RESEARCH INAUGURAL LECTURE

Manipulation of Nutrient Composition in Poultry

Wong Hee Kum

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Abstract

Since the 1990s, food has evolved into an exciting area of the food and nutrition sciences known as functional foods which can provide health benefits beyond basic nutrition. Consumer demand for food products of superior health quality has generated interest in modifying the lipid composition and enriching poultry meat and eggs with beneficial nutrients. Traditionally, eggs have not been regarded as a functional food because of their perceived link with adverse effects on blood cholesterol. However, research over the last 3 decades has shown that dietary cholesterol only has a small effect on plasma cholesterol levels and has little relationship to heart disease incidence. The egg is a nutrient dense food and is now regarded as an excellent, inexpensive, convenient and low calorie source of high quality protein and several important nutrients such as riboflavin, selenium, choline and vitamin B12. Some of the strategies to consider for developing nutrient enriched eggs and meat should include factors such as efficiency of nutrient transfer from feed to the egg and meat, the availability of commercial sources of effective feed forms of the nutrients, the possible toxic effects of nutrients for the chicken and the amount of nutrient delivered with the egg or meat in comparison with RDA (recommended dietary allowance). Omega-3 (ω-3) eggs are the first product in manipulation of egg composition, and enrichment with selenium, lutein, choline, vitamins B, D, E and K, and conjugated linoleic acid has also attracted substantial attention in relation to egg and meat quality. Extensive medical evidences have shown that foods rich in ω-3 polyunsaturated fatty acids can prevent coronary heart disease and stroke, reduction of colorectal and breast cancers and inflammatory disease such as rheumatoid arthritis. Omega-3 (ω-3) fatty acids also play an essential role in the growth and development of brain and eye tissue in the foetus and newborn infant. In addition, ω-3 fatty acids have been widely reported to prevent or reduce psychiatric disorders,

cognitive decline and dementia. Due to its extensive physiological functions in humans, many health and nutrition agencies worldwide have made dietary recommendations for intake of ω-3 fatty acids. Vitamin E is an antioxidant that has many important functions and a primary function is in preventing oxidative stress from free radical formation. Higher dietary levels of vitamin E are able to reduce ascites-related mortality in broiler chickens and alleviate symptoms of heat stress. Studies on selenium nutrition show that humans are receiving less than 50% of the RDA of selenium and this public health issue should be addressed. Effective and sustainable ways to increase selenium intakes should be developed. Poultry eggs can be enriched with vitamin E, long chain ω-3 fatty acids and selenium to meet about 50%, 65% and 75% respectively, of the recommended daily intake for humans and thus play an important role as functional food for consumers. The ability to enrich eggs with these vital nutrients has provided the local egg industry with a unique opportunity to produce an innovative, premium quality and value-added product for the domestic and export markets.

Introduction

Functional foods can be defined as those providing health benefits beyond basic nutrition and include whole, fortified, enriched or enhanced foods which have a potentially beneficial effect on health when consumed as part of a varied diet on a regular basis at effective levels (Milner 2000). Food is also viewed as the principal vehicle to transport us along the road to good health and wellness. The widespread interest in functional foods in the last decade was due to factors such as the growing self-care movement, changes in food regulations and overwhelming scientific evidence highlighting the critical link between diet and health. This interest in functional foods has resulted in a number of new foods in the marketplace designed to address specific health concerns, in particular chronic diseases of aging including cancer, heart disease, osteoporosis, arthritis and age-related macular degeneration. Extensive epidemiological studies have shown that a high intake of antioxidant-rich foods is inversely related to cancer risk. Selenium and vitamin E have been shown to reduce the risk of prostate and colon cancer, while carotenoids may reduce breast cancer risk (Borek 2004). Extensive evidence also showed that foods rich in ω-3 polyunsaturated fatty acids are associated with reduced risk for all-cause mortality, coronary heart disease and stroke.

Many experimental studies have shown that antioxidant vitamins and some phytochemicals selectively induce apoptosis in cancer cells, and prevent angiogenesis and metastatic spread, suggesting a potential role for antioxidants as adjuvants in cancer therapy (Borek 2004). Studies have also shown that humans show variation in ability to increase or depress gene expression (nutrigenomic effect) in response to dietary change or food components and this may account for some of the observed inconsistencies of functional food in the general population (Milner 2004).

Thus, nutrition in the present millennium will be dramatically different than nutrition in the 20th century. The completion of the human genome project has facilitated the identification of humans predisposed to diet-related diseases and 'prescription' nutrition will become the norm, enabling the food and medical industries to provide timely and individualized approaches to disease prevention and health promotion (Hasler 2000).

Overview of the poultry industry

The broiler industry

The Malaysian broiler industry has attained the status of self-sufficiency since 1970s, and full automation and the use of technologies such as enclosed housing with evaporative cooling systems are currently the norm in newly-established broiler farms (Wong and Tan 2009b). These closed houses provide a conducive environment (optimal temperature, ventilation and humidity) for the birds to perform to their full genetic potential. This type of housing also reduces environmental pollution with less emission of NH_3 and less dust, and eliminates the fly problem. Other advantages are the higher bird density, reduced mortality, better flock feed conversion ratio (FCR) and uniformity, and less usage of antibiotics and drugs.

The broiler industry supplies about 70% of the total meat requirements in Malaysia, and is the cheapest source of animal protein. In 2008, the production of broiler meat was valued at about RM5.183 billion, and the average chicken meat consumption of 34.4 kg/person/year in Malaysia (DVS 2009) is among the highest in the world. The broiler industry relies entirely on imported genetic resources and the major commercial breeds are the Cobb and Ross broilers.

Generally, the modern commercial broiler breeds show high growth performance, an ability to thrive on lower cost nutrition, and a high level of uniformity. An example of the tremendous improvement in broiler genetics (Anon. 2006a) can be seen by comparing the growth performance data of the Cobb 500 broilers in 1994 and in 2004. Under optimal conditions, at 42 days, the male broiler of 1994 achieved a live weight of 2.076 kg compared to a live weight of 2.848 kg for the male broiler of 2004. The 1994 and 2004 male broilers took 40.9 and 32.9 days respectively, to achieve live weight of 2 kg (Anon. 2006a).

About 30% of the broilers are channelled through modern processing plants while the remainder is sold as live or dressed birds in wet markets (Wong and Tan 2009b). A thriving downstream processing industry has developed, with chicken frankfurters, cocktail sausages, burgers and nuggets, which in the past had been exclusively imported, are being produced locally now.

The layer industry

The layer industry has attained the status of self-sufficiency since 1980, and like the broiler industry, there is a trend towards increasing the use of environmentally controlled closed housing and automation in feeding, egg collection and egg grading systems. In large layer operations, egg grading machines can grade up to 120,000 eggs per hour, resulting in quicker product handling to the market (Wong and Tan 2009b). The layer industry relies entirely on imported genetic resources, and the major commercial layer breeds used are imported from the European Union; with the Lohmann brown hens from Germany, Hisex brown hens from the Netherlands and the ISA brown hens from France being the major layer breeds used in Malaysia.

The modern commercial layer demonstrates high laying ability, good egg qualities and high feed efficiency. The modern layer is expected to achieve a peak egg production of 93%, lay 300 eggs (equivalent to egg mass of 19.3 kg) with average egg weight of 64 g over 12 months (Anon. 2005b). At present, there are three egg processing plants in operation which produce different forms of liquid eggs for the bakery and confectionary industries. To diversify the product range and increase demand, several producers are marketing 'designer' eggs (Wong 1997b; Wong and Tan 2003) to meet the demand for 'healthier' eggs enriched with nutrients, such as ω-3 polyunsaturated fatty acids, vitamin E and selenium.

In 2008, the industry produced 8.7 billion eggs valued at RM2.091 billion, with exports worth RM232 million (DVS 2009). The per capita egg consumption is 280 eggs per person per year, and the surplus production of about 1,094 million eggs are exported mainly to Singapore and Hong Kong as fresh in-shell eggs.

Challenges in developing a competitive poultry industry

Poultry meat has a comparative production-cost advantage over pork and beef because of its more efficient use of feed (best feed conversion rate) and this has encouraged the worldwide growth of the poultry industry. The poultry egg industry is also undergoing change, in terms of potential for egg processing and more recently, the start of major international trade in shell eggs.

Due to consumer preference, Malaysia will continue with the marketing of live birds, and this effectively excludes imports. However, it limits future expansion and profitability and poses problems of biosecurity in movement of live birds. Further processing is the key to market penetration of poultry meat and eggs (Wong and Tan 2009b) and this is expected to increase.

Another issue occasionally raised by consumer groups is the fear of antibiotics and other chemical residues in meat products, and the dependence on antibiotics in broiler production can be overcome by the use of probiotics, organic acids, herbals and other biologically-based feed supplements. However, the poultry industry has to be fully convinced of their efficacy in production and economical terms (Wong and Tan 2009b), and more collaboration between industry and public research institutions is required.

As the country progresses, land and infrastructure developments (residential, industrial and commercial) continue to encroach onto existing poultry farms (Wong and Tan 2009b), and a major issue is the frequent complaints of foul odour from poultry litter, flies and dust. This inevitably results in the closure of the farms, or moving of the farms to more rural areas, or increased production costs (incurred by investment in closed poultry housing and waste treatment) to reduce pollution and smell.

Further-processing, which contributes to added value, is considered essential to survival in a competitive environment for the broiler and egg industry. Besides cutting cost, the poultry industry should innovate for diverse applications, including for the convenience food sector, food-service and specialty products or niche products for health enhancement.

Over-dependence on imported feed

Grain sufficiency is a key aspect of food security, and forms the basis on which countries formulate domestic agricultural policies. In many regions of Asia, population growth is putting pressure on available cropland, and increasingly imports, rather than local grain production, are seen as a more feasible solution to sustaining the steady rise in Asia's feed grain demand.

The steep increases in world food prices for rice, wheat and corn due to rising oil prices, financial speculation in the commodities market, rising global demand and declining inventories of food grains have created huge problems and challenges for the domestic poultry industry. Food staples such as corn, wheat, soybean and vegetable-based edible oils are now being considered as food, feed and fuel commodities. In addition, grain supply which has been disrupted by adverse climate conditions in the world's largest food-producing nations, and the use of corn for conversion into bio-ethanol to blend with gasoline has resulted in price increases across the whole food chain.

The use of maize for conversion into ethanol to blend with gasoline has given rise to a novel feed product called distiller's dried grains with solubles (DDGS) from ethanol factories using corn as the feedstock. This DDGS by-product from the ethanol plant make up one-third of the original corn feedstock and contains three times more protein than corn and a metabolizable energy (ME) value of 11.6 MJ/kg which is 16% less than the value for corn. Nevertheless, this ingredient is increasingly being used in poultry diets worldwide due to its availability in large quantities (Lumpkins et al. 2004, 2005).

The local poultry sector is very vulnerable because of its dependence on imported feed grains, mainly corn and soybean meal, and these two ingredients make up 80% of a poultry diet. In 2008, the feed import bill exceeded RM5 billion, and it is expected to increase with rising feed costs, tight global supply and rising transportation costs (Wong and Tan 2009b). The price of corn, a major feed ingredient in poultry diets, and soybean meal has risen by 100% from 2006 to July 2008 and as feed costs make up more than 70% of the total cost of poultry production, this factor has severe implications on the sustainability of the poultry sector.

The lack of suitable feed grain varieties, low and unstable yields (due to unsuitable climate conditions for grain corn production) and the high production cost of local ingredients such as corn and feed rice make substitution of imported ingredients uneconomical and too difficult to achieve at present. The constraints and realities of growing feed grains such as corn (Tan and Wong 2005) and other grain substitutes such as cassava, sweetpotato, feed rice and sago have been thoroughly reviewed (Tan 1998; Wong and Tan 2009a). Wong (2009) has reviewed the potential of several non-conventional and novel animal protein feeds locally and suggested that by-products from local poultry processing plants show more promise due to the large quantities available, minimal processing needed and its price competitiveness.

Potential for modifying poultry products

Over the last decade, there has been interest in altering the 'composition' of poultry products. Generally, such compositional changes are related to either the quantity of certain nutrients components of poultry egg or carcass or its nutritional profile as it relates to human health or consumer demand (Wong 2007). Poultry products have come under close scrutiny as consumers have shown an aversion for saturated animal fats and egg cholesterol. There is little benefit to increasing the amino acid profile of poultry products, due to the lack of consumer knowledge about the need or role of amino acids in human nutrition. As poultry meat and eggs are lacking in many minerals and vitamins, fortification with these nutrients can be considered if it is economically achievable through dietary manipulation. However, any potential market advantage to increasing the mineral or vitamin content of poultry products can also be pursued during further processing, rather than during on-farm production of meat or eggs (Naber 1993). As will be discussed in the following sections, the major potential for dietary manipulation lies in changing the quantity and quality of fat-rich components of poultry products.

Designer egg and meat products

During the past four decades, research efforts directed towards reducing shell egg cholesterol content have centred on genetic selection or alteration of the laying hens' diet with various nutrients, natural products, non-nutritive factors, or pharmacological agents. However, the vast majority of these experimental approaches elicited only minimal changes ($<10\%$) at best (Hargis 1988). In contrast, when 3-hydroxy-3-methylglutaryl-coenzyme A reductase inhibitors such as atorvastatin (Elkin et al. 1999), red yeast rice (Wang and Pan 2003; Wong et al. 2005a, b) or pharmacological amounts of copper (Pesti and Bakalli 1998) were orally administered to chickens, yolk cholesterol levels were significantly reduced.

Nutritional manipulation of the total quantity of fat, and its fatty acid profile (Wong 1997a; Wong and Engku Azahan 2004; Wong et al. 2004; Wong et al. 2006; Grashorn 2007; Hayat et al. 2009) in both eggs and meat is achievable but protein, amino acids, and most minerals are less amenable to manipulation through dietary modification. Another alternative is to modify the fat content by increasing the quantity of ω-3 in the chicken egg to produce ω-3 eggs for the health conscious consumer. Omega-3 eggs contain higher levels of ω-3 PUFA like docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) more commonly found in deep sea cold water fish or the terrestrial type ω-3, alpha-linolenic acid found in canola oil, soybean oil, flaxseed, walnut, spinach and mustard greens. Best (2007) has reported that 28 egg and egg products with ω-3 enrichment were launched worldwide in 2006.

Another nutrient is choline, found naturally in eggs and has been identified as contributing to fetal memory and brain development.

Locally, several egg companies market branded eggs to differentiate their products from others in the local market. Besides branding, several local egg producers have marketed designer eggs which include enriched ω-3 eggs, selenium, folate, vitamin E and lower cholesterol eggs. Generally, designer eggs are sold 30–50% more than the regular eggs. The higher cost is due to the higher feed cost, perception of health benefits from consuming these products, packaging, branding, marketing and promotion costs as well as better profit margin incentive for the producer and retailer (Wong 2005). The poultry industry is expected to continue to put emphasis on value-added production of egg products, and research on factors that influence the solids and internal content of an egg is needed. Eggs and meat with novel fats, proteins, antioxidants and functional nutrients can be expected to become more attractive for the health conscious consumers.

The egg as a functional food

The relationship between dietary fat and cardiovascular disease (CVD), which includes coronary heart disease (CHD), myocardial infarction (MI) and stroke, has been well established (Anon. 2005a). However, substantial scientific evidence has identified that the types of fat are more important than the total amounts of fat in determining CVD risk. The main dietary determinants of plasma cholesterol are saturated fat and trans-fat intake (Hu et al. 2001). Cholesterol in the blood comes from that which is made in the liver and that which is absorbed from dietary sources. In most instances, when dietary cholesterol intake increases, the body compensates by decreasing cholesterol production and when cholesterol intake decreases the reverse occurs. This compensatory mechanism is the predominant reason why changes in dietary cholesterol intake may have a limited effect on blood cholesterol levels (Hu et al. 2001).

Traditionally, eggs have not been regarded as a functional food (Wong 1999; Hasler 2000; Wong 2003) because of their perceived link with adverse effects on blood cholesterol. Eggs are also an excellent, inexpensive and low calorie source of high quality protein and several important nutrients, including riboflavin (15% Recommended Dietary Allowance [RDA]), selenium (17% RDA) and vitamin K (31% RDA) (Hasler 2000), and are currently under investigation for their beneficial effects on cognitive function. Choline is a nutrient naturally found in eggs, a nutrient for which a recommended daily intake level was only established in 1998 (Anon. 1998). Choline contributes to fetal memory and brain development; and is part of cellular compounds such as the neurotransmitter acetylcholine and lecithin, a naturally occurring emulsifier present in cell membranes and bile.

Is there a link between egg consumption and heart disease?

The trend in egg consumption in developed countries has seen a steady decline during the 70s and 80s, but since then it has remained constant or increased slightly. The factors causing a declining egg consumption in developed countries include cholesterophobia, changing consumer habits and lifestyle, competing foods in prime (breakfast) market, unimaginative marketing, Salmonella and Avian influenza scare.

Over the last 3 decades, there has been considerable debate on whether eggs in the diet contribute to high blood cholesterol levels and heart disease risk. Over this period, a large pool of data has accumulated showing that dietary cholesterol has only a small effect on plasma cholesterol levels and has little relationship to heart disease incidence.

A meta-analysis (Howell et al. 1997) of 224 published studies found that dietary cholesterol has only a small cholesterol-raising effect, while saturated fat was the major dietary determinant of the plasma cholesterol response (cholesterol-raising effect) to diet while dietary polyunsaturated fatty acids (PUFA) content had a cholesterol-lowering effect. These data were also substantiated by Clarke et al. (1997) in their meta-analysis of 395 metabolic ward studies.

A major US National Institutes of Health study (Hu et al. 1999) found no relationship between egg consumption and cardiovascular disease in a population of 37,851 men and 80,082 women followed over a period of 8–14 years. This study showed that there was no difference in incidences of nonfatal myocardial infarction, fatal coronary heart disease and stroke between those who consumed less than one egg a week and those who ate more than one egg a day. Results from this large epidemiological study clearly show that it is possible to eat an egg a day without increasing coronary heart disease (CHD) risk in healthy men and women. Prior to 1989, the American Heart Association (AHA) recommended consumption of not more than 3 eggs per week per person. From 1990 until October 2000, the AHA recommendation was not more than 4 eggs per week per person. Since October 2000, the AHA (Anon. 2000a) has changed this restriction and one egg daily is permitted provided that consumers can keep their remaining cholesterol intake below the 300 mg daily intake.

A comparison of per capita egg consumption patterns and rates of cardiovascular disease (CVD) mortality (Wong and Tan 2003) for males and females aged 35–74 years from the 22 developed Organization for Economic Co-operation and Development (OECD) countries in Europe, N. America, Japan, Australia and New Zealand using data published by the World Health Organization (WHO) (Tunstall-Pedoe et al. 2000) and per capita egg consumption data from the International Egg Commission (Anon. 2000d) are shown in *Figures 1–2*. Analysis of the relationship between per capita egg consumption and cardiovascular mortality rates in male and female populations for these countries indicates negative relationship. Weekly per capita egg consumption in France, the United States, United Kingdom and Ireland are 5.1, 4.5, 3.3 and 3.1 eggs per week whereas the male CVD mortality rates per 100,000 per year are 225, 401, 498 and 553 respectively. Japan has the lowest male CVD mortality rate (201 per 100,000) associated with the highest per capita egg consumption (6.5 eggs per person per week).

Strategies to consider in egg nutrient enrichment

When considering egg enrichment with nutrients (Surai et al. 2004), several factors need to be taken into account:

(a) Efficiency of nutrient transfer from feed to the egg
(b) Availability of commercial sources of effective feed forms of the nutrient
(c) Possible toxic effects of nutrients for the laying hens (Vitamin A and D are toxic for chickens at high levels)
(d) Amount of nutrient delivered with an egg in comparison with Recommended Dietary Allowance (RDA)

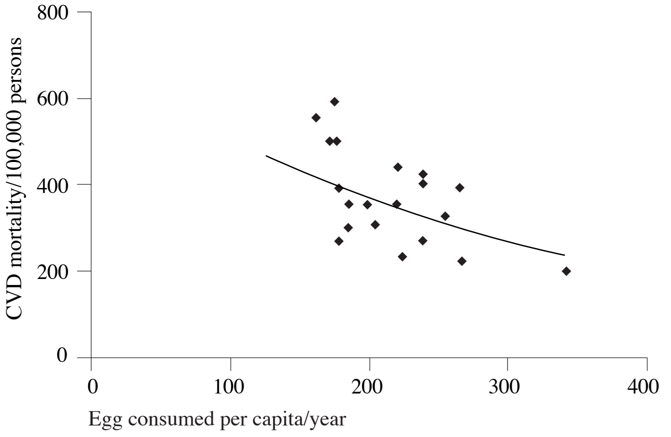


Figure 1. Comparison of egg consumption per capita and male CVD mortality per 100,000 persons in OECD countries
Source: Wong and Tan (2003)

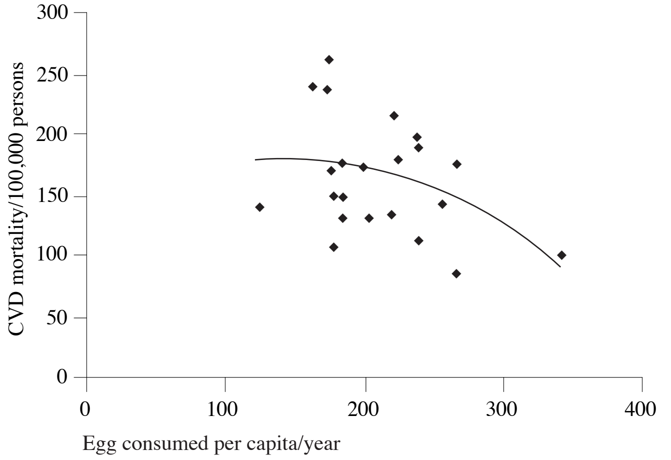


Figure 2. Comparison of egg consumption per capita and female CVD mortality per 100,000 persons in OECD countries
Source: Wong and Tan (2003)

(e) Established health promoting properties of nutrients and their shortage in a modern diet. (Justification for vitamin E inclusion is that it is an important component of antioxidant defenses, diets are deficient in this nutrient and consumption of high doses is beneficial)
(f) Possible interactions with assimilation of other nutrients from the egg
(g) Stability during cooking
(h) Effect of nutrient enrichment on appearance and taste (Vitamin E, carotenoids and selenium do not affect egg taste but help prevent fishy taste in ω-3 eggs)
(i) Possibilities to claim health benefits

Designer meat products

Poultry meat can be enriched with ω-3 fatty acids and selenium in a way that 100 g of enriched tissue meets 70–130% and 30–60% of the recommended daily intake for humans respectively (Grashorn 2007). Some studies have shown that conjugated linoleic acids (CLA) can reduce the risk of certain cancer problems as well as associated heart conditions (Dhiman 2000). However, the occurrence of tough meat due to conjugated linoleic acid enrichment and an increased susceptibility to oxidation for ω-3 fatty acids enriched meat may reduce the use of functional poultry meat. Givens and Gibbs (2006) has suggested that enrichment of meat products with ω-3 and its addition to animal feed to boost levels in animal-derived produce could play a major role bridging the gap between recommended and actual intake in human diets. With ω-3 enrichment, poultry meat could contribute to dietary intake of about 75.0 mg ω-3 per person per day. Best (2007) has reported that 24 poultry meat products with ω-3 enrichment were launched worldwide in 2006.

Omega-3 polyunsaturated fatty acids

Role in human health

Pioneering research in the 1970s by Danish scientists (Dyerberg et al. 1974) showed that Eskimos who consumed lots of seafood had reduced incidences of cardiovascular disorders. The Japanese population (who also consumed plenty of fish) had a sixfold lower incidence of atherosclerosis and heart disease than do Americans. In both Eskimos and Japanese, the ω-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) content of plasma and platelets and tissue phospholipids are significantly increased while the ω-6 fatty acids arachidonic acid is decreased (Kinsella et al. 1990; Simopoulos 1991). Fatty fish (deep, cold water fish) like salmon, mackerel, herring and bluefish are rich sources of ω-3 fatty acids as the fish gets it from the marine algae which are rich in ω-3 fatty acids.

Although ω-3 PUFA have been known to be nutritionally important as early as the 1930s (Burr and Burr 1930), it was not until the 1980s when Holman et al. (1982) demonstrated its importance in human nutrition. Since then, an extensive body of literature has been published over the last three decades on the mode of action and the health benefits of foods rich in polyunsaturated fats and in particular ω-3 fats. Extensive evidence suggests that foods rich in ω-3 PUFA such as cold water fatty fish or fish-oil supplements have also been associated with reduced risk for all-cause mortality, cardiac and sudden death, and stroke (Leaf and Weber 1988; Keli et al. 1994; Wang et al. 2006; Mozaffarian 2008). An increased intake of ω-3 fats is now known to protect against some inflammatory diseases and certain autoimmune disorders. Researchers have also reported an inverse relationship between human blood levels of marine ω-3 fatty acids and the rate of telomere shortening over 5 years (Farzaneh-Far et al. 2010) and these findings raise the possibility that ω-3 fatty acids may slow cellular aging in patients with coronary heart disease. In addition, ω-3 fats play a major role in infant growth and development and have been implicated in many other protective roles (Simopoulos 1991). The absolute amounts of PUFA in the diet are important to human health and the balance between the ω-6 and ω-3 is crucial.

Requirements for essential fatty acids

The fat component in our diet is made up of saturated, monounsaturated and PUFA. The human body can make many fatty acids, but it cannot make linoleic acid, an ω-6 fatty acid and alpha-linolenic acid (LNA), an ω-3 fatty acid (*Figures 3–4*). They are therefore considered essential fatty acids because they are indispensable to body function and they must be supplied by the diet. The ω-3 fatty acids are LNA and its derivatives from metabolism: the long chain (LC) eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). The "3" in ω-3 fatty acids (Holman 1998) denotes that the first double bond is located at the third carbon from the methyl end of the hydrocarbon chain (*Figures 3–4*).

In plants, PUFA are derived from saturated fatty acids (SFA). The SFA are progressively desaturated to form monosaturated fatty acid, oleic acid [18:1(ω-9)] and the PUFA, linoleic acid (18:2 ω-6) and alpha-linolenic acid (18:3 ω-3). The PUFA biosynthetic pathway occurs in virtually all plant cells, hence, ω-6 and ω-3 fatty acids are present in varying proportions in leaves, seeds and oil, and from there, they are incorporated into the human diet.

LNA can be found in vegetable seed oils like flaxseed, canola, soybean and walnuts, spinach and mustard greens. EPA and DHA are found in cold water fish like salmon, mackerel, herring, bluefish, trout, sardines and anchovies and human milk.

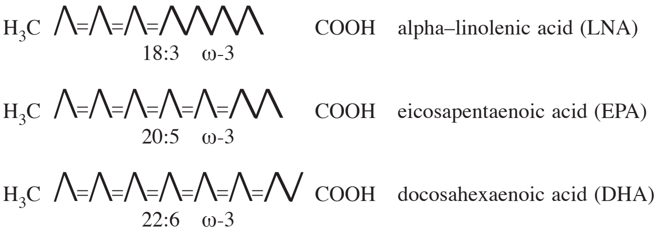


Figure 3. Alpha-Linolenic acid (ω-3) family

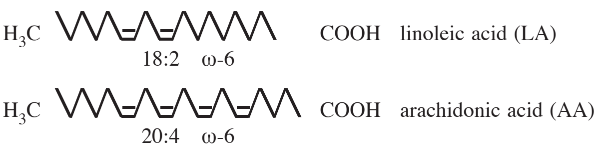


Figure 4. Linoleic acid (ω-6) family

Omega-6 fatty acids consist of linoleic and arachidonic (*Figure 5*). Linoleic acid is found in most vegetables and vegetable oils (corn oil, soybean oil, sunflower oil, cottonseed oil, safflower oil) while arachidonic acid is only found in meats.

LNA (18:3 ω-3) is the major ω-3 fatty acid in the human diet. It has long been thought that its major biochemical role (*Figure 5*) is as the principal precursor for LC PUFA, of which eicosapentaenoic (20:5 ω-3) and docosahexaenoic acid (22:6 ω-3) are the most prevalent. Omega-3's and ω-6's compete for control of important biochemical reactions in our bodies by competing for the desaturases enzymes (Kinsella et al. 1990). These essential fatty acids (EFA) are precursors of the hormone-like eicosanoids (*Figure 6*) like prostaglandins, leukotrienes and thromboxanes that participate in the regulation of heart pressure, heart rate, vascular dilation, blood clotting, immune response, lipolysis and the central nervous system.

When ω-6's dominate, it can lead to overproduction of hormone-like substances called prostaglandins and leukotrienes (*Figure 6*) which in large amounts can disrupt the immune system, initiate the build-up of plaque formations on artery walls, form blood clots and trigger irregular heart rhythms. Findings have also indicated that ω-3 PUFA play an essential role in growth and development of brain and retinal tissue in the newborn infant (Nettleton 1993). DHA is the principal ω-3 fatty acid in tissues and is particularly abundant in neural and retinal tissue (Arterburn et al. 2006).

A large proportion of dietary LNA is oxidized and studies generally show that whole body conversion of 18:3 ω-3 to 22:6 ω-3 is below 5% in humans, and depends on the concentration of ω-6 fatty acids and LC PUFA in the diet (Brenna 2002). Much of the remaining 18:3 ω-3 serves as a source of acetate for synthesis of saturates and monounsaturates, with limited storage of the ω-3 fatty acids in adipose tissue suggesting

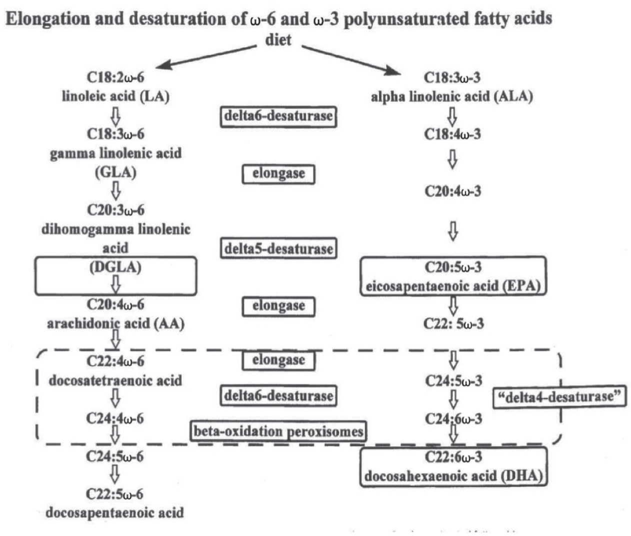


Figure 5. Elongation and desaturation of ω-6 and ω-3 polyunsaturated fatty acids
Source: Simopoulos (2008)

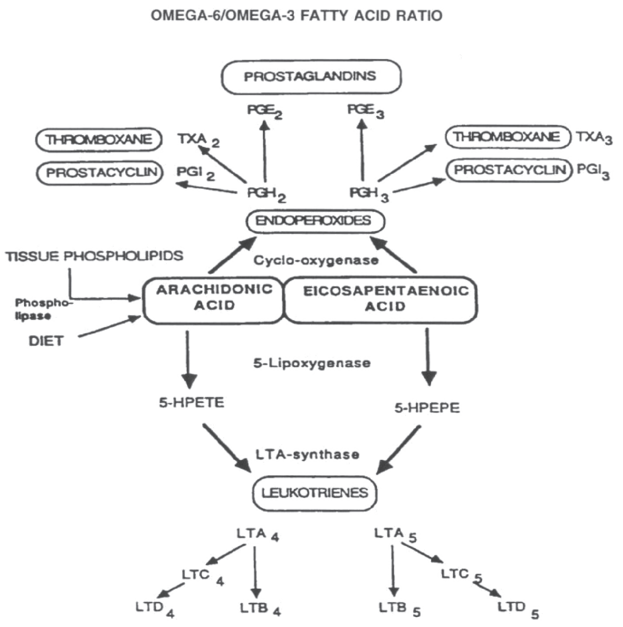


Figure 6. Oxidative metabolism of arachidonic acid and eicosapentaenoic acid by the cyclooxygenase and 5-lipoxygenase pathways (Source: Simopoulos 2008)

that a continued dietary supply is needed. Generally, consumers do not get enough ω-3 fatty acids in their diets as the typical diet is overloaded with ω-6 fatty acids. Currently the ratio of ω-6:ω-3 in Western diets is about 10:1 to 30:1 which researchers say are too unbalanced and should be reduced further to 5:1 to 6:1.

Metabolism of polyunsaturated acids

The oxidative metabolism (*Figure 6*) of arachidonic acid (ω-6) and eicosapentaenoic acid (ω-3) by the cyclooxygenase and 5-lipoxygenase pathways gives rise to precursors of the hormone-like prostaglandins, leukotrienes and thromboxanes. Some of the effects of ingestion of ω-3 (EPA and DHA) from fish or fish oil are as follows:

- Decreased production of prostaglandin E2 (PGE2) metabolites
- A decrease in thromboxane A2, a potent platelet aggregator and vasoconstrictor
- A decrease in leukotriene B4 formation, an inducer of inflammation, and a powerful inducer of leukocyte chemotaxis and adherence
- An increase in thromboxane A3, a weak platelet aggregator and weak vasoconstrictor
- An increase in prostacyclin PGI3, leading to an overall increase in total prostacyclin by increasing PGI3 without a decrease in PGI2, both PGI2 and PGI3 are active vasodilators and inhibitors of platelet aggregation
- An increase in leukotriene B5, a weak inducer of inflammation and a weak chemotactic agent

Diseases associated with inadequate ω-3 consumption

The diseases associated with inadequate dietary ω-3 PUFA as summarized by Simopoulos (1991) are as follows. The imbalance of dietary ω-6:ω-3 can cause:

- atherosclerosis (hardening and narrowing of arteries due to deposits in arterial walls)
- thrombosis (blood clot within heart/blood vessels impeding blood flow)
- arrhythmia (irregular heartbeats)
- hypertension (elevated blood pressure)
- rheumatoid arthritis (degenerative disease of joints)
- visual acuity reduced (impaired vision)
- brain development affected (learning difficulties)
- cancer (breast, colon, pancreas, prostate)
- atopic dermatitis, lupus, psoriasis, migrane, multiple sclerosis
- bronchial asthma, diabetes mellitus and ulcerative colitis

a) Prevention of coronary heart disease

A comparison of fatty acid composition of human plasma total lipids reported by Sugano and Hirahara (2000) showed that ω-6:ω-3 ratios were 2.73 and 3.83 respectively for rural and urban Japanese. By comparison, Japanese Americans and White Americans had ω-6:ω-3 ratios of 11.8 and 16.3 respectively. In both Eskimos and Japanese, the PUFA, EPA and DHA contents in the blood plasma were significantly higher. Dietary ω-3 fatty acids have also been reported to inhibit synthesis of LDL-cholesterol in humans (Illingworth et al. 1984), widely reported to reduce blood triglycerides in humans (Kinsella et al. 1990; Simopoulos 1991) and lower blood pressure in a meta-analysis of 31 studies (Morris et al. 1993).

Siscovick et al. (1995) have reported that a diet high in fish reduced the risk for cardiac arrest by about 50–70% and the reduced risk for cardiac arrest strongly correlated with the amounts of EPA and DHA and this was confirmed by Simon et al. (1995) who reported that serum ω-3 fatty acids was correlated with reduced risk for coronary heart disease. De Lorgeril et al. (1994) showed that eating ω-3 PUFA that are found in fish, rapeseed and soybean oil prevent second heart attacks and a likely explanation is that the ω-3 PUFA prevent clotting and oxidation of LDL cholesterol.

Albert et al. (2002) have observed that men who have higher blood levels of ω-3 fatty acids due to fish consumption, or dietary supplementation with ω-3 fatty acids, have a reduced risk of sudden death due to the antiarrhythmic properties of ω-3 PUFA. This was also supported by Hu et al. (2002) who reported that among women, higher consumption of fish and ω-3 fatty acids is associated with a lower risk of CHD, particularly CHD deaths.

Marchioli et al. (2002) also reported beneficial early effect of low-dose (1 g/d) ω-3 PUFA in reducing total mortality and sudden death in heart patients. The American Heart Association (AHA) guidelines (Anon. 2000a) recommends that adults consume two servings a week of fatty fish, such as canned or fresh tuna, salmon or sardines, because they contain ω-3 fatty acids which experts believe can protect the heart by preventing blood clots and arrhythmia, or irregular heartbeat.

Breslow (2006) concluded that the results of several prospective cohort studies indicate that consuming fish or fish oil containing the ω-3 fatty acids EPA and DHA is associated with decreased cardiovascular death, whereas consumption of the vegetable oil–derived ω-3 fatty acid LNA is not as effective. Randomized control trials in the context of secondary prevention also indicate that the consumption of EPA plus DHA is protective at doses <1 g/d (Breslow 2006). The therapeutic effect appears to be due to suppression of fatal arrhythmias rather than stabilization of atherosclerotic plaques. At doses >3 g/d, EPA plus DHA can improve cardiovascular disease risk factors, including decreasing plasma triacylglycerols, blood pressure, platelet aggregation, and inflammation, while improving vascular reactivity.

b) Infant development, reduction of cancer and inflammatory disease

Omega-3 fatty acid supplements were reported to relieve tender joints and reduce morning stiffness in patients with rheumatoid arthritis, the most common systemic inflammatory rheumatic disease (Simopoulos 1991; Kremer 2000). These supplements affect reproducible alterations in eicosanoid metabolism that aid in amelioration of inflammation (Kremer 2000).

Dietary ω-3 fatty acids have also been extensively reported to be associated with lower colon cancer risk (Caygill and Hill 1995; Bartsch et al. 1999; Biasco and Paganelli 1999). Geelen et al. (2007) have also concluded that fish consumption, and ω-3 fatty acid intake, inhibits colorectal carcinogenesis and reduces colorectal cancer risk, particularly if the intake is relatively large. More recently, Murff et al. (2009) reported that dietary PUFA and the ratio of n-6 to ω-3 PUFA intake may be positively associated with colorectal cancer risk in women, and this association may be mediated in part through PGE_2 production. Several other studies have also reported that dietary ω-3 fatty acids can reduce incidences of breast cancer (Caygill and Hill 1995; Rose 1997; Bartsch et al. 1999; Maillard et al. 2002). Dietary LC ω-3 PUFA is protective for aggressive prostate cancer, and this potential effect may be modified by genetic variation in *cyclooxygenase-2* (*COX-2*), a key enzyme in fatty acid metabolism and inflammation (Fradet et al. 2009).

Omega-3 fatty acids also play an essential role in the growth and development of brain and eye tissue in the foetus and newborn infant (Nettleton 1993; Makrides et al. 1995). Supplementation of infant formula with DHA may be important for the development of childhood intelligence (Willats et al. 1998).

c) Prevention of psychiatric disorders

Freeman (2000) has observed that the ω-3 fatty acids may prove to be efficacious in a number of psychiatric disorders. Mood disorders (Cott and Hibbeln 2001) have been associated with abnormalities in fatty acid composition and diminished ω-3 fatty acid concentrations. Omega-3 fatty acids may also be helpful in the treatment of dementia. Furthermore, ω-3 fatty acids may prove to be a safe and efficacious treatment for psychiatric disorders during pregnancy and breastfeeding. Omega-3 fatty acids are essential dietary lipids that share biochemical actions with lithium and divalproex, two known mood stabilizers that are effective for bipolar disorder. Stoll et al. (1999)

showed that ω-3 fatty acids improved the short-term course of illness in patients with bipolar disorder.

Tanskanen et al. (2001) studied data on fish consumption, depression and suicides among a general population in Finland, and found a decreased risk of suicide among subjects with daily fish consumption compared with non-daily consumption. These results are also consistent with a study (Hirayama 1990) of 265,000 Japanese subjects followed for 17 years, which reported a decreased risk of suicide among subjects with daily fish consumption compared with non-daily consumption. As fish is the major source of ω-3 fatty acids in the human diet, the frequent consumption of fish could lead to a high intake of ω-3 PUFAs, thus decreasing the risk of depression.

A report by Schaefer et al. (2006) from the Framingham Heart Study showed that persons with plasma phosphatidylcholine DHA in the top quartile of values had a significantly (47%) lower risk of developing all-cause dementia than did those in the bottom quartile and greater protection was obtained from consuming 2.9 fish meals per week than from consuming 1.3 fish meals per week. In the Zutphen Elderly Study (van Gelder et al. 2007), fish consumers with a DHA + EPA intake of about 380 mg/d seemed to have less cognitive decline. This amount of DHA + EPA can be obtained from two to three meals of fish per week. The Minneapolis study by Beydoun et al. (2007) also showed that cognitive decline was associated with lower plasma ω-3 fatty acids (DHA +EPA) in the subgroup of subjects with hypertension and dyslipidemia. In each of these studies, the ω-3 fatty acids retarded the decline in cognition over time. One mechanism for the positive effect could be the antithrombotic and antiinflammatory properties of EPA (Blok et al. 1996). The entry of DHA into the brain could correct DHA deficiency in membrane phospholipids in the cerebral cortex in patients with Alzheimer disease and EPA would counter the proinflammatory action of arachidonic acid, which is a precursor of cytokine and proinflammatory eicosanoids that may be associated with greater cognitive decline. The possibility that the ω-3 fatty acids DHA and EPA in fish and fish oil may delay the ravages of Alzheimer disease is thus of great interest. Studies by Albanese et al. (2009) on populations in low and middle-income countries also showed the benefits of fish consumption and the neuroprotective actions of ω-3 PUFA with reduced risk for dementia.

General consensus on the benefits of ω-3 PUFA

Based on current knowledge for which a general consensus exists (Deckelbaum et al. 2008*)*, the benefits of ω-3 PUFA are as follows:

- Pregnancy
  - High fish oil consumption is associated with an increase in gestational length and may reduce the rates of postpartum depression and women are recommended to have 100–300 mg DHA per day

- Infants
  - Current intake levels of DHA:AA (1.4:1 to 2:1) are beneficial for the visual and cognitive development of infants

- Cardiovascular disease
  - Reduced overall mortality after onset of cardiovascular disease
  - Reduced sudden death and arrhythmias, primarily in secondary prevention trials
  - Reduced blood triacylglycerol concentrations with higher doses
  - Limited effect associated with increased ALA

- Mental health
  - EPA plus DHA appear to have better efficacy than either alone
  - ω-3 fatty acids are likely to improve psychotic, depressive, and aggressive symptoms in severe patients

- Aging, dementia and macular degeneration
  - Increased fish and DHA intake are protective against cognitive decline
  - Fish consumption and DHA are associated with a reduced risk of developing Alzheimer disease
  - DHA may improve mental function and reduce aggression in patients with dementia
  - Consuming fish and low linoleic acid is associated with reduced risk of age-related macular degeneration

- Metabolic syndrome
  - To improve insulin sensitivity, ω-3 fatty acids are more useful in prevention than in treatment
  - EPA plus DHA effectively lowers blood triacylglycerol concentrations
  - High doses tend to decrease small, dense LDL concentrations and may improve insulin sensitivity

- Inflammatory and immune response
  - For rheumatoid arthritis, there is a proven therapeutic benefit of EPA plus DHA. All studies that monitored use of nonsteroidal antiinflammatory agents reported a significant reduction in use, and ω-3 fatty acids reduce requirements for corticosteroids
  - Although evidence is weaker for treatment of Crohn disease and psoriasis, ω-3 fatty acids prolong remission in Crohn disease and reduce the requirement for corticosteroids in both conditions

Daily recommended values for omega-3 fatty acids

Dietary recommendations (Gebauer et al. 2006) have been made for ω-3 fatty acids, including LNA, EPA and DHA to achieve nutrient adequacy and to prevent and treat cardiovascular disease. The ω-3 fatty acid recommendation to achieve nutritional adequacy is 0.6–1.2% of energy for LNA; up to 10% of this can be provided by EPA or DHA. A dietary level of 500 mg/d of EPA and DHA is recommended for cardiovascular disease risk reduction (Gebauer et al. 2006) and for treatment of existing cardiovascular disease, 1 g/d is recommended and these recommendations have been embraced by many health agencies worldwide.

Table 1 shows the established daily recommended values for ω-3 fatty acids in humans by several health and nutrition authorities from several countries.

Sources of omega-3

Omega-3 fatty acids are known to be essential for growth and development, and have been positively associated with health and the prevention and treatment of heart disease, arthritis, inflammatory and autoimmune diseases and cancer (Simopoulos 1999a). Accordingly, there are now dietary recommendations and guidelines for ω-3 fatty acid intakes (*Table 1*). To consume two servings of fish per week or to ingest fish oil to get sufficient EPA/DHA raise persistent questions about the sustainability of global fisheries. World captures fisheries production has declined since 1989 (Anon. 2007)

Table 1. International recommendations for long-chain ω-3 fatty acids

Source	Recommendation			n-6:n-3
	Total n-3 % of energy	LNA g	EPA + DHA (mg)	
NATO workshop (Simopoulos 1989)	–	3	800	4:1
UK Committee on Medical Aspects of Food Policy (Anon. 1994a)	0.2	–	100–200	–
ISSFAL workshop (Simopoulos et al. 1999)	1	2.2	650	–
ANC (France) (Martin 2001)	0.8–1	1.8	450 (DHA, 110–120)	5:1
Eurodiet (Anon. 2006b)	–	2	200	–
Health Council of the Netherlands (Anon. 2001)	1	–	200	7.5:1
American Heart Association (Kris-Etherton et al. 2002)	–	–	≥1 g/d (2° prev CHD)	–
US National Academics of Science, Institute of Medicine (Anon. 2002)	–	1.4	≥140	–
European Society of Cardiology (Van de Werf et al. 2003)	–	–	≥1 g/d (2° prev CHD)	–
WHO/FAO (Anon. 2003)	1–2	–	400–1000 (1–2 fish meals/wk)	–
ISSFAL (Anon. 2004a)	–	1.6	≥500	
UK Scientific Advisory Committee on Nutrition (Anon. 2004)	–	–	Minimum 2 portions fish/wk (1 oily); assumes 450 mg	
Ministry of Health and Welfare, Japan (Anon. 1994b)				4:1

ANC = Apports Nutritionnels Conseilles; FAO = Food and Agriculture Organization;
ISSFAL = International Society for the Study of Fatty Acids and Lipids;
NATO = North Atlantic Treaty Organization; WHO = World Health Organization

and are not expected to increase production to meet the increasing seafood demand of a growing human population. Based on current exploitation trends, some scientists have predicted a collapse of all species of non-farmed seafood that are currently fished by the year 2050 (Worm et al. 2006). The major commercial use of fish oil is for aquaculture where 87% of the world's fish oil is used in fish feed (Pike 2005). Only 6% is used for human consumption and the rest is used in animal feed (6%). Thus substitution of the marine long chain ω-3 EPA/DHA from terrestrial sources could alleviate some of the commercial pressures on fish oil and problems associated with over-fishing. Ursin (2003) has demonstrated the feasibility of genetic modification of canola seeds to accumulate the ω-3 fatty acid, stearidonic acid (SDA).

Land-based ω-3 fatty acids represent a sustainable source of ω-3 fatty acids that can be produced on large acreages and delivered to consumers in a wide variety of functional foods. And unlike alpha-linolenic acid, SDA can provide a more efficient conversion to EPA at moderate dietary intakes. The SDA-enriched foods could become a valuable tool for delivering recommended levels of ω-3 fatty acids to large portions of the population. Research focus to increase EPA/DHA in eggs and meat from livestock fed terrestrial ω-3 (LNA) would thus be highly desirable. Researchers are also focusing on developing genetically modified oilseeds that are high in DHA ω-3 fatty acids (Filmer 2006). Generating ω-3 acids from land plants would provide more sources that would increase ω-3 in human diets, reduce reliance on depleting ocean fish stocks and serve as feed source for aquaculture.

Omega-3 PUFA in poultry production

Modification of fatty acid profile in eggs

The fatty acid composition of hen egg yolk can be modified through alterations in the diet. Feeding with sources rich in long-chain (LC) or short chain (SC) ω-3-fatty acids increases the content of these fatty acids in egg yolk (Wong 1997a). Omega-3 enriched eggs can either contain higher levels of the marine type ω-3 PUFA, DHA and EPA which are more commonly found in deep sea cold water fish (such as salmon, mackerel, herring, tuna, bluefish and anchovies), fish oil and marine algae *Schizochytrium* sp. or the terrestrial type ω-3 PUFA, LNA found in canola oil, soybean oil, flaxseed, walnut, spinach and mustard greens (Wong 1997a, b). The total fat content of the ω-3 eggs and the cholesterol level may be less or quite similar to regular eggs.

The saturated fatty acid content of the SC type ω-3 was lower and the PUFA was higher than the regular eggs (*Figure 7*). By comparison there was no significant difference in fatty acid composition between the LC type ω-3 eggs and the control. The egg weights of the LC ω-3 enriched eggs were significantly smaller by 3% than the regular eggs and the decrease in egg size may be related to the effect of nutritional (LC fatty acids) regulation of hormonal metabolism (estrogen activity) in the hen as suggested by Whitehead et al. (1993). Increasing the PUFA content of the ω-3 egg makes it more susceptible to oxidation and vitamin E is generally used to stabilised egg lipids against rancidity and extend the shelf life of the product.

The incorporation of ω-3 PUFA into eggs has been used by scientists to alter ω-6:ω-3 ratio towards the desired dietary ratio. Sources of ω-3 PUFA such as fish oils

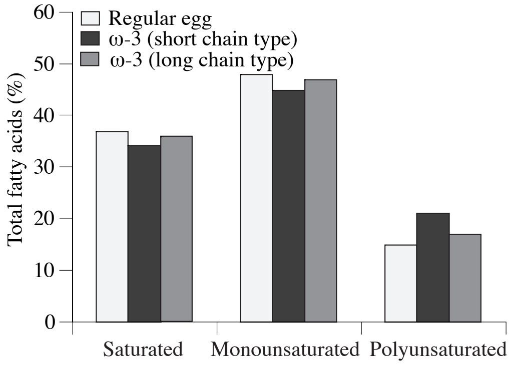


Figure 7. Fatty acid content (%) of total fatty acids in regular and omega-3 eggs
Source: Wong (1997a)

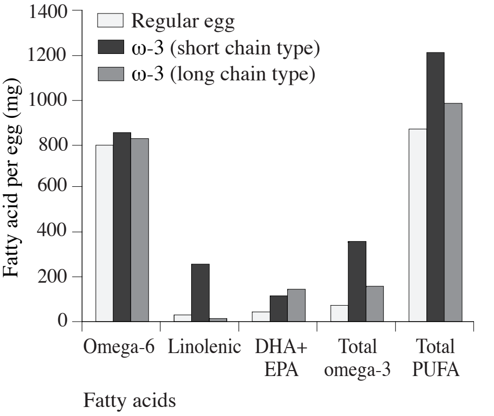


Figure 8. Polyunsaturated fatty acids content in regular and omega-3 eggs
Source: Wong (1997a)

(Shimizu et al. 2001), fish meal (Nash et al. 1995, 1996), marine algae (Herber and Van Elswyk 1996) or a combination of several of the above (Baucells et al. 2000) can be used as supplements in layer diets. However, supplementation with fishmeal or fish oil can exert a negative influence on the sensory properties of the egg (Nash et al. 1996). Supplementation with ω-3 from plant sources results in much lower concentrations of LC ω-3 in the egg (Wong 1997a) as this is due to oxidation of the LNA and low conversion of LNA to DHA (Brenna 2002).

The two major types of ω-3 eggs sold are either the SC ω-3 type eggs predominantly with the terrestrial LNA and the LC ω-3 type eggs predominantly with the marine DHA and EPA (*Figure 8*). For the production over an 8-week period for ω-3 eggs, feed conversion ratio and ME intake required to produce per kg egg by the ω-3 egg production system is as efficient as the conventional egg production system (Wong 1997a). The SC and LC ω-3 type eggs contain 5 and 3 times more ω-3 respectively than the regular egg which has a total of 65 mg ω-3 fatty acids per egg. The ratio of ω-6:ω-3 is 12.1:1, 2.3:1 and 5.1:1 respectively for the regular, SC and LC type ω-3 (Wong 1997a). LNA made up more than 60% of ω-3 content in the SC type ω-3 eggs. In the LC type ω-3 eggs, more than 90% of the ω-3 content is DHA and EPA. By comparison, Jia et al. (2008) have reported ω-3 content of 562 mg per 60 g egg which is very high, but the DHA content level is 91.8 mg per egg.

Other researchers (Bautista-Ortega et al. 2009) have found that modulating egg yolk ω-3 content of breeder hens can enhance chick tissue ω-3 FA and reduce proinflammatory cardiac eicosanoid production without affecting hatchability. Jia et al. (2008) reported that ω-3 enriched eggs can also be produced from canola seed and long-term feeding of flaxseed to laying hens resulted in reduced egg production and eggshell quality. This problem was alleviated with the multi-carbohydrase enzyme which had positive effects on feed utilization, eggshell quality, and ω-3 fatty acid deposition in the egg.

Many health agencies (*Table 1*) worldwide have recommended that consumers get their ω-3 LC-PUFA directly from food especially from marine fish. Although marine fish contain higher levels of LC ω-3 PUFA than ω-3 enriched eggs, their bio-availability is inferior, for they are attached to triglycerides, whilst in ω-3 eggs, the LC ω-3 PUFA are exclusively associated with phospholipids (Megremis 1991). Absorption in the intestine of LC triglycerides from fish is difficult owing to their tendency to form undispersed globules which are difficult to digest. Furthermore, the physiological benefits of ω-3 LC-PUFA from fish may also be impaired through their partial presence at position sn-2 of triglycerides (insensitive to pancreatic 1,3-lipase), their absorption as monoglycerides and their dilution in the adipose tissue (Megremis 1991). In contrast, ω-3 LC-PUFA from eggs are exclusively present at position sn-2 of highly dispersed phospholipids and are thus efficiently released as free fatty acids in the gut by pancreatic 2-phospholipase.

Sensory and storage evaluation

In sensory evaluations, the taste, colour and texture of the ω-3 enriched eggs and regular eggs showed no significant differences in acceptability (Wong 1997a). A weak oily or fishy taste of the eggs were noted in eggs with higher content of LC ω-3 PUFA. Due to supplementation with vitamin E, there were no significant differences between ω-3 PUFA eggs and regular eggs in rancidity parameters (Wong 1997a; Hayat et al. 2009). The qualities of the ω-3 enriched eggs and regular eggs when stored at room temperature or when refrigerated over a 4 week period were also similar. Antioxidants such as vitamin E are added to poultry diets to prevent oxidative destruction of dietary fats and to provide protection for the longer chain PUFA.

Modification of fatty acid profile in poultry meat

Consumer awareness of the health benefits of ω-3 fatty acids is also driving demand for enriched meat with ω-3 fatty acids and this provides an opportunity for the broiler production sector to add value to their product, but enrichment can increase the cost of production. Zuidhof et al. (2009) have suggested that feeding flaxseed for 24 days before processing gave optimal breast meat ω-3 enrichment, carcass weight and meat yield. The LNA was mainly deposited in the tria-cylglycerol (TAG) fraction of both breast and thigh meat (Betti et al. 2009a) and although a significant increase of ω-3 long-chain PUFA was found in the phospholipid and TAG fraction of both tissues, its concentration was low as more than 95% of ω-3 PUFA enrichment was due to LNA.

Human consumption of long-chain ω-3 PUFA (LC ω-3 PUFA) is below recommendations, and enriching chicken meat (by incorporating LC ω-3 PUFA into broiler diets) is a practical means of increasing consumption. Fish oil is the most common LC ω-3 PUFA supplement used but due to over-fishing and depletion of fish stock, this process is unsustainable. Use of fish oil in animal feeding also reduces the oxidative stability of the meat. Rymer et al. (2010) have reported that algal biomass is as effective as fish oil at enriching broiler diets with fish oil with significant difference on the oxidative stability of the meat produced. The concentrations (mg/100 g of meat) of ω-3 PUFA; C20:5 ω-3, C22:5 ω-3, and C22:6 ω-3 were respectively for the control: 4, 15, 24; fresh fish oil: 31, 46, 129; and high algal biomass: 9, 14, 187 in chicken breast meat. These results show that total ω-3 increased by 4.8 and 4.9 times respectively with fish oil and algal supplementation. Betti et al. (2009b) reported that the duration of feeding flaxseed negatively affected the colour characteristics, functional properties, and oxidative stability of broiler meat and suggested a restriction on the duration of feeding to alleviate the problem.

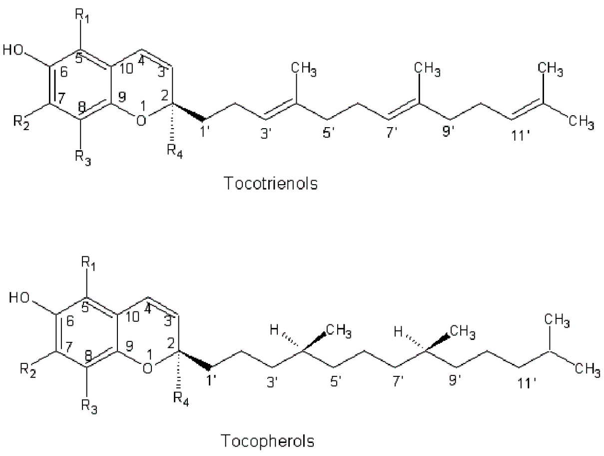
Vitamin E

Role in human health

Vitamin E is a collective term for eight naturally occurring compounds, four tocopherols alpha (α), beta (β), gamma (γ) and delta (δ) and four tocotrienols (α, β, γ and δ), that can exhibit the biological activities of α-tocopherol (*Figure 9*; Theriault et al. 1999). Both structures are similar except that the tocotrienol structure has double bonds on the isoprenoid units. However, these eight isomers of vitamin E are not interconvertible in humans. The α-tocopherol is higher in wheat germ oil, almond and sunflower oil while γ-tocopherol is the major form of vitamin E in corn oil and soybean oil (McLaughlin and Weihrauch 1979). By comparison, tocotrienol content is high in rice bran, barley, oats and palm oil (Tan 2005).

Antioxidant function

Vitamin E's function as an antioxidant is dependent upon its ability to break radical-propagated chain reactions. As a result, the formation of the tocopheroxyl radical, the odd-electron derivative of vitamin E, is an inherent part of any vitamin E based, antioxidative reaction (Ingold et al. 1987). As the principle, lipid-soluble antioxidant in biological membranes, α-tocopherol reacts with many oxidant molecules. In turn, α-tocopherol helps protect cell membranes from lipid peroxidation by trapping peroxyl radicals (Burton and Ingold 1986). It involves the abstraction of a hydrogen atom from the OH group of the tocopherol by a peroxyl (oxidant) molecule. Upon the formation of the tocopheroxyl radical from a reaction between α-tocopherol and an oxidant molecule, α-Toc• is now free to interact with another peroxyl radical [α-Toc• + LOO• LOO-Toc] (Burton and Ingold 1986). The reaction [LOO• + α-TocH LOOH + α-Toc•] produces a stable tocopheroxyl radical, which does not propagate radical chains and lipid



Isomer	R1	R2	R3	R4
α-Tocotrienol/Tocopherol	CH3	CH3	CH3	CH3
β-Tocotrienol/Tocopherol	CH3	H	CH3	CH3
γ-Tocotrienol/Tocopherol	H	CH3	CH3	CH3
δ-Tocotrienol/Tocopherol	H	H	CH3	CH3

Figure 9. Molecular structure of tocotrienol and tocopherol isomers

hydroperoxides. Furthermore, α-tocopherol can be regenerated from the tocopheroxyl radical by an electron donor, like ascorbic acid, and is thereby able to maintain cellular antioxidant protection over a period of time. This synergistic reaction between vitamin C and α-tocopherol has led researchers to investigate the possibility of enhancing vitamin E antioxidant function by incorporating the use of vitamin C.

Vitamin E: Recommended Dietary Allowance (RDA)

The RDA as recommended by the US Institute of Medicine (Anon. 2000c) is 15 mg for adults and this RDA level is based on the prevention of deficiency symptoms rather than on health promotion and prevention of chronic disease. In fact, it has been estimated that more than 90% of Americans do not meet daily dietary recommendations for vitamin E (Maras et al. 2004). Few side effects have been noted in adults taking supplements of less than 2,000 mg of α-tocopherol daily. The tolerable upper intake level for α-tocopherol supplements is 1,000 mg/day of α-tocopherol for adults (Anon. 2000c).

Disease prevention

The main function of α-tocopherol in humans appears to be that of an antioxidant. Free radicals are formed primarily in the body during normal metabolism and also upon exposure to environmental factors, such as cigarette smoke or pollutants. Fats, which are an integral part of all cell membranes, are vulnerable to destruction through oxidation by free radicals. The fat-soluble vitamin, α-tocopherol, is uniquely suited to intercept free radicals and thus prevent a chain reaction of lipid destruction (Traber 2006). Aside from maintaining the integrity of cell membranes throughout the body, α-tocopherol also protects the fats in low density lipoproteins (LDLs) from oxidation. LDLs specifically transport cholesterol from the liver to the tissues of the body and oxidized LDLs have been implicated in the development of cardiovascular diseases. When a molecule of α-tocopherol neutralizes a free radical, it is altered in such a way that its antioxidant capacity is lost (Traber 2006). However, other antioxidants, such as vitamin C, are capable of regenerating the antioxidant capacity of α-tocopherol.

Results from several large observational studies suggest that increased vitamin E consumption is associated with decreased risk of myocardial infarction (heart attack) or death from heart disease in both men and women (Rimm et al. 1993; Stampfer et al. 1993). Supplemental vitamin E intake was also associated with a significantly decreased risk of vascular and other types of dementia (Masaki et al. 2000). Among those without dementia, vitamin E supplement use was associated with better scores on cognitive tests. Although these findings are promising, further studies are required to determine the role of α-tocopherol supplementation in the treatment of Alzheimer's disease and other types of dementia. Vittamin E also helps to improve insulin sensitivity, thus delaying the onset of type 2 diabetes in adults at high risk (Manning et al. 2004).

Research evidence has indicated that vitamin E has anticarcinogenic properties for gastrointestinal cancers. Stolzenberg-Solomon et al. (2009) reported that higher α-tocopherol concentrations may play a protective role in pancreatic carcinogenesis in male smokers. Weinstein et al. (2007) reported that higher prediagnostic serum concentrations of α-tocopherol was associated with lower risk of developing prostate cancer particularly advanced prostate cancer. Most health and dietary research has focused on the potential health effects of α-tocopherol because of its abundance in nature and potent antioxidant effects. Although γ-tocopherol constitutes 70% of the vitamin E in a typical American diet (Jiang et al. 2001), its function in humans is presently unclear as α-tocopherol is the major form of vitamin E in the blood. Increased plasma γ-tocopherol levels have been associated with a significantly reduced risk for development of prostate cancer (Helzlsouer et al. 2000).

Huang and Appel (2003) observed that α-tocopherol supplementation significantly reduces serum γ-tocopherol and δ-tocopherol, both of which may have important biological effects. Thus, the potential health benefits of α-tocopherol supplements may be offset by deleterious changes in the bioavailability of other forms of tocopherols and tocotrienols, which might in part account for the null effects of α-tocopherol supplementation in many prevention trials of cardiovascular disease and cancer and this warrants additional research. Of the vitamin E forms, δ-tocopherol; α-, γ-, and δ-tocotrienol; and derivatives vitamin E succinate and the vitamin E analogue referred to as α-TEA (α-tocopherol ether linked acetic acid analogue) selectively induce cancer cells but not normal cells to undergo a form of cell death called apoptosis (Kline et al. 2004).

There is a lot of evidence that γ-tocopherol and tocotrienols have unique functions different from those of α-tocopherol. The γ-tocopherol appears to be more potent than α-tocopherol in increasing superoxide dismutase (SOD) activity in plasma and arterial tissues (Li et al. 1999). Both α- and γ-tocopherol increase nitric oxide (NO) generation and nitric oxide synthase (cNOS) activity (Li et al. 1999). The γ-tocopherol has been reported to be more effective than α-tocopherol in quenching nitrogen radicals (Cooney et al. 1993). The γ-tocopherol and its major metabolite reduced PGE2 synthesis in both lipopolysaccharide-stimulated macrophages and IL-1b-treated human epithelial cells while α-tocopherol had no effect in epithelial cells (Jiang et al. 2000). A metabolic product of γ-tocopherol, code-named LLU-a, appeared to be a natriuretic factor that is a substance which increases the rate of excretion of sodium ion in the urine, which would appear to have an effect on blood pressure (Wechter et al. 1996).

Tocotrienols, in particular γ-tocotrienol, suppress 3-hydroxy-3-methylglutaryl-coenzyme A reductase (HMG-CoA reductase), a key enzyme in cholesterol synthesis (Khor et al. 1995). Several laboratory studies indicate that tocotrienols affect the growth and/or proliferation of some types of human breast, melanoma and leukaemia cancer cells (Mo and Elson 1999; Yu 1999) and γ-tocopherol was more effective than α-tocopherol in reducing ras-p21 oncogenes in the colonocyte of rats (Stone et al. 2002). Morris et al. (2005) reported that various tocopherol isomers rather than α-tocopherol alone may be important in the vitamin E protective association with Alzheimer disease and cognitive decline in participants aged ≥ 65 years from the Chicago Health and Aging Project.

Vitamin E in poultry production

Vitamin E supplementation in layer production

The interest in modifying egg vitamin composition now extends beyond production considerations to designing a high quality food for human consumption that is of consistent nutrient composition. Several researchers have reported on the production of eggs enriched with different levels of tocopherols (Grobas et al. 2002; Mori et al. 2003; Wong 2005). Tocopherols enriched eggs can be produced through dietary manipulation

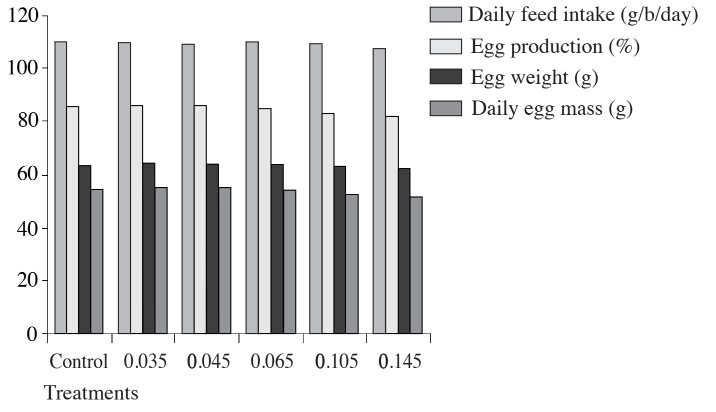


Figure 10. Effects of α-tocopherol supplementation on feed intake, egg production and egg mass
Source: Wong (2005)

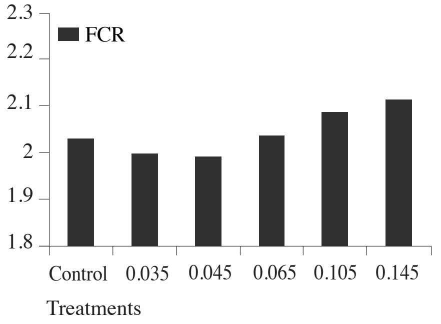
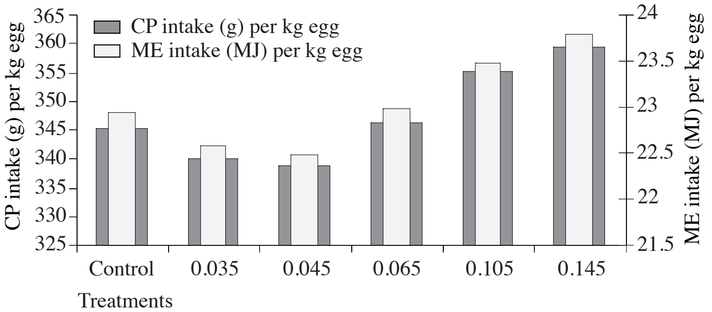


Figure 11. Effects of α-tocopherol supplementation on feed conversion ratio (FCR)
Source: Wong (2005)



Source: Wong (2005)

Figure 12. Effects of α-tocopherols supplementation on use of ME and CP for egg production

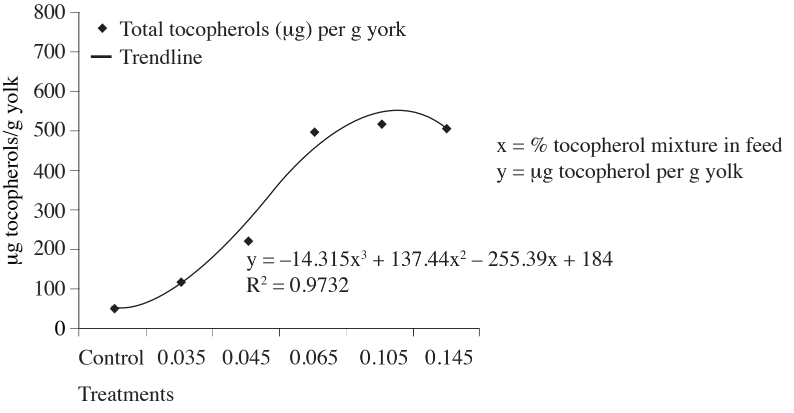


Figure 13. Effect of α-tocopherols supplementation on yolk tocopherol concentration
Source: Wong (2005)

and the effects of supplementation with d-α-tocopherol mixture levels at 0.035, 0.045, 0.065, 0.105 and 0.145% in least cost rations poultry rations is shown in *Figures 10–13*.

With the exception of supplementation at 0.145% level, addition of the tocopherol mixture to diets of Lohmann Brown layers over a 32 week period (Wong 2005) showed no significant differences in feed intake, egg weight and egg production between treatments (*Figure 10*). However, egg production, egg weight and daily egg mass were significantly lower in the 0.145% supplemented group compared to the control and the 0.035% and 0.045% tocopherol supplemented group. As the dietary concentration of α-tocopherol increased, efficiency of uptake of α-tocopherol from feed to yolk decreased linearly. The study showed that the most effective use of dietary CP and ME for egg production was with tocopherol mixture supplementation at 0.045%.

The feed conversion efficiency ratio (FCR) (*Figure 11*) was significantly better for the control, 0.035% and 0.045% tocopherol supplemented group compared to the 0.145% supplemented group. ME and CP intake required to produce a kilogramme egg was significantly better for the control, 0.035% and 0.045% tocopherol supplemented group compared to the 0.145% supplemented group (*Figure 12*). The tocopherol content in egg yolk showed that it increased with increasing tocopherol supplementation, peaking at 0.065% supplementation (*Figure 13*) and there were no further benefits with additional tocopherol supplementation. The relationship between dietary tocopherol supplementation and yolk tocopherol concentration is represented by the regression equation shown in *Figure 13*.

Vitamin E is present as α, β, γ, δ tocopherol isomers and tocotrienol isomers in eggs (*Figures 14–15*). The α-tocopherol is the main isomer form of vitamin E present in eggs with substantial amounts of γ-tocopherol in all eggs. Isomers of

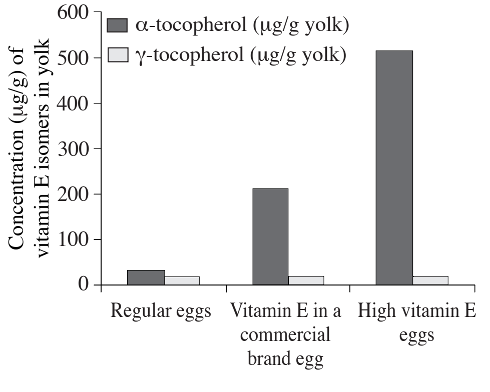


Figure 14. Comparison of α and γ-tocopherols in regular and enriched eggs
Source: Wong and Sundram (1998) and Wong (2005)

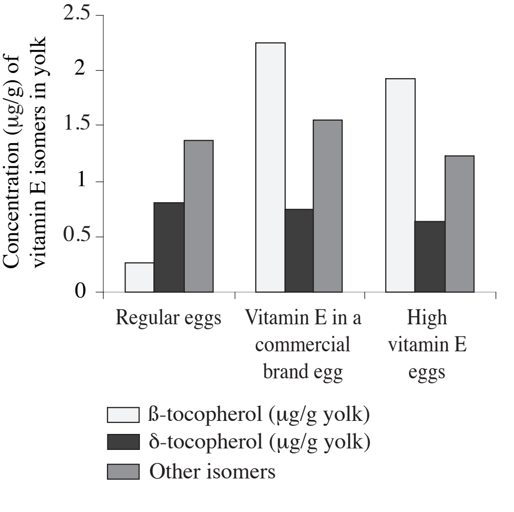


Figure 15. Comparison of beta, delta and other vitamin E isomers in regular and enriched eggs
Source: Wong and Sundram (1998) and Wong (2005)

β and δ-tocopherol are present in very small amounts and may not contribute much to the vitamin E activity in eggs (Wong 1997a; Wong and Sundram 1998). Isomers of α-tocotrienols were also detected and these isomers are mainly supplied by palm oil. The tocopherols were, however, only detected in the yolk component of the egg and not in egg white. The yolk α-tocopherol concentration values in this study was three times and 34% higher than the control and the 600 mg/kg α-tocopheryl acetate supplemented group respectively as reported by Mori et al. (2003). The authors also did not determine the concentration of the other isomers especially the γ-tocopherol which can appear in considerably quantities. There were no differences in egg quality (shell thickness and albumen quality of eggs) from hens fed diets supplemented with vitamin E compared to the basal diet (Mori et al. 2003). Increasing the dietary concentration of α-tocopherol resulted in decreasing efficiency of uptake of α-tocopherol from the feed to the yolk.

The average egg has α-tocopherol concentration of 50 µg/g yolk (*Figure 13*) and studies here by Wong (2005) show that levels of 10 fold (up to 500 µg tocopherol/g yolk) were achievable. With tocopherols concentration of 500 µg/g yolk, an egg can contain about 7.5 mg tocopherols and thus individuals could acquire half their daily vitamin E needs by consuming 1 egg per day. Factors that influence egg vitamin E content include nutrition, age and genetics of the laying hen. Data from egg output and vitamin level and feed intake showed the efficiency of vitamin transfer to be about 34.0% with the 0.065% tocopherol mixture. A comparison between brown layer breeds show that the Shaver breed was 14.3% more efficient than ISA breed in the efficiency of vitamin E transfer to the yolk (Wong 2005). Other layer breeds evaluated such as the Lohmann Brown and Hyline Brown were also less efficient for vitamin E transfer to the yolk compared to the Shaver breed.

Additional benefits of vitamin E supplementation in layer production reported by researchers include improved feed intake, egg production, vitelline membrane strength (VMS), yolk and albumen solids and foam stability (Kirunda et al. 2001) in heat stressed hens. Puthpongsiriporn et al. (2001) reported that supplementation of vitamin E in layer diets enhance egg production and increase antioxidant properties of egg yolks and plasma of White Leghorn hens during heat stress. As ω-3 fatty acid enriched eggs were more susceptible to lipid oxidation, supplementation with vitamin E can increase the lipid stability of PUFA enriched eggs (Galobart et al. 2000) and was effective throughout the storage of spray-dried eggs.

Vitamin E supplementation in broiler production

Mortality in broiler chickens associated with fluid accumulation in the abdominal cavity (ascites) is the ultimate consequence of an excessively high blood pressure in the pulmonary circulation known as pulmonary hypertension syndrome (PHS). Ascites is a metabolic disorder caused by an imbalance between oxygen supply and its requirement to sustain fast growth rate and high feed efficiency in broilers (Decuypere et al. 2000). PHS (ascites) has a multifactorial etiology, apparently involving free radicals and antioxidant mechanisms in the pathogenesis and higher dietary levels of vitamins E are able to reduce ascites-related mortality in broiler chickens (Roch et al. 2000a).

Vitamin E has been shown to modulate immune system functions in various species. Vitamin E was reported to improve phagocytic ability of the immune system (Boa-Amponsem et al. 2000) in broilers. Konjufca et al. (2004) reported that supplemental α-tocopherol acetate enhances Fc-receptor-mediated macrophage phagocytic activity at early stages (up to 3 weeks) of broiler growth. Niu et al. (2009) observed that heat stress (23.9–38 °C) severely reduced growth performance, feed intake, feed conversion and immune response of broilers, while dietary vitamin E supplementation improved the immune response of broilers under heat stress. Both primary and secondary antibody responses were significantly increased by dietary vitamin E when birds were exposed to heat stress. Vitamin E was also reported to reduce the lipid oxidation (malondialdehyde concentration) in breast and thigh meats of meat during refrigerated storage (Goñi et al. 2007).

Selenium

Biological functions

Selenium is of fundamental importance to human health as it is an essential component of several major metabolic pathways, including antioxidant defence systems, thyroid hormone metabolism and immune function. Selenium was discovered by the Swedish chemist, Berzelius, in 1818 and he called the new element 'selenium', after Selene, the Greek goddess of the moon (Oldfield 1987). It is a trace element that is essential in small amounts in the human body, but can be toxic in larger amounts. First reported to be nutritionally essential in 1957 by Schwarz and Foltz, selenium functions in the active site of selenium dependent enzymes and is also involved in immune and neuropsychological function. More than 30 selenoproteins have been identified and the biological functions of 15 have been characterized (Brown and Arthur 2001). The four selenium-containing glutathione peroxidases (GPx) are the cellular or classical GPx, plasma or extracellular GPx, phospholipid hydroperoxide GPx, and gastrointestinal GPx. Although each GPx is a distinct selenoprotein, they are all antioxidant enzymes that reduce potentially damaging reactive oxygen species (ROS). Unlike animals, plants do not appear to require selenium for survival. However, when selenium is present in the soil, plants incorporate it into compounds that usually contain sulfur such as selenomethionine.

Selenium in plants and soils

Plant foods are the major dietary sources of selenium in most countries. In Finland, Sweden and New Zealand, the prevalence of selenium deficient soils make it necessary for selenium-enriched fertilizers to be used in agriculture (Rayman 2000). Animals that eat grains or plants that were grown in selenium-rich soil have higher levels of selenium in their muscle. The decline in blood selenium concentration in many countries has potential public health implications, particularly in relation to chronic diseases prevalent to the Western world such as cancer and cardiovascular disease (Rayman 2000; Brown and Arthur 2001). In the United Kingdom, the BAGELS project entitled Biofortification through Agronomy and Genotypes to Elevate the Levels of Selenium (BAGELS) is underway to increase selenium in wheat (Adams 2008). The underlying rationale is that Selenium-biofortified wheat is a potential strategy for increasing the dietary intakes of selenium, thus improving human health for most of the population.

The bioavailability of organic selenium compounds in foods is generally high (apparent absorption of 70–95%), particularly from plant foods, where most selenium is in the selenomethionine form while selenite, on the other hand, is more likely to be 60–70% absorbable (Lyons et al. 2003). The many recent evidence that consumption of selenium in excess of RDA may provide substantial cancer protective benefits (Clark et al. 1996; Rayman 2000) for humans has provided an impetus for scientists to develop food enriched with selenium leading to selenium enriched eggs, milk, meat and vegetables.

Role in human health

Nutrition and health

While selenium deficiency diseases have long been recognised, evidence is now mounting that less-overt deficiency may also cause adverse health effects and, furthermore, that supra-nutritional levels of selenium may give additional protection from some diseases. A British study (Rayman 2000) on selenium nutrition estimates that humans, worldwide are receiving less than 50% of the recommended daily allowance (RDA) of selenium. Selenium content in the standard British diet was reported to have fallen by 50% in the past two decades to between 29 and 39 micrograms. The recommended selenium intake for adults (µg/day) in various countries is shown in *Table 2*.

Avoidance of deficiency diseases is no longer seen as an adequate goal for nutrition as people are now seeking to optimise dietary intake so that they may postpone the onset of degenerative diseases and avoid long spells of incapacity in their older years (Rayman 2002; Akbaraly et al. 2005).

Many studies have shown that deficiency of selenium is accompanied by loss of immuno-competence, as significant amounts of selenium is found in immune tissues

Table 2. Recommended selenium intake for adults (µg/day) in various countries

Country	Men	Women
USA and Canada (RDA)	55	55
Australia (RDI)	85	70
United Kingdom (RNI)	75	60
World Health Organization (NR)	40	30
Europe (PRI)	55	55
Germany, Austria, Switzerland (RNI)	30–70	30–70

RDA = Recommended dietary allowance; RDI = Recommended dietary intake;
RNI = Reference nutrient intake; NR = Normative requirement estimate;
PRI = Population reference intake
Source: Thomson (2004)

such as spleen, liver and lymph nodes. Selenium has strong interactions with heavy metals such as Cd, Ag and Hg in marine foods and may protect against the toxic effects of these metals (Furst 2002). However, Rayman (2000) has suggested that binding of selenium to these metals may reduce the bioavailability of selenium from foods.

Recommended dietary allowance (RDA)

The American and British Recommended Dietary Allowance (RDA) for adults range from 55 to 75 micrograms (μg) of selenium daily (Anon. 2000b; Rayman 2000).

Brazil nuts have the highest selenium content of any food and other moderately good sources of dietary selenium include kidney, crab, liver, other shellfish, and fish. In general, meat, poultry, fish, cereals and bread contribute most of the selenium in human diets. Best known as an antioxidant and for its role in fertility, selenium is now being researched in several long-term studies as a preventive against various forms of cancer.

The USA Institute of Medicine (Anon. 2000b) has set a tolerable upper intake level for selenium at 400 μg per day for adults to prevent the risk of selenium toxicity. Combs (2001) considered it probable that the WHO, European Union and USA estimates of the upper safe limit of selenium intake of 40 μg per adult per day as too conservative Under normal conditions, a selenium intake of less than 1,000 μg/day (or 15 μg/kg bodyweight) does not cause toxicity (Neve 1991; Poirier 1994; Whanger et al. 1996; Taylor 1997).

Disease prevention

a) Cancer

Many epidemiological surveys, intervention studies, cohort and case control studies reported since the 1970s in medical journals worldwide, support the relationship between selenium levels and cancer incidence (Schrauzer et al. 1977; Clark et al. 1991; Clark et al. 1996; Rayman 2005). Scientists also reported that high selenium levels in blood (reflecting high selenium in the diet) lead to reductions in cancer levels. In Japan and Venezuela (daily selenium intake exceed 200 μg), incidences of breast, lung, prostate and intestinal cancer were significantly lower than in Germany and the USA (daily selenium intake 70 μg).

Despite its necessity for optimum health, selenium content of foods is becoming a health issue in many parts of the world. Evidence is accruing that selenium intake affects the risk of cancer and may inhibit its spread from a primary tumour. In the UK, deaths from cancer (CancerStats 2010) in adults outnumber deaths from heart disease and stroke, and it is projected that one in three of the European population will be diagnosed with cancer during their lifetime (Globalcan 2008 2010).

At present, there are many ongoing large population studies on selenium supplementation in North America and Europe. The PRECISE (Prevention of cancer with selenium) study (Rayman 2000) involves 52,000 people from Britain, USA, Holland, Belgium, Finland, Sweden and Denmark and looks at selenium supplementation and cancer incidences.

Thomson (2004) reported that current evidence suggests that a plasma level of around 120 μg/litre may be optimal for protection against some cancers and this generally equates to a selenium intake of at least 105 μg/day for a 70 kg person (Combs 2001), and in some individuals (under high oxidative stress), up to 200 μg/day. Peters et al. (2003) reported that higher serum selenium concentrations were associated with reduced prostate cancer risks in men who also reported a high intake of vitamin E, in multivitamin users, and in smokers.

The inability of selenium supplementation to reduce prostate cancer risk may be due to individual genetic make-up and Chan et al. (2009) had reported that men with a variant of the manganese superoxide dismutase (*SOD2*) gene had an increased risk of aggressive disease with selenium supplementation while others had lower risk.

b) Heart disease

Selenium may also be protective against cardiovascular disease as indicated by some epidemiological findings (Brown and Arthur 2001; Wei et al. 2004). Evidence from several recent studies suggests that oxidative stress from free radicals can promote heart disease and selenium is one of a group of antioxidants that can help limit the oxidation of LDL cholesterol and thereby help to prevent coronary artery disease. Flores-Mateo et al. (2006) in their meta-analysis study have reported that selenium concentrations in several tissues were inversely associated with coronary heart disease risk in observational studies. However, they also cautioned that evidence from large ongoing trials is needed to establish low selenium concentrations as a cardiovascular disease risk factor.

c) Emerging diseases

The emergence of new viral diseases or the increase in infection from known viruses is often attributed to such things as global warming, destruction of the rain forest, agricultural practices, etc. However, the influence of host nutrition on the evolutionary process of RNA viruses is rarely considered. Beck et al. (2003) have demonstrated that inoculation of certain strains of coxsackievirus or influenza virus into selenium-deficient mice can lead to the production of more virulent strains of virus. They have suggested that further research is needed to assess the possible role of malnutrition in contributing to the emergence of novel viral diseases.

Selenium and cognitive function

There are many indications that selenium is important to the brain as low plasma selenium in the elderly was significantly associated with senility and accelerated cognitive decline and brain selenium concentrations in Alzheimer's patients were significantly reduced (Rayman 2000). Selenium is widely distributed throughout the body, but is particularly well maintained in the brain; even upon prolonged dietary selenium deficiency (Chen and Berry 2003) and changes in selenium concentration in blood and brain have been reported in Alzheimer's disease and brain tumors.

Selenium in poultry production

Selenium supplementation in layer production

Several levels and sources of selenium supplements (selenium yeast) and inorganic sources (selenite and selenate) have been evaluated in typical corn-soybean meal based layer diets to develop the selenium enriched egg (Wong 2005). The selenium enriched eggs can be produced through dietary manipulation and the effects of supplementation with various selenium mixture levels at 0.11, 0.12, 0.13, 0.14, 0.15 and 0.18% in layer rations is shown in *Figures 16–18*.

The optimal selenium supplementation levels were determined by selecting the best FCR, most economical cost and the highest level of selenium transfer into the egg as determined by production parameters and least cost formulations. At adequate selenium intake, there were no benefits to production parameters (egg production and egg weight) with selenium-yeast or inorganic selenium supplementation (*Figure 16*). There were also no significant differences in feed conversion ratio (FCR) between the control and selenium treatments (*Figure 17*).

The relationship between dietary selenium supplementation and egg selenium content is shown in *Figure 18* and the relationship is also described by the equation shown. Treatment at 0.15% was most efficient for selenium transfer into the egg and further supplementations do not substantially increase selenium levels. Selenium was measured from both the yolk and egg white component of the egg suggesting that it is

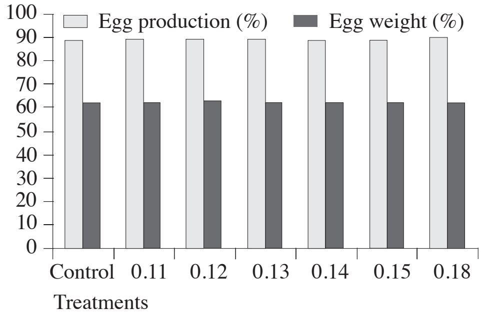


Figure 16. Effect of Se supplementation on egg production and egg weight
Source: Wong (2005)

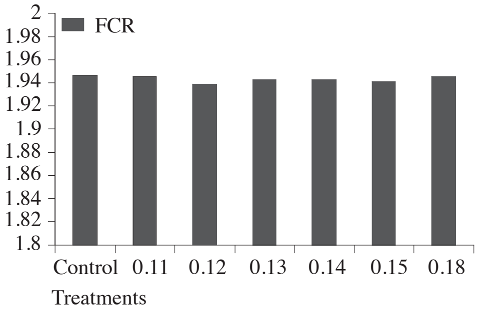


Figure 17. Effect of Se supplementation on feed conversion ration (FCR)
Source: Wong (2005)

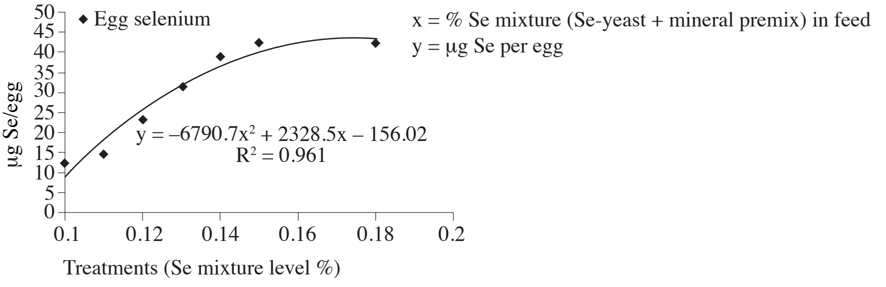


Figure 18. Effect of dietary Se supplementation on egg selenium (µg/egg)
Source: Wong (2005)

present in both water soluble and fat soluble forms. Pappas et al. (2005) reported that the efficiency of selenium transfer into the egg was greater in low selenium treatments compared with high selenium treatments. The majority of selenium from the low selenium treatments was deposited in the yolk, whereas in high selenium treatments, the selenium was deposited evenly in the yolk and albumen. High selenium treatments had greater Haugh Units reading compared with low selenium treatments. Latshaw (1975) reported that tissues and eggs from hens fed natural selenium was higher than from hens fed selenite selenium and dialysis in a pH 11 solution removed most of the liver selenium from selenite feeding compared to only a small percentage from the feeding of natural selenium compounds.

Generally, the maximum allowable level (0.3 ppm) used in commercial poultry diets is well below toxic levels. Ort and Latshaw (1978) reported that hatchability of fertile eggs was decreased by 5 ppm, egg weight decreased by 7 ppm and egg production decreased by 9 ppm of selenium in the diet.

Selenium supplementation in broiler production

Selenium status and its impact on capillary membrane stability has also been found to be related to ascites incidence. The main mechanism for pulmonary hypertension syndrome (ascites) is an increase in intravascular pressure occurring secondary to right ventricular failure. The increased pressure pushes fluid out of blood vessels and into the abdominal cavity, hence the occurrence of ascites (Roch et al. 2000b). They hypothesized that dietary vitamin E level and selenium interact to affect ascites incidence by increasing stability of the red blood cell membrane. They found that ascites mortality rate decreased with addition of 250 IU/kg vitamin E, 0.3 ppm selenium from organic selenium alone, or the combination of vitamin E and 0.6 ppm selenium from selenite.

In several broiler performance trials, organic selenium supplementation showed a positive effect on weight gain and FCR compared to controls (Spring 2008). Birds supplemented with increasing levels of selenium were better able to cope with the challenges of the reoviruses wasting disease. Several studies have also shown that supplementation with organic selenium reduces drip loss in meat (Spring 2008). The improved membrane integrity from organic selenium supplementation is linked to better osmotic regulation and control, reducing the amount of water lost from the tissue as either oedema in living animals or drip loss in meat. Water holding capacity is also an important characteristic of meat, as it determines the level of exudative loss in packaging and during cooking, and the juiciness of meat. The researchers have suggested that the prooxidant effect of inorganic selenium is detrimental to cell membranes causing higher levels of drip loss. Organic selenium exerts an antioxidant effect on the birds' cellular membranes and tissue structures resulting in less exudative losses from meat.

Sensory and storage evaluation

Selenium enriched eggs were shown to be acceptable in storage and sensory evaluation tests. Evaluations of the taste, colour, texture of the selenium eggs and conventional eggs showed no significant differences in acceptability. Haugh unit readings show that the selenium enriched eggs had consistently higher readings (better quality) compared to conventional eggs when stored at room temperature over a period of 7 days (Wong 2005). Improvement in egg antioxidant status with selenium supplementation has been reported by Wakebe (1998) who observed higher selenium, vitamin E and higher Haugh unit readings in these eggs. Gajčević et al. (2009) reported that blood glutathione peroxidase (GSHPx) activity was higher and egg Haugh unit readings and TBARS (thiobarbituric acid reactive substances) values were better in the organic selenium supplemented eggs compared to controls.

The colour intensity of the egg yolk supplemented with the natural carotenoid, capsanthin and capsorubin was consistently higher in selenium eggs (Wong 2005) compared to the control as determined by the Roche Yolk Color Fan test and this was due to the protective antioxidant effect of selenium.

Future directions in research and development

Tackling metabolic disorders in poultry

With genetic advances and increasingly higher egg production, the problem of eggshell quality is becoming more serious and a better understanding of Ca flux of the hen throughout the entire 24-hour cycle of egg formation (Clunies and Leeson 1995) and interaction with nutrition, housing, environment, and health status of the bird is needed. The major health concerns for poultry production are metabolic disorders such as sudden death syndrome (SDS), skeletal disorders, and ascites in broilers; and cage layer fatigue and fatty liver in layers. Metabolic disorders such as SDS and ascites can be prevented by growing broilers more slowly but require further research in commercial environments. The growth reduction can be achieved by using low nutrient density diets, mash diets, physical feed restriction, or more commonly by extended periods of darkness. Slowing early growth rate without too much loss in feed utilization may be practical as during the first week of growth, some 80% of feed is used for growth and only 20% used for maintenance (Leeson and Summers 2001).

Rapid and reliable nutrient analysis

A major weakness in the food supply chain is the present quality control procedures, and rapid analysis systems should be developed. Although near infrared analysis has been used for 3 decades in feed analysis, there is little R&D to expand and enhance its usage. The major feed ingredients like corn and soybean meal account for about 80% in poultry diets and have often been regarded to be more or less consistent in terms of nutritional value; regardless of where they are harvested, processed, stored and transported. However, Liu and Liu (2008) have shown that apparent metabolizable energy (AME) varied by 588 kcal/kg for corn and 804 kcal/kg for soybean meal between the highest and lowest indicating a considerable variation of nutritional composition. Rapid and reliable analysis of the available nutrient contents of feed ingredients is the key issue in practical diet formulation.

Protein ingredients make up about 45% of the total cost of poultry feed rations and in 2008, the total cost of imported protein feeds and amino acid supplements used by the poultry feed industry is estimated at RM1.9 billion. A major constraint to the use of local feed ingredients is the scarcity of information on amino acid content and digestible amino acids of these feeds. These parameters are complex, tedious and time consuming and expensive to determine by the feed industry and MARDI can provide the expert information and service to the feed industry locally and regionally. As the conventional method of amino acid analysis is expensive and requires two days for sample preparation and analysis, research to develop rapid and reliable amino acid analysis methodology is needed for efficient utilization of feed protein and to increase the precision of formulating poultry diets.

Nutrient enriched poultry products

Consumer demand for food products of superior health quality will ensure continued development of new egg and meat products for niche markets. With nutritional manipulation, the nutrient composition of poultry meat and eggs can be enhanced with ω-3 fatty acids, selenium and vitamin E. Further R&D emphasis on nutrient manipulation should be put on developing meat and eggs products with additional nutrients for health enhancement. Developing eggs with more beneficial nutrients such as the all-in-one-egg with higher DHA, vitamin B12, vitamin D3, choline, folate, selenium, conjugated linoleic acid, tocotrienols, lutein, zeaxanthin, phytonutrients, antioxidants and lower cholesterol can be considered. As long chain ω-3 fatty acids have many proven health benefits and marine sources of these fats are being depleted; the challenge is to develop egg and meat products containing high levels of EPA and DHA from plant ω-3 sources.

Alternative feeds

Feed substitution to replace imported feed ingredients such as corn, soybean meal and fishmeal has been on-going for more than 3 decades and the goal of significant replacement from local sources is still elusive. Research on improving PKC through physical and chemical processes should be emphasized as the technology for large scale production is available and further studies to effectively use this product in practical and cost competitive least cost formulations is required. Emphasis on the effective use of by-products from the rice industry (rice bran, broken rice and rice polishing), sweetpotato and cassava and use of in-feed enzymes to improve digestibility of feeds should continue. More focus should be put on the use of poultry processing plant waste products for aquaculture production. Feed pelleting and extrusion technology could be used for further processing to improve digestibilities and overcome anti-nutrient factors in sweetpotato and cassava and its leaf meal as well as mulberry and gliricidia leaf meal for poultry monogastric production.

Ideal protein concept in diet formulation

Efficient nutrient management is a major concern for the poultry industry and as poultry typically utilizes only 45% of consumed dietary protein (De Boer et al. 2000), it is thus costly to the producer and wasteful in terms of N utilization. Reducing the crude protein content of poultry diets and maintaining the level of important amino acids through use of supplemental amino acids can help to alleviate heat stress by improving heat dissipation during hot weather (Chew et al. 1997). As there is a direct relationship between diet protein and the level of N excreted in poultry manure (Lopez and Leeson 1995), efforts to lower feed cost by reducing feed protein should be emphasized. The ideal amino acid profile (%) for layers as proposed by Bregendahl et al. (2008) relative to lysine (100) are as follows: Arginine (107), Isoleucine (79), Methionine (47), Total sulphur amino acids (94), Threonine (77), Trytophan (22) and Valine (93). By comparison, the ideal amino acid profile (%) for broilers as proposed by Mack et al. (1999) relative to lysine (100) are as follows: Arginine (112), Isoleucine (71), Total sulphur amino acids (75), Threonine (63), Trytophan (19) and Valine (81).

Growing concerns about the environmental impact of poultry production may lead to the addition of environmental factors such as N and P pollution as parameters in feed formulation schemes in the future. The ideal protein concept can thus provide a precise ratio of essential amino acids needed and minimizes N excretion. This concept uses lysine as a reference amino acid, with the requirements for all other indispensable amino acids expressed as a percentage of lysine and can help reduced the required nutrient safety margins or over-formulation as is widely practiced presently by the feed industry.

Discussion

The poultry industry is the most advanced sub-sector of the livestock sector in Malaysia and it has remained competitive due to its adoption of the most modern production technologies, imported breeds and most advanced feeding and management systems. As the industry depends greatly on imported feeds, a solution to this problem of dependency should be found. Substitution of imported feed ingredients is a major challenge and commercial grain corn production in Malaysia has not yet proven to be viable.

The Malaysian poultry industry should re-orientate itself to meet the challenges of a global and market-driven world. In coping with globalization, the industry should continue to enhance production efficiency and product quality, and should also be sensitive to consumer needs as well as to environmental concerns.

Growing health consciousness, increasing awareness for healthy nutrition and research linking food components to disease prevention and health enhancement has an increasingly significant impact on the consumer's food choices. In the last decade, the consumer's perception is that products for human consumption that are low in animal fats and cholesterol are 'healthier'. Omega-3 fatty acids have important visual, mental, and cardiovascular health benefits throughout the human life cycle. Simopoulos (1999b) has suggested that modern agricultural practices significantly reduced the ω-3 content of most modern foods.

Mantzioris et al. (2000) have shown that foods that are strategically or naturally enriched with ω-3 fatty acids can be used to achieve desired biochemical effects without the ingestion of supplements or a change in dietary habits. They also conclude that a wide range of ω-3 enriched foods could be developed to support large scale programmes on the basis of the therapeutic and disease-preventative effects of ω-3 fatty acids.

Vitamin E is an antioxidant that has many important functions and a primary function is in preventing oxidative stress from free radical formation. It enhances the immune system, helps prevent cancer by preventing cell damage, thins the blood, inhibits platelet aggregation, improves vasodilation, circulation, blood flow and protects against cardiovascular disease.

Higher dietary levels of vitamins E are able to reduce ascites-related mortality in broiler chickens, enhance immune system, alleviate symptoms of heat stress and increase antioxidant properties of egg yolks. As a big proportion of the population do not meet daily dietary recommendations for vitamin E (Maras et al. 2004), eggs with high tocopherol content (7.5 mg tocopherols per egg) can contribute substantially to the individual's daily needs for this critical nutrient.

Studies on selenium nutrition show that generally, humans are receiving less than 50% of the RDA of selenium. The impact of this deficiency and sub-optimality in global health terms is difficult to quantify, but is likely to be enormous given the high prevalence of various cancers, cardiovascular diseases, viral diseases and exposure to environmental pollutants throughout much of the world (Combs 2001) and countries should address this major public health issue and develop effective, sustainable ways to increase selenium intakes.

As for the safety of selenium supplementation in humans, an expert panel of the European Food Safety Authority (Anon. 2009) has concluded that a cause and effect relationship has been established between the dietary intake of selenium and protection of DNA, proteins and lipids from oxidative damage, normal function of the immune system, normal thyroid function and normal spermatogenesis and food manufacturers can make health claims based on proposed wording such as "selenium is necessary for normal cardiovascular function" or "selenium is beneficial for prostate health" or "selenium supports better brain functioning".

The many recent evidence that selenium supplementation in excess of RDA may provide substantial cancer protective benefits for humans has thus provided an impetus for scientists to develop foods enriched with selenium. Many poultry trials have shown that organic selenium improves animal growth and efficiency, especially under stressful commercial conditions, demonstrating a healthy return on investment; and offers excellent opportunities for producers. As humans are receiving less than 50% of the RDA, selenium enriched eggs can help to meet most of the individual's daily needs for this critical mineral.

Over the last decade, designer eggs especially ω-3 enriched eggs have made substantial progress into supermarket shelves in North America, Europe, Australia, Japan, Korea, Thailand and Malaysia. The ability to enrich eggs with ω-3 PUFA, vitamin E and selenium have provided the local egg industry with a unique opportunity to produce an innovative, premium quality and value-added product for the domestic and export market.

Many poultry companies are continuing to develop enriched eggs and meat that have higher levels of dietary antioxidants, vitamins and better lipid profiles through manipulation of poultry diets. Continued investigation in the areas of efficiency of dietary nutrient transfer, sensory evaluation and product stability are needed if significant improvements in the health quality of foods available to the consumer are to be made. Nutrient enriched poultry eggs and meat can thus play an important role as functional food for consumers.

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Profile: Wong Hee Kum

Born on 10 August 1954 in Kuala Lumpur

Education

Primary and Secondary School:

- Batu Road Primary School, Kuala Lumpur
- Victoria Institution, Kuala Lumpur

Tertiary:

- B.Sc (Hons.), Microbiology, University of Otago, New Zealand, 1979
- M.Sc, Microbiology, University of Otago, New Zealand, 1981

Work experience and achievement

Mr. Wong Hee Kum started his working career as a research officer in the Feed Resources and Animal Nutrition Branch of the Livestock Research Division of MARDI in 1981.

He has extensive research experience on energy, protein, mineral and vitamin nutrition in goats, sheep, cattle (dairy and beef), broiler and layer chickens and fish. He has also carried out research work on food design and safety, feed supplementation, feed toxicology, rumen microbiology and rapid detection of antibiotic residues.

Mr. Wong has a long and keen interest in functional foods and nutraceuticals and subscribe to the theory that functional foods can provide a physiological or medical benefit to protect against or retard the progression of diseases. In 1998, he successfully developed the complete package technology to produce eggs enriched with omega-3 fatty acids and vitamin E with lower cholesterol content. This technology was licensed to LTK (Melaka) Sdn. Bhd. and sold widely under the LTK Omega Plus brand since 1999. In 2003, he developed the complete package technology to produce selenium enriched eggs. The technology was also licensed to the same producer and the product is sold widely under the LTK Selenium Plus brand and exported under the Telur Mas brand. He is also the technical consultant to one of the largest accredited export layer farms in Malaysia.

At present, he is the Deputy Director of the Animal Nutrition Programme in the Strategic Livestock Research Centre, MARDI. He has also served on the Judging panel at ITEX (2009, 2010) and was a member of the National Key Economic Area (NKEA) laboratory for the Agriculture Sector (2010). He was a member of the Australian Asian Fibrous Agricultural Residues Research Network (AAFARR) from 1985 to 1987, panel member for priority setting in animal biotechnology for the Seventh Malaysia Plan

(1996–2000), panel member MOSTE Science and Technology Sector (2000), National Codex sub-committee on drug residues in food (1991 – to present), SIRIM sub-committee on dairy cattle feed and SIRIM committee on egg products (2008 – present).

Publications

Mr Wong has published more than 125 scientific articles (in journals, books and proceedings) locally and overseas. He participates very actively in the conference and publication activities of the Malaysian Society of Animal Production (MSAP) and was chairman of the scientific sub-committees and the chief editor of the proceedings for the 1992, 2002 and 2006. He is a member of the editorial committee of the Malaysian Journal of Animal Sciences and Journal of Tropical Agriculture and Food Science. At the international level, he was the chief editor for the publications of the 11th Animal Science Congress 2004 (Asian-Australasian Association of Animal Production Societies) and an editor of the book Recent Advances on the Nutrition of Herbivores (1991).

Awards

Mr Wong is recognized and known nationally and internationally for the development of designer egg technologies. He has received innovation awards from ITEX (2003, 2006), MTE (2007) and British Invention Show, London (2007). His research efforts have been recognized by MARDI with Awards for Excellence Service in 1998 and 2006; and the Award for Excellence in Commercialization of Technology in 2004.

Appendix:
Papers presented as Research Inaugural Lectures (*Syarahan Perdana Penyelidikan*)

No.	Date	Presenters	Title of papers
1	14 July 2009	Dr. Johari Jiken Abdullah	The Brakmas cattle – Potential beef breed for meat production in Malaysia
2	20. Aug. 2009	Dr. Azizan Ab. Rashi	Improving beef production in Malaysia
3	22 Oct. 2009	Dr. Kamariah Long	Unlocking the miracle of lipases
4	24 Nov. 2009	Latifah Mohd.Nor	Challenges of the fresh cut fruits industry in Malaysia
5	23 Feb. 2010	Ismail Abu Bakar	Strategies for mitigation of carbon emission in peatland
6	23 Feb. 2010	Wong Hee Kum	Manipulating nutrient composition in poultry
7	6 Apr. 2010	Fadelah Abdul Aziz	Blooming heritage: Wild orchid species to beautiful orchid hybrids
8	18 May 2010	Che Rohani Awang	Adding value to local aquatic resources
9	1 July 2010	Dr. Zamri Ishak	Elevating biosensor research in food and agriculture – Integrating the tools of biotechnology and nanotechnology
10	5 Aug. 2010	Dr. Mohamad Roff Mohd. Nor	The battle against virus diseases of chilli: How can we win?
11	5 Oct. 2010	Dr. Mohmad Mustafa	Livestock Entrepreneur Development- Is there a future for commercial Boer goat and Dorper sheep entrepreneurs in Malaysia?
12		Mohd. Zainal Ismail	Issues relating to traditional food mechanization

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