containing one-third fewer calories or one-half of the fat of the reference food may be labeled as "light". If >50% of calories in a food are derived from fat, the fat content of the "reduced-fat" version must be reduced by 50% (6). The term "calorie free" and "low calorie" can only be used on products with <5 and <40 cal per serving, respectively, and "reduced" or "fewer calories" can only be used on products that have <25% of the calories in the regular product (9).

Although labeling regulations do not require a specific listing of fat replacers on the "Nutrition Facts" panel, the amount of fat replacers added to foods will affect labeling information. Fat replacers, like all other ingredients, must be listed in order of predominance in the list of ingredients (6). The number of calories listed in the nutrition label must equal the digestible calories contained in a serving of food. In the case of a nondigestible ingredient, the manufacturer must have data to demonstrate the level of digestible calories (9).

1.4. Regulatory Aspects of Fat Replacers. Under the FDA regulations, fat replacers fall into one of two categories: food additives or generally recognized as safe (GRAS) substances. Each category has its own set of regulatory requirements. The GRAS substances are those, which are generally recognized by scientific experts as being safe for specific use in food on the basis of an extensive history of use or on the basis of published scientific evidence. Fat replacers made with a combination of existing ingredients, eg, as starches, gums, fibers, or proteins, that are widely used in the food supply require no special approval. The GRAS substances can be used if they have been shown to be safe through long-term ingestion and use. Many GRAS substances are similar to substances already present in food. Examples of GRAS substances used as fat replacers are cellulose gel, dextrins, guar gum, and gum arabic. Microparticulated protein fat mimetics are also considered as GRAS substances. Some GRAS ingredients used in a new or unfamiliar way may need a petition that affirms them as GRAS, eg, a new fiber extracted from a plant that is regularly ingested.

New substances not present in the food supply must be approved as food additives. A food additive is defined as any substance, the intended use of which may reasonably be expected to result, directly or indirectly, in its becoming a component or otherwise affecting the characteristics of any food. Even food additives, which are in the food supply, may require a special petition for use in a food category when no such approval exists or when the amount needed is greater than currently permitted. Food additive petitions for fat replacers forced review boards to employ different methodologies because, unlike most food additives, which would be used only in extremely small amounts, fat replacers might be used in macronutrient amounts. Food additives must be evaluated for safety and approved by FDA before they can be marketed. Examples of food additives are polydextrose, carrageenan, and olestra, which are used as fat replacers.

1.5. Safety of Fat Replacers. Consumer safety concerns over ingredients added to compensate for fat removal highlight the need for educating the general public about fat replacers and their proper application (11). Based on the GRAS status of the majority of these substances, the FDA provides assurances that the current fat replacers are safe to use in foods (12).

Fat replacers could potentially be consumed in large quantities, given their widespread use in reduced-fat products. Few, if any, health concerns have been raised regarding the adverse impact of carbohydrate- or protein-based fat replacers. Fat-based substitutes derived from modifying length or numbers of fatty acids also seem to have no known safety issues. Polydextrose and olestra are two products with known concerns about excessive use. Polydextrose can have a laxative effect, which requires a labeling disclaimer when present at specified levels. Olestra may cause leaky and fatty stools and loss of fat-soluble vitamins

(13). However, as mentioned previously, the FDA removed the safety warning required for olestra-containing products in 2003 after review of the existing evidence. In general, there is limited evidence at the present time on the long-term adverse consequences associated with the consumption of these or any other reduced-fat foods by adults. Overall, the majority of fat replacers pose no health concerns for adults. However, further research is required to study the safe use of these products by children and adults and to evaluate fully their long-term health effects.

1.6. Routes for Fat Replacement. Fat replacers are becoming an important part of the American diet. Many Americans are looking for ways to enjoy their favorite foods while maintaining a low calorie diet. Food scientists are developing new food additives that will mimic the function of fats in foods while keeping the calorie contents of foods low. Dietary fat substitutes are food constituents able to replace, completely or partially, dietary fat in such a manner that certain physical and organoleptic properties of the food product involved are left unaltered as far as possible (6). Today, a broad range of fat replacers can be found. Each has its own strengths, weaknesses, and restrictions.

There are three principal approaches that can be used to replace fat in the diet. The first involves use of carbohydrate- and/or protein-based fat mimetics (3,6), and this approach is most common. The second includes replacement of fat by synthetic fat-like ingredients, which are generally referred to as fat substitutes. The third involves the use of emulsification techniques that can be used in low fat spreads. The fat content of an oil-in-water food emulsion can be reduced by replacing some of the fat inside the oil droplets with small water droplets. This type of system is referred to as a water-in-oil-in-water (w/o/w) multiple emulsion. Since it has proven difficult to make w/o/w emulsions that are stable for extended periods, this approach is not widely used. Since fat replacers may contain calories, food manufacturers using these products should ensure that the final product is not only reduced in fat, but also reduced in calories.

Fat replacers are called by many synonyms with various tones in their usage. The terms used to describe ingredients that can replace fat are as follows: fat replacers, fat substitutes, fat mimetics, fat extenders, fat analogues, and fat barriers. Their definitions are given in Table 4. The fat replacers developed to date generally fall into one of three categories: carbohydrate, protein, and fat based (Table 5).

2. Carbohydrate-Based Fat Replacers

Carbohydrate-based fat replacers are food ingredients based on starch, cellulose, dextrins, maltodextrins, polydextrose, gums, or fiber, generally polymers that have been modified physically, chemically, or enzymatically to provide fat-like properties in the water phase (3). They help replace the mouthfeel of fats, provide lubrication, and slipperiness. They also add bulk, viscosity, structure, and texture to food products. Carbohydrate-based fat replacers can provide up to 4 kcal/g if the carbohydrate is fully digestible. However, when mixed with water, they provide only $\sim$1 kcal/g, compared with 9 kcal/g for fat. Thus, carbohydrate-based fat mimetics provide the mouthfeel, but not the other properties of fat, and they provide less energy than fat. There are many carbohydrate-based fat replacers available for use in foods, but cannot replace fats in frying. They can be successfully used for reducing the fat in a low moisture food system, but not for completely replacing it. The FDA has affirmed many of the carbohydrate-based fat replacers as GRAS substances (14). Carbohydrate-based fat replacers are used in a variety of foods including baked goods, dairy products, spreads, frozen desserts, salad dressings, sauces, chewing gums, confectionery, and processed meats. Some examples of various carbohydrate-based fat replacers used in foods and their applications are summarized in Table 6.

2.1. Cellulose. Cellulose is a polymer of D-glucose units liked by beta-1,4-glycosidic linkages. It has several properties that make it an ideal fat replacer: It functions like a fat in water and forms a gel in the presence of water; it provides the mouthfeel of fat; it has the glossy, opaque appearance of fat; and it has no caloric value. Different cellulose-based fat replacers can be obtained by the type of processing used (a) mechanical grinding (ie, powdered cellulose); (b) chemical depolymerization and wet mechanical disintegration (ie, microcrystalline cellulose); and (c) chemical derivatization (ie, methyl cellulose, sodium carboxymethylcellulose, and hydroxypropyl methylcellulose). Cellulose-based fat replacers are used to stabilize foams and emulsions, increase viscosity, modify texture, and add dietary fiber. They can replace some or all of the fat in foods and is widely used in dairy products, sauces, frozen desserts, and salad dressings. Finely ground microparticles of cellulose disperse throughout the food to provide a noncaloric network with the smoothness and flow properties similar to fat. Powdered cellulose, microcrystalline cellulose, and cellulose gels present a wide variety of possibilities in terms of water-binding, film-forming, viscosity, pulpiness, and gelling (6).

Avicel was the first carbohydrate-based fat replacer, a microcrystalline cellulose gel that was developed in the mid-1960s as a stabilizer, but in the 1990s began to be used as a fat replacer. Microcrystalline cellulose is a purified, naturally occurring fraction of cellulose. It is composed of anhydroglucose units linked together through a beta(1–4) glycosidic bond. It is a hydrophilic, water insoluble, linear, high molecular weight polymer consisting of ordered, crystalline areas. Microcrystalline cellulose forms a colloid with a rheology similar to that of fat, setting up an insoluble network that immobilizes water and imparts a creamy mouthfeel. Commercial forms of microcrystalline cellulose are sold as free flowing powders. Powdered grades of microcrystalline cellulose are insoluble and chemically inert.

2.2. Insoluble Fiber. Insoluble fiber is made up from the structural material of the cell walls of plants. It consists of cellulose, hemicellulose, and lignin. The principal sources of insoluble fiber are wheat bran, whole grain products, and vegetables. Insoluble fiber-based products cannot be digested by the human digestive tract and thus provide virtually no calories. Insoluble fiber is an important tool for fat and calorie reduction. Modified fibers can be used in processed meats, pasteurized cheeses, baked products, frozen desserts, salad dressings, nondairy creamers, canned soups, and other food products. Some examples of modified fibers are given below.

1. Oatrim: Oatrim is a new healthy, fiber-based fat replacer used in no fat–low fat formulas. It was developed and patented by the USDA and contains a mixture of beta-glucans and amylopectins (15). Oatrim also contains minute quantities of lipids, proteins, and minerals. Beta-glucan (soluble dietary fiber) also helps lower serum cholesterol, blood glucose and insulin response, making attractive health claims possible. Oatrim is produced via partial hydrolysis of oat flour or bran by alpha-amylase. It is a soluble and tasteless powder that can be incorporated into food as a dry powder or as a gel. Oatrim succeeds because of its ability to form, through heating and cooling, a shortening-like gel, which has about nine times less energy value than fat. Oatrim can withstand pasteurization processing conditions and is heat stable for baking, but is not suitable for frying (3).This product is licensed for commercialization to several companies, including ConAgra (Omaha, Nebr.), Quaker (Chicago, Ill.), and Rhone-Poulenc (Cranbury, N.J.). Oatrim can be used to replace fat in various food products, including dairy products, confectionery, baked goods, cereals, frozen desserts, and meat products.
2. Z-Trim: Z-Trim, also developed by the USDA, is a fat replacer made from low cost agricultural by-products, eg, hulls of oats, rice, corn, soybean and peas, or bran from corn and wheat (16), by completely disintegrating their cellular structure to form greatly reduced particle size powders that form gels with a smooth texture and increased water-holding capacity. It can also replace the moistness and density that fat contributes to foods. All of these properties make it possible for the reduced fat foods to taste like the traditional foods that are rich in fat. Z-Trim is a tasteless and insoluble fiber, which passes unmetabolized through the human body, and hence it contributes no calories (16). Z-Trim applications include baked goods, dairy products, pasta, snack foods, reduced-calorie cheeses, hamburgers, and nutritional drinks (16). Again, as expected, this product is not suitable for deep fat frying.
3. Nu-TrimX: Nu-TrimX is a new generation of hydrocolloid product consisting of solubilized beta-glucan with greatly reduced insoluble cellulose. This provides greater ability to produce functional foods with more beta-glucan and less fat. It is produced by a natural extraction process that removes coarse fiber components from milled oat, or barley materials, eg, oat bran, oat flour, defatted oat fines, or barley flour. Incorporation of Nu-TrimX into food products is easily achieved with standard processing equipment. A general rule-of-thumb is that 10 g of Nu-TrimX and 90 g of water will replace 100 g of fat; a caloric value of 40 compared to 900 calories for the fat. This product is expected to transform treats like cookies, cakes, and creamy desserts into low calorie, high fiber foods.

2.3. Gums. Gums, also referred to as hydrocolloids, are high-molecular weight carbohydrates that have traditionally been used as stabilizers, thickeners, and viscosity enhancers. There are numerous plant and marine gums that find applications as fat replacers. Plant- and marine-based products, eg, gum Arabic, guar gum, xanthan gum, locust bean gum, carrageenan, alginates, and pectin have virtually no calories. These have a wide variance in functional characteristics, including heat, shear and pH stability, type of texture, and thermoreversibility. Low concentrations (0.1–0.5%) of gums form gels, which can increase viscosity, provide texture and fat-like mouthfeel, and promote a creamy texture within the food. Gums can be used in reduced calorie and fat-free salad dressings, soups and sauces, desserts and ice cream, dairy products, and baked goods. They can also be used to reduce the fat content in formulated foods, eg, processed meats and desserts.

Gum arabic is produced from the acacia tree grown primarily in semiarid regions of the Sudan and Senegal. However, the main source of commercial gum arabic is *Acacia Senegal*. Gum arabic is a complex mixture of saccharides and glycoproteins, which gives it one of its most useful properties. It is perfectly edible; produced in Nature, gum Arabic is 95% soluble fiber calculated on a dry basis. Its caloric value is less than half that of starches and maltodextrins. In food products, gum Arabic is used as a functional ingredient. It is water- soluble and forms colorless, tasteless solutions. Food applications of gum arabic have been developed from its unequaled combination of properties. Emulsification, acid stability, low viscosity at high concentration, adhesive and binding properties, and good mouthfeel characteristics have been used in a variety of food applications.

Guar gum is obtained from the endosperm of the guar plant. The guar plant is grown commercially in India and Pakistan and some is cultivated in the southwestern United States. Guar gum is soluble in cold water and produces highly viscous, pseudoplastic solutions. Locust bean gum, also known as carobgalactomann, is obtained from the endosperm portion of the seeds of a tree widely grown in the Mediterranean region. Both guar and locust bean gum are neutral polysaccharides composed of a linear chain of alpha-1,4-linked beta-D-mannose to which single alpha-D-galactose units are attached via alpha-1,6 linkages. Guar and locust bean gums have a synergistic effect with xanthan gums. Guar gum and locust bean gum have numerous food applications, including frozen desserts, ice cream, baked goods, low fat cheese products, sauces, and dressings.

Gum tragacanth (*Astragalus gummifer*) is derived from the large tap root and branches of a small perennial shrub found in the Middle East, especially Iran. Gum tragacanth, is a related exudate gum consisting of a mixture of polysaccharides including an arabinogalactan containing α-L-arabinofuranose and 1-4-linked β-D-galalactopyranose and an acidic complex poly-1-4-linked α-D-galalacturonate. It is used as an acid-resistant thickener and emulsifier in sauces, salad dressings, and confectionery lozenges.

Xanthan gum is produced by fermentation of bacteria *Xanthomonas campestris*. It is readily soluble in cold or hot water and exhibits a highly viscous, pseudoplastic rheology. Xanthan gum is stable over a wide range of pH and temperatures. It functions as a highly effective stabilizer in low fat foods, eg, dressings, sauces, and mayonnaises.

Pectin is extracted commercially from citrus peel and has been extracted from apple pomace. It consists of partial methyl esters of polygalacturonic acid. Commercial pectins are divided into two groups based on the degree of methyl esterification. The degree of methyl esterification is defined as the percentage of galacturonic acid units that are methyl esterified. Pectins with a degree of methyl esterification <50% are designated as low methoxyl pectin, whereas pectins with a degree of methyl esterification >50% are designated as high methoxyl pectins. Low methoxyl pectins require a certain amount of calcium to form gels with desirable properties, while high methoxyl pectins require sugar and acid. Gels formed by pectin can be used to replace fat in various food products including baked goods, mayonnaise, spreads, processed cheese, soups, sauces, and desserts. In 1991, pectin was introduced to the market by Hercules Inc. (Wilmington, Del.) under the brand name Slendid as a fat replacement ingredient. Slendid is almost calorie-free with a neutral taste and is stable to shear, heat, and salt. The use of Slendid can reduce the fat content in mayonnaise from 80 to 3%.

2.4. Dextrins. Dextrins are produced from the starches extracted from tapioca, corn, potato, and rice. They are well known for their ability to mimic several fat sensations, including mouthcoating, the melting sensation, and the richness of fat. They are traditional ingredients modified to provide enhanced functionality in reduced-fat systems. The degree of digestible carbohydrates determines their ability to lower the overall caloric content, as well as fat content. Dextrins can form heat-stable gels, which makes them acceptable for use in some cooked foods. They are commonly used in salad dressings, puddings, spreads, frozen desserts, and dairy foods. They provide 4 kcal/g of food. A typical example is N-oil, marketed by National Starch and Chemical Corp. (Bridgewater, N.J.), which can partially or totally replace fat or oil in foods, giving the illusion of a high fat content.

2.5. Maltodextrins. Maltodextrins are produced by the partial hydrolysis of starch either by acid treatment or by enzymes. Hydrolysis of starch in maltodextrins produces up to 20 dextrose units of varying polymer lengths, referred to as the dextrose equivalence. Maltodextrins are polysaccharides consisting of glucose joined at alpha 1–4 bonds with a dextrose equivalent of <20. They are produced by partial hydrolysis of starch either by acid treatment or by enzymes. The dextrose equivalent is an indication of the number of reducing groups present after breakdown of the starch polymer by hydrolysis. For example, a dextrose equivalent of 100 indicates complete hydrolysis to 100% glucose. Maltodextrins are prepared from potato, corn, wheat, or tapioca starches and can be used in various food applications. They are GRAS ingredients and can be used as a fat replacer, texture modifier, or bulking agent in dairy products, salad dressings, spreads, sauces, baked goods, frozen meat, and frozen desserts. Their caloric contribution is only 4 kcal/g (6). Some examples of commercial products recommended for fat replacers are described below.

1. Maltrin: Maltrin, manufactured by Grain Processing Corp. (Muscatine, Iowa), is a type of maltodextrin derived from natural corn starch. Corn starch is extracted from the kernel through a process of wet milling. The starch is cooked, and then treated with an acid and/or enzyme to break the starch into smaller polymers. They are generally sold as dried powders and are considered GRAS food ingredients. Maltrins do not contain significant quantities of protein, fat, or fiber. Maltrins are cold-water soluble and possess low or no sweetness. They are easily digestible and provide 4.0 kcal/g. Corn-based maltodextrins are safe for patients with celiac

disease since they do not contain proteins from wheat, barley, oats, or rye. Maltrins are most often categorized by dextrose equivalence. Matrins are defined by the FDA as products having a dextrose equivalent of <20. They are excellent solid builders for standard and low fat products. Matrins are recommended for numerous food products, including baked goods, confections, frostings and glazes, processed meats, snacks and cereals, salad dressings, and low fat spreads.

2. Paselli SA2: Paselli SA2, manufactured by Avebe America Inc. (Princeton, N.J.), is a potato starch-based maltodextrin with a dextrose equivalent of <3.0. It has unique properties based on its amylose/amylopectin ratio peculiar to potato starch. It is available as a white powder. The pH of the product is in between 5.5 and 7.0 in aqueous solution. This product contains only 0.1% protein and 0.06% fat that helps stabilize dried food mixes compounded with it. It provides 4 kcal/g. Gels made from this product provide a smooth, bland texture and a fat-like mouthfeel. Paselli SA2 has had commercial success as a fat replacer in a variety of food products. It can replace a large portion of fat in baked goods, mayonnaise-type products, cheese, sour cream, salad dressings, and low fat ice creams.
3. Instant N-oil: Instant N-oil, manufactured by National Starch & Chemical Co. (Bridgewater, N.J.), is a maltodextrin made from tapioca starch. Tapioca starch is produced commercially by wet milling the tuberous roots of tapioca species. Tapioca starch has a more bland flavor than cereal- or potato-based starches. The caloric value of this product is 4 kcal/g. Applications of instant N-oil include salad dressings, puddings, spreads, dairy-type products, and frozen desserts.
4. TrimChoice: TrimChoice is made from oat flour. It is developed by A.E. Staley Manufacturing Co. (Dacatur, Ill.). In addition to maltodextrins, it also contains beta-glucan. Beta-glucan is the major soluble fiber found in oats. The combination of maltodextrin and beta-glucan is said to provide a fat-like mouthfeel. The caloric value of TrimChoice is 1–4 kcal/g. It can be used in baked goods, fillings and frostings, frozen desserts, dairy beverages, cheese, salad dressings, processed meats, and confections.

2.6. Modified Food Starch. Starches and starch derivatives provide many functions in fat replacement systems. When moist heat is applied to starch, the granules gelatinize, forming a mixture of thick, soft, and creamy consistency. Starches are commonly derived from wheat, corn, rice, potato, and tapioca. However, most starches are further modified when used in fat-replacement systems. Starches can be modified by acid or enzymatic hydrolysis, to produce smaller polymers, or by cross-linking or substitution. Modified food starch is a fat replacement ingredient, which can mimic the mouthfeel that fat provides in foods. It has a caloric content of 1–4 kcal/g. Modified food starch is produced as a fine powder. When liquid is added, a slurry is made and sheared to form a smooth, creamlike substance that has similar properties to shortening. Modified food starch can also be used as a bulking agent and texture modifier. It is used in combination with emulsifiers, gums, proteins, and other food starches to make dairy products, salad dressings, sauces, baked goods, and fillings (6).

Another fiber-containing ingredient that can take the place of fat in foods is resistant starch. Because of its reduced caloric content, it functions mainly as a bulking agent, although it can have other beneficial effects in the finished product. Resistant starches are starches and products of starch degradation, which resist enzymatic digestion and act like dietary fiber. Resistant starch is present in many foods. It is naturally found in coarsely ground or chewed cereals, grains, or legumes. It also can be found in bananas, high amylose starch, and raw potato as naturally resistant or ungelatinized granules. A third type of resistant starch is generated via retrogradation of starch during food processing. This variety can occur naturally in products such as bread, cereals, and cooked potatoes. Resistant starches, waxy, highly cross-linked, and modified starches are effective in high moisture systems, eg, salad dressings, low fat spreads, meat emulsions, icings and fillings, and bakery products, eg, layer cakes. They can neither be recommended for use in low moisture systems, eg, cookies and crackers, nor can they replace frying oils. However, fat absorption can be reduced by coating the product with specialty starches.

Stellar is a modified starch fat replacer introduced by A.E. Staley Company in 1991. It is offered in several physical forms, eg, agglomerates and hollow spheres, and is prepared by acid modification. It is used in most fats and oils replacement applications including dairy products, baked goods, salad dressings, and meats.

2.7. Polydextrose. Polydextrose, a condensation polymer of glucose, is a reduced-calorie bulking agent that can replace some of the fat in foods while maintaining a pleasant texture and mouthfeel. It can also be used as a texturizer, thickener, stabilizer, and cryoprotectant. Polydextrose is a complex carbohydrate made from glucose, sorbitol, and citric acid. It is prepared by a vacuum melt process involving polycondensation of glucose in the presence of small amounts of sorbitol and citric acid in the ratio of 89:10:1, respectively. Sorbitol functions as a plasticizer and citric acid as a catalyst in the polymerization. Polydextrose is an odorless, white to light cream amorphous powder, and has virtually no sweetness. Calorie reduction occurs because polydextrose has an energy value of $\sim$1 kcal/g compared with fat at 9 kcal/g. Polydextrose was approved by the FDA in 1981 for use in products in several food categories. Polydextrose does not have much flavor of its own. It can partially replace both fat and sugar in some low-calorie versions of high calorie foods. The use of polydextrose in some of the products in these categories results in substantial reductions in fat. This product is currently used in baked goods, chewing gums, gelatins, frostings, puddings, and frozen dairy desserts. Polydextrose, improved polydextrose (Litesse) and super improved Polydextrose (Litesse II) are currently marketed by Danisco in the U.S. Litesse has demonstrated its versalitity as a partial fat replacer in many foods including baked goods, beverages, confectionery, spreads, and frozen dairy products.

3. Protein- Based Fat Replacers

Protein-based fat replacers are derived from many different types of protein, but soy, milk, egg, whey protein, gelatin, or wheat gluten are common. Proteins can act as simple fat replacers, eg, gelatin, or be modified to mimic the properties of fat, as is the case with Simplesse, a microparticulated whey protein normally available in gel or in powder form. Controlled denaturation using heat or enzymes can change the structure and behavior of the protein. Such changes can provide characteristics that make them suitable as fat replacers. They can also help stabilize emulsions. Only small amounts are needed, which drops the caloric content of the final product. Proteins can be microparticulated to form microscopic coagulated round deformable particles that mimic the texture and mouthfeel of natural fats and oils. Proteins are important whipping agents, emulsion stabilizers and dough strengtheners (6). Protein-based fat replacers have been used in margarines, butter, cheese, dairy products, sour cream, coffee creamers, salad dressings, mayonnaise-containing products, soups, sauces, baked goods, and frozen desserts. These substances generally give a better mouthfeel than do carbohydrate-based counterparts. Often, a combination of these fat replacers can have tremendous potential in the development of fat-modified foods with greater acceptability while lowering the total energy and fat intake. Similar to carbohydrate-based substances, protein-based fat replacers cannot be used for frying (6). Fat replacers from protein do provide 4 kcal/g, but they may provide only 1–4 kcal/g either because they hold water or are used in lesser amounts than fat. Typical examples of various protein-based fat replacers used in foods and their applications are summarized in Table 7.

3.1. Microparticulated Protein. The use of microparticulated proteins has made it possible to replace fat in foods while maintaining traditional sensory attributes. Simplesse is a patented natural multifunctional dairy ingredient made from whey protein concentrate that undergoes a unique proprietary microparticulation process. It is a versatile product that provides significant functional benefits in a wide range of full and low fat food applications. Microparticulation is the key for creating multifunctional properties. Through this special process of heating and blending, egg protein, and milk protein are combined and formed into minute particles that are 1–1.5 μm in size (6). These particles are spherical and smooth and prevent the formation of large protein agglomerates. As a result of their consistently small size and uniform shape, Simplesse microparticles in suspension behave like a creamy fluid and provide a unique set of functionalities. Its texture is due to its ability to form a colloid, similar to the way fat is dispersed in homogenized milk. It differs from other whey protein concentrate mainly by virtue of rheology; it is produced by a mechanical, rather than a chemical process. Simplesse was introduced in 1988 by the NutraSweet Corporation, a division of Monsanto Corporation (St. Louis, Mo.), and is currently marketed by CP Kelco (Wilmington, Del.). Simplesse is promoted as a competitor for premium ice creams. In petitioning FDA for approval of simplesse, NutraSweet compared the fat, cholesterol, and caloric content of a super-premium vanilla ice cream containing 16% butterfat with a frozen dessert using simplesse. A 4-oz serving of the ice cream provided 19 g of fat, 97 mg of cholesterol, and 274 calories, whereas the same size serving of frozen dessert containing Simplesse had <1-g fat, 14-mg cholesterol, and 120 cals (17). Regular ice cream, with ~10% fat, contains ~7 g of fat, 30 mg of cholesterol, and 135 cal/4-oz serving. In Februray 1990, Simplesse became the first fat replacer approved by the FDA for use as a thickener or texturizer in frozen desserts. It can replace up to one-third of fat in frozen foods. In

1994, FDA approved the use of Simplesse in yogurt, cheese spreads, cream cheese, and sour cream. Because it is made from proteins, Simplesse cannot be used in high temperature food applications eg, frying or baking. It can, however, be put on hot foods, eg, baked potatoes. It can also be used to replace some of the fat in margarine, butter, yogurt, sour cream, salad dressings, mayonnaise, and margarine. On a dry basis, Simplesse provides 4 kcal/g, whereas a hydrated gel provides 1.3 kcal/g. Four ounces of traditional ice cream, eg, contains 283 cal while the same amount of Simplesse ice cream would contain 130 cals. Simplesse provides fat-like creaminess. However, similar to other proteins, it tends to mask flavor (6). When it is heated, protein gel and the texture effects are lost. Products containing simplesse may not be suitable for people on protein restricted diets. People who are allergic to milk proteins or egg proteins may have an allergic reaction to this product.

3.2. Modified Protein/Denatured Protein. Dairy proteins, eg, whey protein concentrates, total milk proteins, and caseinates, have long been the ingredients of choice in stabilization and emulsification systems because of their unique functional characteristics. In particular, caseinates and hydrolyzed caseinates are integral elements in many dairy products, imitation dairy products, and nutritional formulations.

Dairy-Lo is manufactured from high quality modified whey protein concentrate using controlled denaturation. This product contributes only 4 kcal/g. Modified whey protein helps improve texture, flavor, and stability of low fat foods. It is typically used in sour cream, frozen dairy desserts, cheese, baked goods, yogurts, dips, and sauces. Its ability to prevent shrinkage and iciness in frozen foods makes it especially desirable as fat replacement ingredient in those products. Whey protein concentrates are better suited for thinner products, eg, salad dressings. Because of their gelling characteristics, whey protein concentrates impart viscosity in reduced-fat meat products where both texture and moisture are important. In comminuted meats, whey protein concentrates can be useful in combination with caseinates as well as gums. Dairy-Lo was developed by Ault Foods in Canada and is marketed in the United States by Pfizer Inc. (New York, N.Y.). It can be used at 2–5% in frozen dairy products. For labeling purposes, it is classified as a whey protein concentrate. Caseinates and total milk proteins are the best choices when a viscous mouthfeel is the goal. Their unique structure gives them the ability to hold water that, in turn, imparts lubricity to the mixture. Either one also functions well as an emulsifier in products that have low levels of fat, eg, a reduced-fat coffee creamer, as opposed to a completely fat-free product.

3.3. Gelatin. Gelatin is a mixture of water-soluble proteins made by extracting the collagen from the bones, skin, and ligaments of animals. Although gelatin is 98–99% protein by dry weight, it has less nutritional value than many other protein sources. Gelatin is unusually high in the nonessential amino acids glycine and proline (ie, those produced by the human body), while lacking certain essential amino acids (ie, those not produced by the human body). It contains no tryptophan and is deficient in isoleucine, threonine, and methionine. Gelatin as a fat replacer can provide structure, viscosity, and smooth mouthfeel. It is useful as a viscosity modifier and imparts a creamy texture. It is commonly used in making jelly-like confections. Gelatin is fat-free, yet its smooth texture is similar to that of fat. Consequently, gelatin is very useful as an additive to food that marketed as low fat, or fat-free.

3.4. Vegetable Protein. Although vegetable proteins are not considered as ingredients for low fat food formulations, they play an important role in the production of low fat meat products. They have water binding capacity and can form gel structures that improve the texture of processed meats. Soy-based vegetable proteins are the most common. Soy proteins can impart structure, viscosity, creaminess, and opacity, but somewhat powdery mouthfeel in some products. Soy proteins are not meant to replace the fat in foods, but to reduce the fat content of foods, especially meat products. They are also used in some beverages and in weight-loss products.

4. Lipid-Based Fat Replacers

Lipid-based fat replacers are either TAGs that have been modified or are synthesized to have structures, physical and chemical properties similar to TAGs, and can replace an equal amount of fat. The majority of fat-based replacers are emulsifiers, emulsions with little fat, or lipid analogues. Emulsifiers stretch the functionality of low fat levels and replace the functionality of fat when used in combination with other ingredients. Manipulating the composition of the fatty acids esterified to the glycerol reduces the calories while maintaining the chemical structure of the triacylglycerol. Replacement of the fatty acids of triacylglycerols with alternative acids is achieved through hydrolysis and random transesterification of medium- and long-chain triacylglycerols to create these low calorie fats. Generally, these fats are neither hydrolyzed nor absorbed by the body in the same manner as normal fat and, thus, contribute substantially fewer calories. Physically and chemically, they resemble triacylglycerols, are stable to cooking or frying temperatures, and theoretically replace fat on a 1:1 gram-for-gram basis. As with other fat reduction ingredients, lipid-based ingredients are highly versatile and can be used in a wide variety of foods, including baked goods, confections, chocolate, cheese, margarines, and spreads. In addition, some of the ingredients can replace fats for frying. Selected examples of various lipid-based fat replacers used in foods and their applications are reported in Table 8. The most prominent examples of lipid-based fat replacers are Caprenin, Salatrim, Bohenin, and medium-chain triacylglycerols (MCTs).

4.1. Caprenin. Caprenin, a semisynthetic TAG, is the ester of glycerol with three natural fatty acids: capric ($C_{10:0}$), caprylic ($C_{8:0}$), and behenic ($C_{22:0}$) acids (5). It consists mainly of TAGs with 38, 40, and 42 carbon atoms. Caprenin contains equimole proportions of caprylic, capric, and behenic acids corresponding to 22.6, 26.7, and 50.7% by weight, respectively. All of these fatty acids are derived from natural food sources. The two shorter chain fatty acids, caprylic, and capric acids, are derived from palm kernel and coconut oils. The very long-chain behenic acid is produced from rapeseed oil (18) and is also found in peanuts and marine oils. Caprenin is digested, absorbed, and metabolized by the same routes as other triacylglycerols. Behenic acid is only partially absorbed ($<20\%$) by the body, and the medium-chain fatty acids have lower caloric densities than long-chain fatty acids. As a result, the available energy in caprenin is only ~5 kcal/g (19), about one-half of that for most fats. This product was commercialized by Procter & Gamble Company (Cincinnati, Ohio) as a cocoa butter replacer. During the synthesis of caprenin, glycerol is thermally esterified with behenic acid derived from hydrogenated rapeseed oil. The glycerol monobehenate is subsequently esterified with capric and caprylic acids or their anhydrides from coconut and palm kernel oils. The final product is purified by molecular distillation and a combination of one or more of thermal winterization, bleaching, and steam deodorization (20). Its melting behavior is similar to that of cocoa butter. Hence, it is intended to replace some of the cocoa butter in confectionery coatings. It is digested, absorbed, and metabolized by the same pathway as other TAGs (21). The Procter & Gamble Company filed a GRAS affirmation petition for use of caprenin as a confectionery fat in soft candy bars, and in confectionery coatings. However, caprenin cannot be used for frying foods. Absorption, digestion, and metabolism studies have been conducted on caprenin (22,23). Several clinical studies suggested that despite its lower energy content, caprenin slightly increased lipoprotein levels. In one study with 30 adult males fed caprenin at 34 g/day for 8 weeks, total serum cholesterol, low-density lipoprotein (LDL) and high-density lipoproteins (HDL) were increased by 8, 20, and 13%, respectively (24).

4.2. Salatrim (Benefat). Salatrim, which is an acronym for short- and long-chain acyl TAG molecule, is a family of structured TAGs based on the use of at least one short-chain fatty acid (acetic and/or propionic and/or butyric acids) and at least one long-chain fatty acid (principally stearic acid) (25). As with naturally occurring TAGs, the physical and functional properties of salatrim are dictated by the type of fatty acids used, and their ratio to one another, as well as their position in the TAG molecule. Due to the lower energy density of short-chain fatty acids and the reduced absorption of stearic acid, the available calories derived from Salatrim averages 5 kcal/g or 55% of the caloric value of conventional fats. The constituent fatty acids, acetic, propionic, and butyric acids contribute 3.5, 4.9, and 5.9 kcal/g, respectively, based on heats of combustion. In addition, the glycerol portion of Salatrim has a heat of combustion of 4.3 kcal/g.

Salatrim can be produced via interesterification of highly hydrogenated canola or soybean oils with TAGs of acetic, propionic, or butyric acid (26). The interesterification reaction provides a complex mixture of TAGs. One portion of the mixture consists of molecules with one long-chain fatty acid residue and two short-chain residues. Also present are molecules with two long-chain fatty acids and one short-chain fatty acid. Salatrim is separated from raw material vegetable oils and short-chain TAGs during the manufacturing process. Salatrim contains 0 g of trans fat. Safety studies have shown no effect on serum cholesterol, no effect on absorption of fat-soluble vitamins, and have verified the safety of the molecule. Salatrim was developed and commercialized by Cultor Food Science Inc. (Ardsley, N.Y.) under the brand name, Benefat (18). It has the taste, texture, and functional properties of conventional fats and oils. It can be produced to have different melting profiles by adjusting the amounts of SCFAs and LCFAs used in their chemical synthesis. Salatrim, like caprenin, cannot be used for frying (6). Because of the SCFAs, these fats may be prone to hydrolysis upon exposure to the high heat encountered during frying conditions, which may cause the development of off-flavors. It has the ability to function effectively in low moisture foods and to overcome most of the problems caused by other fat-based replacers (27), eg, polyol esters. One product in the market that contains Benefat is the reduced fat baking chips introduced in 1995 by Hershey Food Corporation (Hershey, Pa.). The Hershey's Reduced Fat Baking Chips claim "50% less fat" on the front panel, but the total fat on the Nutrition Facts panel reflects the total amount of fat in the product including Salatrim. A footnote states that Salatrim is partially digestible, explaining the front label claim. In the United States, products containing Salatrim may bear a reduced-calorie claim under the provisions of the NLEA Act, which permits the use of self-determined digestibility coefficients for energy content of ingredients. The digestibility coefficient for Salatrim is 5/9.

Salatrims are designated by their main fatty acid components. For example, Salatrim 23SO contains primarily acetic (C_2) and propionic (C_3) acids interesterified with hydrogenated soybean oil (SO), whereas salatrim 4CA contains butyric acid (C_4) interesterified with hydrogenated canola oil (CA). A GRAS affirmation petition for Salatrim was filed in December 1993 and was accepted for filing by the FDA in June 1994. Salatrim may be sold in the United States, Japan, Korea, and Taiwan, where it is considered food, and in Australia, New Zealand, and Mexico, where it meets existing regulations on fats and oils. The first product, trademarked Benefat No. 1, was developed to replace cocoa butter in confectionery applications. Salatrim can be used to replace fully utilized fat in a wide array of products such as confectionery and baked goods, caramel and toffee, peanut spreads, savory dressings, dips and sauces, and dairy products, eg, frozen dairy dessert, sour cream, and cheese (28). Benefat B shortening is the latest member of the Benefat family of Salatrim. Cultor Food Science (Ardsley, N.Y.), launched Benefat B shortening for baking applications. Benefat B is a 1:1 replacement for fat in bakery applications, eg, cookies, brownies, cakes, pie crust, cream fillings, and muffins.

4.3. Bohenin. Bohenin, glycerol 1,3-dibehenate 2-oleate (BOB), is a TAG-containing behenic acid at the *sn*-1 and *sn*-3 positions and oleic acid at the *sn*-2 position (6). Bohenin is manufactured by Fuji Oil Co. Ltd. (Osaka, Japan), which had filed a FDA GRAS affirmation petition in 1994. It can be produced by interesterification of triolein and behenic acid (22:0) or an ester in the presence of a *sn*-1,3-stereospecific lipase. Bohenin is hydrolyzed to behenic acid and 2-oleoyl glycerol prior to absorption. Behenic acid is a saturated fatty acid that occurs naturally in most edible fats, including most seed oils, animal milk fat, and marine oils. Oleoyl-monoacylgycerol is a common product of human digestion of edible fats and oils typically used in western diets. The manufacturing process is similar to that used to produce a similar TAG, cocoa butter substitute, which FDA has affirmed as GRAS (6). This product has a high melting point ($\sim 52^{\circ}$C) and it is able to form β_2-crystalline polymorphic structures. These two properties assist with its functionality as an antibloom agent, and facilitate the chocolate tempering process. The specifications for bohenin are consistent with the Food Chemical Codex specifications for edible fats and oils (29).

Bohenin can inhibit fat bloom when added to chocolate. Hence, it is intended for use as a tempering aid and as an antibloom agent in the manufacture of chocolate and chocolate coatings. It can be used at a level not exceeding

5% by weight of the total fat in chocolate and chocolate coatings. In 2000, FDA stated that it has no objections to the Fuji Oil claim that bohenin is GRAS under the intended conditions of use (29). In its GARS submission to the FDA, Fuji Oil discussed the relevant published scientific articles relating to (a) the physical characteristics and functionality of bohenin; (b) sampling, detection, and analysis of commercial fats and oils; (c) detection and analysis of bohenin in food; (d) consumption of behenic acid from currently consumed fats and oils; (e) metabolism of TAGs containing behenic acid; (f) hydrolysis of bohenin to behenic acid and 2-oleoyl glycerol prior to absorption; (g) safety of other TAGs containing behenic acid; and (h) safety of behenic acid. After reviewing Fuji Oil's GRAS submission, the agency has listed the Notice as No. GRN 000050. The FDA has not, however, made its own determination regarding the GRAS status of bohenin. The caloric value of bohenin has not been published anywhere. However, given its fatty acid profile, and using the 0.29 absorption coefficient determined for behenic acid in caprenin, the caloric content has been calculated to be ~5 kcal/g (20).

4.4. Medium-Chain Triacylglycerols. Medium-chain triacylglycerols, commonly abbreviated MCTs, are medium-chain fatty acid esters of glycerol. The MCT is a colorless or slightly yellowish, oily liquid, practically insoluble in water, and is miscible with alcohol, methylene chloride, light petroleum, and fatty oils. Their chemical composition is of a shorter length than the long-chain fatty acids present in most other fats and oils, which accounts for their name. They are also different from other fats in that they have a slightly lower caloric content and are more rapidly absorbed and burned as energy, resembling carbohydrate more than fat. Medium-chain fatty acids are fatty acids containing from 6 to 12 carbon atoms. These fatty acids are constituents of coconut and palm kernel oils and are also found in camphor tree drupes. Coconut and palm kernel oils are also called lauric oils because of their high content of the 12 carbon fatty acid, lauric or dodecanoic acid. The oil extracted from coconuts contains ~9.6–18.0% of $C_{8:0}$ and $C_{10:0}$ fatty acids, while the oil extracted from palm kernels contains ~5.0–11.2% of $C_{8:0}$ and $C_{10:0}$ fatty acids. These oils are hydrolyzed to medium chain fatty acids and glycerol. The glycerol is removed and the fatty acids are fractionated by distillation. The fractionated fatty acids are then re-esterified with glycerol to form MCTs. The MCTs used for nutritional and other commercial purposes are derived from lauric oils. In the process of producing MCTs, lauric oils are hydrolyzed to medium-chain fatty acids and glycerol. The glycerol is drawn off from the resultant mixture, and the medium-chain fatty acids are fractionally distilled. The medium-chain fatty acid fraction used commercially is mainly comprised of the eight carbon caprylic or octanoic acid and the 10 carbon capric or decanoic acid. There are much smaller amounts of the six carbon caproic or hexanoic acid and the 12 carbon lauric acid in the commercial products. The caprylic- and capric-rich mixture is finally re-esterified to glycerol to produce medium-chain triacylglycerols that are mainly glyceral esters of caproic (C_6) caprylic (C_8), capric (C_{10}), and lauric acid (C_{12}) in a ratio of ~2:55:42:1.

The physiology and biochemistry of MCTs are very different from those of long-chain triacylglycerols. Upon ingestion, MCTs are partially hydrolyzed to medium-chain fatty acids (MCFAs) by lingual lipase in the stomach, and then completely broken down by pancreatic lipase inside the intestinal lumen. The MCFAs are then absorbed via the portal vein to the liver rather than through the thoracic duct lymph system, the common route for the absorption of triacylglycerols containing long-chain fatty acids. A minor fraction of MCFAs by-pass the liver and are distributed to peripheral tissues via the general circulation. Since MCT, in contrast with long-chain fatty acids, does not require pancreatic enzymes or bile salts for digestion and absorption, medium-chain triacylglycerols is better handled in those with malabsorption syndromes than are the long-chain fatty acids. These syndromes include pancreatic disorders, hepatic disorders, gastrointestinal disorders, and disorders of the lymph system. The MCFAs are catabolized mainly in the liver hepatocytes to medium-chain fatty acyl coenzyme A (CoA) esters, or are used to synthesize longer chain fatty acids. Medium-chain fatty acyl CoAs (mainly of caprylic and capric acids) are transported into mitochondria, where they are metabolized, initially by medium-chain acyl CoA dehydrogenase, to acetoacetate and beta-hydroxybutyrate. Acetoacetate and beta-hydroxybutyrate may be further metabolized in the liver to CO_2, H_2O and energy, and may enter other metabolic pathways in the liver or be transported by the systemic circulation to other tissues, where they are metabolized to produce CO_2, H_2O, and energy. The oxidation of MCT produces 8.3 kcal of energy per gram ingested. The MCTs are therefore easier to metabolise, which could be advantageous to those who are critically ill and those with carnitine deficiencies. Medium-chain triacylglycerols are available in several medical food products, many for use in a hospital setting.

Due to its unique absorption and metabolism characteristics, MCT oil has been used therapeutically since the 1950s in the treatment of fat malabsorption, cystic fibrosis, epilepsy, weight control, and to increase exercise performance. The MCTs have also been used in an increasing number of food and nutrition applications, as they offer a number of advantages over long-chain triacylglycerols, which are metabolized differently and absorbed less quickly. These MCTs are also used primarily as emulsifiers in various human and veterinary pharmaceutical preparations and in cosmetics. They are also being used in an increasing number of food applications.

Neobee. Neobee, manufactured by Stepan Company (Maywood, N.J.), is derived by esterifying glycerol with mixtures of capric and caprylic acids, which are fractionated from coconut or palm kernel oils (6). It is processed to achieve high oxidative stability (500 AOM hours at 100°C) and low color, and then is further refined to remove residual fatty acids, resulting in a product with essentially no odor or flavor. It has fewer calories and one-eighth the metabolizing time of long-chain fats. It uses a unique metabolic pathway, traveling directly to the liver rather than through the lymphatic system and, thus, does not accumulate as fat in the body. Neobee provides 6.8 kcal/g versus 9.0 for conventional fats. Its low caloric value along with its tendency to increase satiety makes it well suited for use in reduced-fat food products. This class of specialty lipids includes different products. For example, Neobee 1053 and Neobee M-5 contain both capric and caprylic acids while Neobee 1095 is made up of only capric acid (30). Neobee 1095 is a solid product. Therefore, in certain applications, which require solid fats, this product may be desirable. Neobee 1814 is a MCT derivative produced via interesterification of MCT with butter oil (31). This product contains one-half of the long-chain saturated fatty acids found in conventional butter oil and is an ideal candidate to replace butter oil in numerous applications. Neobee 1814 may serve as a flavor carrier and acts as a textural component for low fat food products (30). Neobee MLT-B is a MCT that mimics the solid-fat index of partially hydrogenated vegetable oil. In June 1994, a GRAS affirmation petition for use of MCTs in food products was accepted for filing by the FDA.

Neobee is slightly polar in nature, so it can dissolve a variety of substances that are soluble in conventional fats and oils as well as substances that are known to be lipid soluble. Hydrocarbons, esters, ketones, alcohols, and acids are miscible with this product. Incorporating Neobee into flavor systems may enhance integrity of products because of its high oxidative stability and favorable organoleptic properties. The unique metabolic and functional properties of Neobee products, as a result of their chemical structure, make them versatile ingredients in numerous pharmaceutical and food applications. The low viscosity and ease of dispersability of this product make it suitable for use as moisture barriers, lubricants, and antistick agents in confections and baking applications.

Captrin. Captrin, manufactured by Stepan Company (Northfield, Ill.), is the proposed common name for a group of MCTs that use primarily linear saturated fatty acids, eg, capric and/or caprylic fatty acids (6). Captrin may be labeled as MCTs, capric/caprylic TAGs, glyceryl tri(caprylate/caprate), caprylin, caprocaprylin TAGs, or structured lipids. The ingredients are obtained by the hydrolysis of coconut or plam kernel oil followed by fractionation and separation of the desired fatty acids that are esterified with glycerol to form MCTs. The predominant fatty acids available from coconut and palm kernel oils include caproic, caprylic, capric, and lauric acids. Captrin contains a minimum of 45% TAGs, not >40% diacylglycerols (DAGs) and not >10% MAGs. The range of weight percent of fatty acids are as follows: caprylic, 1–99% and capric, 1–99%. Captrin has good oxidative stability, a slightly yellow color, free of suspened matter with a bland odor and flavor. The solubility of captrin is similar to that of conventional TAGs, eg, it is insoluble in water and soluble in organic solvents. Captrin may be hydrolyzed to yield the components fatty acids and glycerol. The physical and solubility characteristics are such that the substance has unique technological functions in foods. The caloric value of captrin is 8.3 kcal/g (20). The primary use of captrin is as flavor carriers for fat-free food products. A first line of product was based on interesterification of butter oil and MCTs. In June 1994, FDA accepted for filing a GRAS petition for Captrin from Stepan Company (Northfield, Ill.).

Captex. Captex MCTs are manufactured by ABITEC Corporation (Columbus, Ohio). Captex 300 EP, Captex 355 EP, Captex CA, and Captex MCT-70 are commonly known as MCTs, are produced via esterification of capric and caprylic acids with glycerol (6). The capric and caprylic acids are produced via a fractionation process. Captex 300 EP and 355 EP function in nutritional foods as a readily available energy source for athletes, bodybuilders, and exercise enthusiasts. Captex 350 is a fully refined MCT interesterified with coconut oil. Captex 810D is a structured TAG prepared from selected vegetable oils and glycerol. It can be used in pharmaceuticals for parenteral and enteric hyperalimentation. Captex 810D, prepared with medium-chain fatty acids, is rapidly absorbed, oxidized, and utilized via its unique metabolic pathway. These products are soluble in many organic solvents and are miscible with mineral and vegetable oils. They can replace some or all of long-chain fatty acid components in food, creating a lower calorie food without losing the typical sensory attributes. Potential applications for Captex MCTs include snacks, main meals, frozen and refrigerated foods, among others. The smoke, flash, and fire points of Captex products are lower than those of conventional fats, make them more suitable for low heat applications.

5. Lipid Analogues

Fat replacers of this category, also referred to as synthetic fats, may offer the functionality of fat without the calories. They are neither decomposed by digestive enzymes nor fermented in the large intestine. These substances have the same physical characteristics as fats. Typically, these ingredients use food-grade materials to create a molecule that resist lipase hydrolysis of the ester bond during the digestion process. The design strategies include substituting the fatty acid and glycerol with a fatty alcohol and organic acid, replacing a sugar molecule for glycerol, or adding to the structure of the glycerol so that the fatty acid is no longer adjoining that portion of the molecule (6). The best known examples are olestra, sorbestrin, esterified propoxylated glycerol (EPG), dialkyldihexadecylmalonate (DDM), polycarboxylic acid esters, and ethers and polyglycerol esters (PGE).

5.1. Olestra. Olestra, a type of sucrose fatty acid polyester (SPE), is the first calorie-free fat substitute approved by the FDA. As opposed to the glycerol backbone of TAGs, olestra has a sucrose backbone, to which six to eight long-chain fatty acids (predominantly C_{18}) have been added. Each molecule contains at least 70% octa fatty acid esters with 1% or less hexaesters. The common constituent fatty acids are $C_{16:0}$, $C_{18:0}$, $C_{18:1}$, $C_{18:2}$, and $C_{18:3}$ fatty acids. Olestra is unique among the SPEs in that it is manufactured according to strict criteria specified by the FDA (32). It is a mixture of hexa-, hepta-, and octaesters synthesized by esterifying sucrose with long-chain fatty acids. Olestra is synthesized from sucrose and vegetable oils (soybean or cottonseed) (33) and it has physical properties comparable to conventional fats used in savory snacks and crackers. Olestra prepared from short-chain fatty acids is solid, whereas olestra produced from unsaturated fatty acids is liquid at room temperature. This product looks, tastes, and functions like real fat, but its formulation causes it to pass through the gastrointestinal tract totally unabsorbed, contributing no calories to the diet.

The melting point of olestra is 60°C. Values of smoke and flash points are 249 and 288°C, respectively. Olestra has an AOM peroxide value of 100 ppm at 2 h. This product is stable under ambient and high temperature storage conditions and has an acceptable flavor. The main advantage of olestra is that it has all of the characteristics of fat without adding calories. Its appearance, texture, mouthfeel, thermostability, and half-life are similar to those of conventional fats and oils. The manufacturer of olestra, Procter & Gamble Co. (Cincinnati, Ohio), petitioned FDA in 1987, for use of olestra as a calorie-free replacement for fats and oils. The petition included results of >100 animal studies and 98 human studies, including a number of safety studies, several chronic feeding trials, and clinical trials.

In 1990, the petition was amended to seek only the approval for fat replacement of up to 100% in savory snacks, including fried snacks and snack crackers. Procter & Gamble has decided to use the brand name Olean for the ingredient. In January 1996, the FDA approved the use of olestra in potato chips and other savory snacks. To date, the only approved use of olestra is as a replacement for the fat used in the production of some savory snacks, eg, potato chips, corn chips, tortilla chips as well as cheese puffs and curls, and crackers. Using olestra in place of conventional fat to fry these products reduced their calories substantially. For example, a 1-oz serving of potato chips fried in olestra contains no fat and 70 cal. A 1-oz serving of regular chips contains 10 g of fat and 160 cal. Olestra also has a potential for use in margarines, salad dressings, cheese, ice cream, and frozen desserts. So far, it has been approved only for commercial uses, but it would also potentially be suitable for home applications.

Extensive testing in animals and humans has shown that consumption of olestra decreases the absorption of certain fat-soluble vitamins, eg, A, D, E, and K, and carotenoids (34). Because olestra is a lipophilic compound, and passes through the body unabsorbed, it carries certain fat soluble compounds with it. Because of this, FDA insisted that foods made with olestra be fortified with fat-soluble vitamins. Animal and clinical studies showed that these vitamins could be offset by incorporating higher amounts of fat-soluble vitamins to olestra-containing foods (35,36). Numerous research studies (35–40) have shown that olestra does not significantly interfere with the absorption of macronutrients (eg, carbohydrates, TAGs, and proteins), and water-soluble micronutrients, and vitamins D and K. The impact of olestra on the absorption and efficacy of lipophilic drugs eg, oral contraceptives, diazepam, and propranolol, has been investigated. Results indicate that there was little possibility of interfering with the absorption or bioavailability of lipophilic drugs. Olestra passes through the gastrointestinal tract without being absorbed and it may be associated with gastrointestinal cramping, potential anal leakage, diarrhea, and loose stools in some individuals (41,42). It was suggested that soft stools could be prevented by using olestra with semisolid consistency or by increasing the viscosity of the olestra or product. To warn consumers of potential gastrointestinal and nutrient side effects, products made with olestra used to have the following label statement, per the FDA: This product contains olestra. Olestra may cause abdominal cramping and loose stools. Olestra inhibits the absorption of some vitamins and other nutrients. Vitamins A, D, E, and K have been added. The safety studies showed that olestra is not toxic, mutagenic, carcinogenic or teratogenic, and considered safe. The reason is because olestra, for the most part, is not digested or absorbed.

Many clinical studies have shown that olestra has potential to benefit some individuals. For example, this product can help people lose weight, benefit those at high risk of cardiovascular disease, coronary heart disease, obesity, and colon cancer. Olestra can also inhibit cholesterol absorption and lower blood cholesterol levels (43). In one study, 20 men with normal cholesterol levels were fed a diet containing 750 mg cholesterol/day along with either butter or a butter–Olestra blend. Olestra was fed at a level of ~14 g/day. The group receiving the Olestra absorbed ~18% less cholesterol than the group receiving all butter (44).

In another study, 24 healthy, normal-weight men with normal cholesterol levels were fed 300 or 800 mg of cholesterol in a typical American diet containing 20% of its calories as protein, 40% as fat, and 40% as carbohydrates. Subsequently, olestra was added to each of the diets. Adding olestra to the diet lowered both total and LDL cholesterol (45). Crouse and Grundy (46) also studied the impact of Olestra on cholesterol metabolism in obese men. In this study, 11 overweight men were fed low calorie (1000 kcal/day), low cholesterol (19 mg/day) diets containing 21% of calories from fat with and without 62 g of Olestra/day for a 6-week period. Beyond the 20% decrease in plasma cholesterol caused by weight loss, Olestra feeding resulted in another 12.5% reduction in plasma cholesterol in six subjects, but had no significant effect on plasma cholesterol in the other five subjects. Grundy and co-workers (47) reported that in nondiabetic patients, calorie-restricted diet plus sucrose polyester exhibited a reduction in total and LDL cholesterol by 20 and 26%, respectively. In diabetic patients with hypertriacylglycerolemia, caloric restriction showed a marked reduction in plasma triacylglycerols with or without sucrose polyesters. Calorie-restricted diet apparently reduced cholesterol by decreasing cholesterol synthesis (47).

Organoleptic evaluation studies have shown that Olestra can reduce the fat content of snack foods without affecting taste. The reduction in fat intake accomplished by the substitution of Olestra snacks for full-fat snacks can be a positive step toward a person's improved health and weight control. For example, a 30-g bag of potato chips made with vegetable oil contains $\sim$10 g fat and 160 cal. This same bag of potato chips made with Olestra contains no fat and only $\sim$70 cal. A reduction in fat intake of 10 g/day, which could be accomplished by substituting one bag of potato chips made with olestra for regular potato chips per day, would save the same number of calories over a year as those in 3.6 kg of fat (48). Numerous studies have confirmed that olestra can help reduce the percent of calories from fat in the diet.

Products containing Olestra for use in foods no longer have to carry the warning that eating such foods may cause abdominal cramping and loose stools in some individuals, or that it inhibits the body's absorption of vitamins A, D, E, and K. However, manufacturers will still be required to add vitamins to Olestra-containing products to compensate for Olestra-induced nutritional losses. The labeling change was made after the FDA conducted a review of several postmarket studies submitted by Proctor & Gamble. In August 2003, The FDA reported label warnings were no longer warranted because "real-life" consumption studies showed Olestra caused only infrequent and mild gastrointestinal effects. For example, a 6-week study with $>$3000 people showed the group consuming Olestra-containing chips experienced only a minor increase in bowel movement frequency compared to those who consumed full-fat chips. In May 2004, FDA approved the use of olestra in prepackaged ready-to-heat popcorn, eg, microwave popcorn. The original FDA approval of Olestra in savory snacks included prepackaged ready-to-eat but not ready-to-heat popcorn.

5.2. Sucrose Fatty Acid Esters. Sucrose fatty acid esters (SFEs), manufactured by Mitsubishi-Kasei Food Corporation (Tokyo, Japan), are a mixture of mono-, di-, and triesters of sucrose with fatty acids that are derived from edible vegetable or hydrogenated edible vegetable oils and fats. These SFEs are manufactured by interesterification of sucrose with methyl esters of fatty acids in the presence of food-grade solvents. Unlike olestra, SFEs are easily digested by pancreatic lipases, so they provide calories. The SFEs exhibit hydrophilic and lipophilic properties because of the 5–7 free hydroxyl groups with 1–3 fatty acid esters, which give the product an emulsifying and surfactant functionality. In 2003, the FDA stated that it has no objections to the Mitsubishi Chemical Corporation claim that SFE is GRAS for use as an emulsifier in beta-carotene, beta-apo-8-carotenal, and canthaxanthin color preparations when they are added to beverages, crackers, soups, and sauces. After extensive review of the Mitsubishi's GRAS submission, the agency has listed the Notice as No. GRN 000129 and SFEs have been approved in the United States for use as emulsifiers, texturizers, and stabilizers in several food categories. There categories includ shortenings, margarines, baked goods, frozen desserts, and spreads.

5.3. Sorbestrin. Sorbestrin is a low calorie fat replacer based on sorbitol fatty acid esters (6). It was discovered in the late 1980s by Pfizer Food Science Group and is currently under development by Danisco Cultor America Inc. (Ardsley, N.Y.). Sorbestrin is a mixture of tri-, tetra-, and pentaesters of sorbitol. It is a clear liquid and has a cloud point of 15°C. It has a bland oil-like taste and can serve as a reduced calorie fat substitute. It is thermally stable and is intended for use in frying and baking. Sorbestrin is typically produced by transesterification of sorbitol with fatty acid methyl or ethyl esters (6). The fatty acids are obtained from conventional vegetable oils, eg, those from sunflower, soybean, safflower, or cottonseed. The fatty acid composition of sorbestrin typically consists of 80% oleic (18:1), 10% linoleic (18:2), 4% stearic (18:0), 4% palmitic (16:0), and <1% of linolenic (18:1), arachidic (20:0), eicosenoic (20:1), and behenic (22:0) acids. Unlike fully esterified sucrose polyesters, sorbestrin is partially absorbed. Several clinical studies have shown that sorbestrin is well tolerated at up to 30 g/day intake. Based on the results of isotope-labeled disposition studies and clinical metabolism studies, sorbestrin has a caloric content of ~1.5 kcal/g. The regulatory approval of sorbestrin has not been obtained, and hence it is still not in commercial use.

5.4. Esterified Propoxylated Glycerols. Esterified propoxylated glycerols (EPGs) are produced by reacting glycerol with propylene oxide to form a polyether polyol, which is subsequently esterified with fatty acids. The structure of EPG is similar to TAGs, except that an oxypropylene is incorporated between the glycerol and the fatty acids. The average number of oxypropylene groups, which are incorporated into glycerol is called the propoxylation number (49). The physical properties of the finished product depend on the type of fatty acids esterified. The number of propylene oxide groups and selection of fatty acids give the products a range of functionality. Although many polyols are acceptable, the glycerol triol is preferred. Preferred fatty acids are C_{14}–C_{18} fatty acids. Preferred sources of fatty acids are those from corn, olive, soybean, lard, and tallow. The EPG is patented by ARCO Chemical Technology (Newtown Square, Pa.) and CPC International, Inc. (Englewood Cliffs, N.J.). Esterified propoxylated glycerol is partially digestible and its contribution to caloric intake is zero. It is heat stable and can be used for baking and frying. Animal studies indicate that EPG is safe and resistant to hydrolysis (50,51). They can substitute for fats in margarines, fried foods, frozen desserts, salad dressings, and bakery products. However, there has been no evidence of regulatory submissions of this product.

5.5. Dialkyldihexadecylmalonate. Dialkyldihexadecylmalonate (DDM) is a mixture of hexadecyl dioleylmalonate and dihexadecyl dioleylmalonate fatty acid esters of malonic and alkylmalonic acids. The DDM can be synthesized by reacting malonyl dihalide with a fatty alcohol. Dialkyldihexadecylmalonate, developed by Frito-Lay, Inc. (Plano, Tex), is noncaloric and its absorption is negligible. It exhibits high thermal stability (52) and is suitable for high temperature frying and baking. Frying of potato and tortilla chips in DDM produces crispy chips with reduced oiliness (53). The DDM, consisting of a monomer and a dimer, has a melting point below body temperature, but higher than that of conventional frying oils. Because it is stable when heated and not absorbed, DDM has the potential for use in a blend with conventional frying oils to make reduced-calorie frying oils. Mixtures of DDM with other oils, eg, soybean oil, constitute frying oils with caloric values 33–60% lower than the natural oil. Animal studies with DDM has shown that $<0.1\%$ of it is absorbed (54). Rat studies have also found no toxic effects. Frito-Lay Inc. has been studying this fat replacer since 1986, however, there is no evidence of regulatory submission or commercial development of this product.

5.6. Polycarboxylic Acid Esters and Ethers. Esterification of polycarboxylic acids with selected alcohols produces noncaloric, nondigestible, heat resistant organic compounds that retain the functional attributes of fats and oils. Polycarboxylic acids have two to four carboxylic acid groups in a polycarboxylic acid backbone esterified with saturated or unsaturated straight or branched long-chain alcohols (from C_8 to C_{30}). These compounds have been proposed as thermally stable low calorie fat replacers (55,56). They have physical and functional properties similar to those of the typical TAGs. However, they are not susceptible to enzymatic hydrolysis and do not contribute calories to the diet. Typical examples of polycarboxylic acid esters and ethers include trialkoxytricarballylate (TATCA), trialkoxycitrate (TAC), and trialkoxyglyceryl ether (TGE), among others. The TATCA resembles a natural TAG with polycarboxylic acids with two to four carboxylic acid groups, eg, tricarballic acid replacing glycerol and saturated or unsaturated alcohols replacing the fatty acids. It is a nonhydrolyzable, edible, oil-like compound and is being evaluated by researchers at Best Foods Division of CPC International, Inc. (Englewood Cliffs, N.J.). The TATCA has been suggested as a replacer for vegetable oils in margarines and salad dressings. It can also be used to replace vegetable oil in cooking applications. Research indicated that TATCA was poorly digested by animals (55). Weight gain results in rats showed that TATCA has a low caloric value compared to corn oil (55,56). Animal studies indicate that moderate-to-high dose levels (1.0–3.0 g) of TATCA resulted in anal leakage, depression, weakness, and fatalities among animals (55,56). The deaths were attributed to starvation or laxative effects as a result of interference with nutrient absorption rather than to toxicity. Trialkoxycitrate (TAC) has a structure similar to TATCA, with a hydroxyl group on the central carbon. Studies showed that TAC did not appear to have the thermal stability to be used for frying (55). Although limited animal research has been reported for these compounds, the approval of these products for human use has not occurred thus far. The TGE exhibits viscosities and surface tensions similar to vegetable oils at room temperature. Production of TGE at large-scale was found to be difficult and time consuming. While functional properties may allow TGEs use as a fat replacer, manufacturing problems would make commercial production difficult.

5.7. Polyglycerol Esters. Polyglycerol esters (PGEs) have been used as food additives for many years. In the United States, they were based on polyglycerols made by condensation of glycerol. During the synthesis, the first step involves the preparation of polyglycerols via polymerization of glycerol under alkaline conditions at 230°C (57). This process results in high levels of residual glycerol and cyclic components, as well as broad distributions of oligomers in the polyglycerol moiety. Chemically, PGEs may be formed by esterification of vegetable oil fatty acids, largely saturated or monounsaturated, to one or several hydroxyl groups of polyglycerol. As glycerol is a trifunctional molecule, it may condense with itself to give polymers. These polyglycerols are hydroxy-containing ethers, diglycerol being the simplest example. If the primary hydroxyls are the only ones concerned in the reaction, the products are linear, but if the secondary hydroxyl groups are also involved, branched chains are formed. Thus, several diglycerol molecules can be formed, but if the polymerization proceeds to tri-, tetra-, and higher glycerols, the number of possible isomers increases exponentially. It has been found that cyclic products can also result from intramolecular reactions. The PGEs can be purified through fractionation, molecular distillation or solvent crystallization. The fractionated PGEs are more functional and can be used at lower concentration (58). Some examples of PGEs include decaglycerol decaoleate, triglycerol monostearate, octaglycerol monostearate, and octaglycerol monopalmitate, among others. These PGEs are made from edible oil sources, eg, those from cottonseed, corn, soybean, palm and peanut, and are approved for use under the Code of Federal Regulations 21 CFR 172.854 (59). Despite the technical name, there is no known toxicity and they are regarded as safe (60). The PGEs have an estimated caloric value of 6–7 kcal/g, however, the net caloric value may be as low as 2 kcal/g due to partial absorption (61).

These compounds function as emulsifiers and/or lubricants in various food, cosmetic, and pharmaceutical applications. Their amphiphilic properties enable their use in the stabilization of various suspensions. In foods, they are used as emulsifying agents in the production of fine bakery, chewing gum, and in replacement of fats. Polyglycerol esters have been touted as replacements for fats to reduce human calorie consumption. The PGEs are dispersible in water and soluble in oil. Its hydrophilicity and lipophilicity greatly change with the degree of its polymerization and the kind of fatty acid. Its hydrophilic–lipophilic balance (HLB) ranges from 3 to 13. It has a variety of functions depending on these conditions, and is usable for various purposes. It is used in many types of food as an oil-in-water and water-in-oil emulsifier for milk products containing acid and salt and a modifier to control the crystallization of fats. The PGEs are extensively used in icings, toppings and cake mixes, ice cream, other desserts, bakery and pastry products, chewing gum, coffee whitener, butter and other spreads, milk powder for baby food, and imitation milk powders. The PGEs can also be used as a vehicle for drugs (dissolved or suspended), as a wetting agent, to help the wetting of a suspended powder, as a thickener. Owing to its high viscosity, it can be mixed with vegetable oils, to increase viscosity thus preventing separation.

BIBLIOGRAPHY

"Fat Replacers" in *ECT* 4th ed., Vol. 10, pp. 239–252, by R. E. Morse, Consultant, and N. Singer, Nutrasweet; "Fat Replacers" in *ECT* (online), posting date: December 4, 2000, by R. E. Morse, Consultant, and N. Singer, Nutrasweet.

CITED PUBLICATIONS

1. Dietary Guidelines for Americans 2005. U.S. Department of Health and Human Services (HHS) and U.S. Department of Agriculture (USDA). Dietary Guidelines Advisory Committee (DGAC) Report, Washington, D.C., January 12, 2005.
2. U.S. Department of Agriculture (2005). MyPyramid.gov.http://www.mypyramid.gov, 2006, September 15.
3. *Calorie Control Commentary*, Vol. 24, No. 1, Calorie Control Council, 2006.
4. A. A. Hedley, C. L. Ogden, C. L. Johnson, M. D. Carroll, L. R. Curtin, and K. M. Flegal, *JAMA.* **291**, 2847 (2004).
5. A. K. Kant, B. I. Graubard, and A. Schatzkin, *J Nutr.* **134**, 1793 (2004).
6. S. P. J. N. Senanayake and F. Shahidi, in F. Shahidi, ed., *Bailey's Industrial Oil and Fat Products*, 6th ed., Vol. 3, John Wiley & Sons, Inc., New York, 2005, p. 503.
7. J. Wylie-Rosett, *Circulation* **105**, 2800 (2002).
8. U.S. Food and Drug Administration, *A Food Labeling Guide-Appendix A.*, June 1999.
9. FDA Backgrounder BG 99-5: *The Food Label*, US Food and Drug Administration, Washington, D.C., May, 1999.
10. Council Regulation 2991/1994/EC. Laying down standards for spreadable fats. Official Journal L316, 9/12/94, December 5, 1994.
11. B. J. Archer, S. K. Johnson, H. M. Devereux, and A. L. Baxter. *Br. J. Nutr.* **91**, 591 (2004).
12. Food and Drug Administration. Guide to Nutrition Labeling and Education Act (NLEA) Requirements (1994) http://www.fda.gov/ora/inspect_ref/igs/nleatxt.html, 2006, August 2.
13. A. A. Burns, M. B. E. Livingstone, R. W. Welch, A. Dunne, A. Reid, and I. R. Rowland, *Int J. Obes. Relat. Metab. Disord.* **25**, 1487 (2001).
14. S. S. Cho, and L. Prosky, in S. S. Cho, L. Prosky, and M. Dreher, eds., *Complex Carbohydrates in Foods*, Marcel Dekker Inc., New York, 1999, p. 411.
15. G. E. Inglett, C. J. Carriere, and S. Maneepun, in J. Shi, C. Ho, and F. Shahidi, eds., *Asian Functional Foods*, CRS Press, Boca Raton, FL, 2005, p. 103.
16. G. Inglett, *Agr. Res.*, August (2003).
17. M. Segal, *U.S. Food and Drug Admininstration: FDA Consumer*, December 1990.
18. J. W. Finley, A. McDonald, and L. P. Klemann, in F. D. Gunstone and F. B. Padley, eds., *Lipid Technologies and Applications*, Marcel Dekker, Inc., New York, 1997, p. 501.
19. D. R. Webb and R. A. Sanders, *J. Am. Coll. Toxicol.* **10**, 3 (1991).
20. M. H. Auerbach, L. P. Klemann, and J. A. Heydinger, in *Structural and Modified Lipids*, Marcel Dekker, Inc., New York, 2001, p. 485.

21. W. E. Artz and S. L. Hansen, in R. E. McDonald and D. B. Min, eds., *Food Lipids and Health*. Marcel Dekker, Inc., New York, 1996, p. 385.
22. D. R. Webb and R. A. Sanders, *J. Am. Coll. Toxicol.* **10**, 325 (1991).
23. D. R. Webb, J. C. Peters, and R. J. Jandacek, *J. Am. Coll. Toxicol.* **10**, 341 (1991).
24. G. M. Wardlaw, J. T. Snook, S. M. Park, P. K. Patel, F. C. Pendley, M. S. Lee, and R. J. Jandacek, *Am. J. Clin. Nutr.* **61**, 535 (1995).
25. R. E. Smith, J. W. Finley, and G. A. Leveille, *J. Agric. Food. Chem.* **42**, 432 (1994).
26. L. P. Klemann, K. Aji, M. M. Chrysam, R. P. D'Amelia, J. M. Henderson, A. S. Huang, M. S. Otterburn, and R. G. Yarger, *J. Agric. Food. Chem.* **42**, 442 (1994).
27. J. Giese, *Food Technol.* **4**, 78 (1996).
28. R. Kosmark, *Food Technol.* **50**, 98 (1996).
29. U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition, Washington, D.C., Office of Premarket Approval, *Agency Response Letter: GRAS Notice No. GRN 000050*, 2000.
30. J. A. Heydinger and D. K. Nakhasi, *J. Food Lipids*, **3**, 251 (1996).
31. U. S. Pat. 952,606 (1990) V. K. Babayan, G. L. Blackburn, and B. R. Bistrian.
32. Food and Drug Administration (FDA), *Fed Regist.* **61**, 3118 (1996).
33. J. Giese, *Food Technol.* **3**, 130 (1996).
34. D. A. Cooper, D. R. Webb, and J. C. Peters, *J. Nutr.* **127**, 1699S (1997).
35. D. A. Cooper, D. A. Berry, M. B. Jones, A. L. Kiorpes, and J. C. Peters, *J. Nutr.* **127**, S1589 (1997).
36. T. Schlagheck, J. Kesler, M. Jones, N. Zorich, L. Dugan, and J. Peters, *J. Nutr.* **127**, S1666 (1997).
37. D. Y. Jones, K. W. Miller, B. P. Koonsvitsky, M. L. Ebert, P. Y. Lin, M. B. Jones, and H. F. DeLuca, *Am. J. Clin. Nutr.* **53**, 1281 (1991).
38. D. Y. Jones, B. P. Koonsvitsky, M. L. Ebert, M. B. Jones, P. Y. Lin, B. H. Will, and J. W. Suttie, *Am. J. Clin. Nutr.* **53**, 943 (1991).
39. G. Dasher and co-workers, *FASEB J.*, **8**, A443 (1994).
40. N. Zorich and co-workers, *FASEB J.*, **8**, A735 (1994).
41. R. G. La Barge, *Food Technol.* **1**, 84 (1988).
42. M. J. Mellies, C. Vitale, R. J. Jandacek, G. E. Lamkin, and C. J. Glueck, *Am. J. Clin. Nutr.* **41**, 1 (1985).
43. J. W. Finley and G. A. Leveille, in E. E. Ziegler, and L. J. Filer, Jr., eds., *Present Knowledge in Nutrition*, 7th ed., ILSI Press, Washington, D.C., 1996, p. 581.
44. R. J. Jandacek, M. M. Ramirez, and J. R. Crouse, *Metabolism* **39**, 848 (1990).
45. C. J. Glueck, F. H. Mattson, and R. J. Jandacek, *Am. J. Clin. Nutr.* **32**, 1636 (1979).
46. J. R. Crouse and S. M. Grundy, *Metabolism* **28**, 994 (1979).
47. S. M. Grundy, J. V. Anastasia, Y. A. Kesaniemi, and J. Abrams, *Am. J. Clin. Nutr.* **44**, 620 (1986).
48. R. Hunt, N. L. Zorich, and A. B. R. Thomson, *Can. J. Gastroenterol.* **12**, 193 (1998).
49. U.S. Pat. 6,361,817 (2002) B. C. Sekula and J. W. Golebiowski.
50. U.S. Pat. 4,861,613 (1989) J. F. White and M. R. Pollard.
51. Eur. Pat. 00571219/ EP B1, (1997) L. W. Masten.
52. B. G. Swanson, in F. Shahidi, ed., *Nutraceutical and Specialty Lipids and Their Co-Products*, CRC Press, Boca Raton, Fla., 2006, p. 329.
53. Anonymous, *Food Technol.* **44**, 92 (1990).
54. Anonymous, *J. Am. Oil Chem. Soc.* **66**, 868 (1989).
55. D. J. Hamm, *J. Food Sci.* **49**, 419 (1984).
56. U. S. Pat. 4,508,746 (1985) D. J. Hamm.
57. R. C. McIntyr, *J. Am. Oil Chem. Soc.* **56**, 835A (1979).
58. U. S. Pat. 6,436,459, (2002) M. Martinez-Serna Villagran, S. P. Zimmerman, J. D. Reed, P. Seiden, S. M. Brower.

59. U.S. Food and Drug Administration, Department of Health and Human Services, *Code of Federal Regulations, Title 21- Food and Drugs, Part 172- Food Additives Permitted for Direct Addition to Food for Human Consumption.* U.S. Government Printing Office, Vol. 3, Revised as of April 1, 2002. p. 89.
60. W. R. King, W. R. Michael, and R. H. Coots, *Tox. Appl. Pharm.* **20**, 327 (1971).
61. W. R. Michael and R. H. Coots, *Toxicol. Appl. Pharmacol.* **20**, 334 (1971).

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Table 1. **Major Sources of Fat in the U. S. Food Supply**[a]

Food group	Percent of total fat in food supply
meat, poultry, and fish	30
grain products	25
milk and milk products	18
fats and oils	11
vegetables	9
other	7

[a]From Ref. 3.

Table 2. **Most Popular Reduced-Fat Products in the U. S.**[a]

Food group	Percent reduced-fat consumers
low-fat or skim milk	74
reduced-fat cheese/dairy products	65
reduced-fat salad dressings/ sauces/ mayonnaise	60
reduced-fat margarine	46
reduced-fat chips/ snack foods	40

[a]From Ref. 3.

Table 3. **Nutrient Content Claims for Fat-Containing Foods**

Claims	Definition
low fat	a serving containing no >40 cal, and 3 g or less fat
fat-free	a product containing 0.5 g or less fat per serving
reduced fat	25% or less fat than a full-fat product per serving
percent fat free	a product must be low fat or fat-free, and the percentage must accurately reflect the amount of fat in 100 g of the food
light	an altered product containing one-third fewer calories or 50% of the fat in the reference food
calorie-free	a product with fewer than 5 cal per serving
low calorie	a product with <40 cal per serving
reduced or fewer calories	25% or fewer calories than regular product per serving
lean	meat, poultry, seafood, and game meats containing <10 g of fat per serving
extra lean	meat, poultry, seafood, and game meats containing <5 g of fat per serving

Table 4. **Terminology of Fat Replacers**

Term	Definition
fat replacer	an ingredient that can be used to replace fat, yielding fewer calories than fat and may or may not provide nutritional value
fat substitute	a synthetic compound, usually having a similar chemical structure to conventional fats and oils, designed to replace some or all of the functions of fat without any energy contribution, and is usually indigestible or unabsorbable
fat mimetics	a fat replacer that can mimic one or more of the organoleptic and physical functions of fat, and usually requires a high water content to achieve its functionality
fat extender	a fat replacement system, containing a proportion of fat combined with other ingredients, designed to optimize the functionality of fat, thus allowing a decrease in the usual amount of fat in the product
fat analog	a compound that provides food with many of the characteristics of fat, but altered digestibility and altered nutritional value
fat barrier	an ingredient system that provide a barrier for products that use fat as a heat exchange medium

Table 5. **Main Categories of Fat Replacers**

Carbohydrate based	Protein based	Lipid based
starch/ modified food starch	microparticulated protein	Caprenin
dextrins	modified protein/ denatured protein	Olestra/ Olean
maltodextrins	vegetable protein	Salatrim/ Benefat
polydextrose	protein blends (contain carbohydrates and fat)	Captex
inulin		Neobee
cellulose		Captrin
fiber		Bohenin
gums		Sorbestrin
polyols		Esterified propoxylated glycerol
Z-trim		Trialkoxytricarballylate
Nu-Trim		Dialkyl dihexadecylmalonate
Oatrim		Polyglycerol ester
		Partially esterified polysaccharides
		Emulsifiers (mon- and diglycerides)
		Fat blends (contain carbohydrates and fat)

Table 6. **Some Examples of Carbohydrate-Based Fat Replacers and Their Applications**

Trade names	Chemical composition	Manufacturer/ Supplier	Applications
Avicel	microcrystalline cellulose	FMC BioPolymer (Philadelphia, Pa.)	bakery products, salad dressings, frozen desserts, ice cream, meat products, sauces
N-Oil	dextrins	National Starch & Chemical Co. (N.J.)	salad dressings, puddings, spreads, dairy-type products, frozen desserts, sauces
Keltrol	xanthan gums	CP Kelco (San Diego, Calif.)	baked goods, salad dressings, reduced-fat margarines, soups and sauces
Fibrim	fiber	Protein Technologies International (St. Louis, Mo.)	reduced-calorie baked goods, extruded products, liquid beverages, cereals
Paselli	maltodextrins	Avebe America Inc. (Princeton, N.J.)	dressings, spreads, sauces, frozen desserts, frostings, fillings
Litesse	polydextrose	Danisco (New Century, Kans.)	frozen desserts, baked goods, fruit spreads and fillings, nutrition bars, beverages, confections
Slendid	pectin	Hercules Inc. (Wilmington, De.)	baked goods, cookies, frostings, processed meats, salad dessings, spreads, frozen desserts, soups, sauces
N-Lite	modified starch	National Starch & Chemical Co. (N.J.)	dairy products
Fibruline	inulin	Cosucra SA (Warcoing, Belgium)	frozen desserts, baked goods, icing, fillings
ChitoClear	chitosan	Primex Ingredients ASA (Norway)	snacks, noodles, bread sticks, soups
Oatrim	β-glucan	conAgra (Omaha, Nelfr.)	baked goods

Table 7. **Some Examples of Protein-Based Fat Replacers and Their Applications**

Commercial name	Chemical name/ composition	Manufacturer/ supplier	Applications
Simplesse	microparticulated egg white and whey protein concentrate	NutraSweet Co. (Ill.)	baked goods, milk/dairy products, salad dressings, frozen desserts, mayonnaise-type products, margarine-type products, coffee creamer, soups, sauces
Dairy-Lo	partially denatured whey protein concentrate	Pfizer Inc. (New York, N.Y.)	dairy products, mayonnaise-type products, baked goods, frostings, salad dressing
Trailblazer	egg white and xanthan gum	Kraft General Foods (Ill.)	frozen desserts, baked goods, spreads, butter, salad dressings
Lita	microparticulated zein protein from corn gluten coated with a polysaccharide	Opta Food Ingredients Inc. (Mass.)	frozen desserts, baked goods, spreads, butter, salad dressings, chocolate and confectionery
Dairylight	partially denatured whey protein concentrate	Ault Foods Ltd (Canada)	frozen desserts, nondairy products, yogurt, cheese, spreads

Table 8. **Examples of Fat-Based Fat Replacers and Their Applications**

Commercial names	Chemical name/ composition	Manufacturer/ supplier	Applications/ potential applications
Salatrim/ Benefat	SCFA ($C_{2:0}$–$C_{4:0}$) and LCFA (Predominantly $C_{18:0}$)	Nabisco Foods Group (East Hanover, N.J.)	baked goods, dairy products, confections, snacks, margarines and spreads
Caprenin	medium-chain triacylglycerols	Procter & Gamble Co. (Cincinnati, Ohio)	soft candies, confections
Olean	sucrose polyester	Procter & Gamble Co. (Cincinnati, Ohio)	baked goods, fried foods, mayonnaise, salad dressing
Bohenin	oleic and behenic acids	Fuji Oil Co. Ltd. (Osaka, Japan)	confections
Sorbestrin	sorbitol polyester	Cultor Food Science, Inc. (Ardsley, N.Y.)	baked goods, fried foods, formulated products
EPG	esterified propoxylated glycerol	ARCO Chemical Technology (Greenville, Delf.)	formulated products, baked goods, fried foods
Neobee	medium-chain triacylglycerols	Stepan Co. (Northfield, Ill.)	high-energy protein bars, ready-to-drink nutritional beverages, high performance wellness foods, snack products
Captrin	medium-chain triacylglycerols	Stepan Co. (Northfield, Ill.)	high energy protein bars, ready-to-drink nutritional beverages, high performance wellness foods, snack products
DDM	dialkyl dihexadecylmalonate	Frito-Lay Inc. (Plano, Tex.)	potato and tortilla chips
PGE	polyglycerol ester	Danisco Cultor USA, Inc. (New Century, Kams.)	baked goods, cakes, ice cream, butter, spreads, milk powder
sucrose fatty acid esters	sucrose with 1–3 fatty acids	Mitsubishi-Kasei Food Corp.	baked goods, margarine, shortening