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EFFECTS OF PROCESSING ON SOYBEAN NUTRIENTS AND POTENTIAL IMPACT ON CONSUMER HEALTH: AN OVERVIEW

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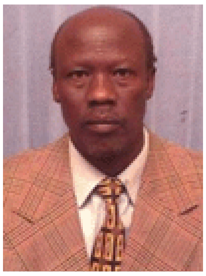

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ABSTRACT

Production of soybeans and consumption of soy products is increasing worldwide mainly due to acclaimed health benefits. Processing can alter soybean sensory appeal, nutritive value and potentially affect consumer health. This review of the literature examines these issues. Despite potential changes in nutritive value during processing, soy foods processing below 100^{o}C for short periods, may not adversely affect nutritive value. However, heat inactivation of trypsin inhibitors, denaturation of soybean globulins and haemagglutenins, increases soy protein bioavailability. Excessive heating can impair nutritive value by making lysine unavailable, as serine, cystine and cysteine are converted to a dehydroprotein intermediate that reacts with lysine to form lysinoalanine. Tryptophan and methionine are also lost during excessive heating. The acylation reaction catalyzed by alkali, generates lysinoalanine, an unavailable and potentially toxic compound. In rats, ingestion of lysinoalanine results in diarrhoea, pancreatic hyperplasia, and loss of hair. At levels present in foods, protein-bound lysinoalanine does not cause nephrotoxicity in humans. Heat treatments at alkaline pH result in destruction of arginine, which is converted to ornithine, urea, citrulline and ammonia, while cysteine is converted into dehydroalanine. Serine, threonine and lysine are also reduced at alkaline pH. These conditions may be present during alkali refining of soy oil. Carbohydrates with free reducing groups react with carbonyl groups on proteins as part of the Maillard reaction. Heat treatments at alkaline pH and above 200^{o}C cause isomerization of amino acids, leading to formation of racemic mixtures of L and D forms. Since D isomers have reduced bioavailability and some including D-proline are reported to be toxic, racemization of an essential amino acid reduces its nutritional value. Changes in lipids include oxidation, loss of lipid-soluble vitamins and change of fatty acids from *cis* to *trans* isomers. Autoxidation of unsaturated fatty acids initiates free radical formation leading to destruction of unsaturated fatty acids, with potential reduction of essential fatty acid content. Oxidized lipid-protein interaction products are important precursors of atherosclerotic plaques in vivo. Carotenoids are lost on bleaching, thereby reducing Vitamin A potential. Vitamin E is lost during oil refining. Roasting and toasting have no effect on soy isoflavones, but organic solvents remove them, while fermentation increases their bioavailability. Dehulling reduces total mineral content but most soy minerals follow protein or meal, while sodium and potassium are lost in wash water. To minimize adverse changes, minimal washing, fermentation, reduction of hydrogenation temperature and thermal processing below 100^{o}C for short periods, are recommended.

Keywords: Soybean nutrients, processing, human health

INTRODUCTION

There are many procedures that food raw materials go through before they are finally available as edible food products. In food processing, these procedures are commonly referred to as unit operations. They include: cleaning, coating, concentrating, heating and cooling (heat exchange), drying, disintegrating, mixing, pumping and separating [1]. This order does not, however, give their natural sequence or their relative importance when applied in the preparation of food products.

Each of the above unit operations has other accompanying and minor procedures. For example, mixing includes agitating, beating, heating, blending, diffusing, dispersing, emulsifying, homogenizing, kneading, stirring, whipping and working, depending on the product being manufactured [1]. The unit operations are selected and combined into more complex integrated processing systems peculiar to each factory operation to enable the conversion of food raw materials into specific end products.

This review of the literature examines how different processing procedures affect the properties of the soybean (SB), soy derived foods, and thereby the potential health benefits or demerits of consuming nutrients of processed soybean and soy foods.

Trends in Soybean Production

The SB (*Glycine max* (L) Merrill family *Leguminosae*) originated in the Orient, probably in China [2]. In the Orient as in many other SB producing parts of the World, the main products from soybeans are oil and meal, alongside a variety of non-fermented and fermented soy foods. The US, Brazil, Argentina and Bolivia are the major SB producers in that declining order, while China is the world’s major importer of soybeans [3]. Approximately 81, 34 and 99% of the SB crop grown in the US, Brazil and Argentina is genetically modified [4], so that SB seed or soy food imports from these countries by African processors and consumers are potentially genetically modified.

Due to intense research over the last 5 decades or so, the discovery of health benefits associated with soybeans and their products as human food, has led to increasing worldwide production and consumption. In 2007, the global production of soybeans rose to 221 million metric tons (MT) [5]. Africa produced approximately 1.3 million MT of soybeans in 2007 [5] (about 0.5% of global output) up from 0.6 million MT in 2002 (more than 100% increase in 5 years) [5]. The 2009/2010 estimated global output is 259 million MT [6].

The output of SB from Africa is low despite the long history of SB growing in Africa, dating as far back as 1889. The FAO statistics for SB production feature 19 African countries. In the context of African production, Nigeria leads with 49% of the output with others being Uganda (17%), South Africa (15%), Zimbabwe (8.4%), Ethiopia (2.7%), Rwanda (2.0%), Egypt (1.7%) and the Democratic Republic of Congo (1.4%) [7]. Others with less than 1% output each include Cameroon, Zambia, Gabon, Tanzania, Liberia, Burkina Faso and Morocco.

Kenya is a very small producer even in the African context. Kenya's production in 2008 stood at about 2,100 metric tons [5]. In Kenya, Western Province is the leading soybean producer accounting for more than 50% of the national small holder production in 2003, with Central Province and Nyanza accounting for 11-12% of the national output [4]. Kenya's Central Bureau of Statistics estimates that Kenya imports 70,000-100,000 tons of soybeans annually with 18-26% of the vegetable oil consumed in Kenya being soy oil [7].

Two major problems were found in trying to introduce whole soybeans on a home level in Africa; they took too much time and fuel to cook and the taste was not well accepted. Due to the long time cooking of soybeans in order to soften them, it is likely that nutritional changes associated with thermal effects on nutrients can result.

There are concerted efforts to increase SB growing in Africa (in Kenya, South Africa, Nigeria, Algeria, Botswana, Uganda, Tanzania, Zambia and Zimbabwe) [6]. This is bolstered by the worldwide demand, the touted health benefits from SB consumption, and the help of the International Soybean Center (INTSOY) at Urbana-Champaign, Illinois, USA [6]. The worldwide demand for soybeans and the need to substitute soy products imported by African countries from the US and other major SB producers, may lead to further interest in growing soybeans on a larger scale than currently. In view of the increasing production and importation by African countries of SB and its products, the effects of different processing procedures on SB nutrients and the potential impact on SB consumer health needs to be examined for the sake of educating consumers. This literature overview aims to do that.

MAJOR SOYBEAN NUTRIENTS

The proximate composition of the SB varies with the variety, growing season and location [9]. However, reasonable average figures for the major nutrients are 40% protein, 20% lipid, 35% carbohydrate and 5% ash on a dry weight basis [2]. To ensure stability during storage of the mature soybeans, a moisture content of 12-15% is desirable [2]. The moisture content at harvest is critical for their subsequent handling. If too moist, considerable energy will be expended during drying, while if they are too dry, they may be brittle during harvest, leading to potential deterioration of oil quality and increased refining costs [9]. Also, a moisture content at harvest greater than 13% may lead to mould growth, and, due to the metabolism and growth of mould, moisture and temperature will both increase in the storage space leading to accelerated deterioration of SB food value [10]. Where *Aspergillus flavus* and other moulds are present, the potential for the formation of aflatoxins and other toxigenic mycotoxins is real.

Refined soy oil fraction is not 100% triglyceride, and the minor components which include phospholipids and lecithin, can influence the colour and stability of the refined oil. Soy oil has about 80% of its fatty acids being unsaturated, with the predominant unsaturated fatty acid being linoleic [11]. The relative reactivity of oleic, linoleic and linolenic is 1:10:20 [12]. As the linolenic acid in SB oil has been blamed for the relative instability of the oil to oxidation, efforts have been expended into breeding low linolenic acid varieties by genetic modification [13].

Protein is the second major component of the SB (after the oil) that has commercial value. Soy protein has an amino acid composition that complements that of cereals, although it is limiting in the sulphur-containing amino acids (especially methionine) for most species including humans [2].

Lipid extraction of soybeans with hexane at 60-70 °C for 30-40 min does not adversely affect soy protein solubility, the enzymatic activity of the defatted flour, or its trypsin inhibitor activity. In contrast to other phytohaemagglutenins, soy haemagglutenins do not seem to exert much effect on the nutritive value of soybeans [2]. Soybeans are an excellent source of lipoxygenase which has been used to bleach the carotenoids of wheat flour instead of the use of bromides and related chemical compounds. As the beans mature, the content of monosaccharides declines and the complex carbohydrates-raffinose, stachyose and sucrose increase. These are normally present in the mature bean at levels of 1, 4 and 5%, respectively [2]. Although stachyose and raffinose are not digested and absorbed as nutrients by humans, the intestinal microflora in the human gastrointestinal tract metabolize these oligosaccharides, resulting in gas production causing flatulence in humans. The insoluble carbohydrates-mainly cellulose, hemicellulose and pectins, are the equivalent of the insoluble dietary fibre. Soybeans contain nutritionally significant amounts of calcium and iron [14]. Due to phytic acid, the bioavailability of some minerals such as zinc may be affected adversely [15].

An Overview of Soybean processing

SB processing is all the steps necessary to convert the intact soybean to usable final food products. Due to its high fat, low carbohydrate, negligible starch, and compact texture, SB does not soften as readily as many other seeds upon cooking, without prior soaking in water [2]. The major products from SB are oil and feedstuff, alongside minor products that include full-fat soy flours, soy concentrate, soy protein isolates, and lecithin. The initial preparatory steps for preparing SB for further processing into the various individual products include cleaning, drying, cracking, and conditioning. Due to the mild conditions at which these procedures are performed, any loss in nutritive value is insignificant. The preparatory steps that may affect the nutrient content of the SB are dehulling and drying. Dehulling, which results in the removal of the hulls from the soybeans, potentially reduces the total mineral content of the bean [14]. However, this step is necessary for the subsequent oil extraction and preparation of other products. When the drying step is done at temperatures of 60-70 °C for short periods, no significant nutrient losses result, and, consequently, no major health related benefits are lost or adverse effects introduced at this processing stage. Drying may, however, cause denaturation of soy protein leading to a reduction of thermally unstable amino acids including cystine, methionine, cysteine, tryptophan and lysine [16]. The extent of loss of these essential amino acids is a function of the pH, temperature and time of treatment. Lipid-protein interaction may also affect the bioavailability of some amino acids leading to the reduction of the essential fatty acid and amino acid content [17]. Refining, bleaching and hydrogenation are important aspects of SB oil processing. Although bleaching and refining may reduce the lipid-soluble vitamin and essential fatty acid content of the oil, hydrogenation (addition of pure hydrogen gas under pressure to the oil in the presence of a catalyst while agitating and heating) has the most profound impact on the properties of the final oil product. Hydrogenation results in interesterification (the shifting of double bonds and formation of considerably different triglycerides from the original), and an increase in the melting range of the oil and the solids fat index; this makes the oil plastic and hard [13].Due to potential selectivity during hydrogenation and based on hydrogenation conditions, any reduction of linolenic acid content can reduce reversion (formation of off-flavours at low oxidation rates of oil) [13]. This is an advantage, although this also has the disadvantage of potentially reducing the nutritive value of the oil through saturation of the double bonds of the unsaturated fatty acids.

During the fermentation of soy foods including miso, complex carbohydrates are broken down by carbohydrases into monosaccharides and disaccharides that include glucose, fructose, mannose and sucrose. Tannins are broken down into simpler derivative compounds by phytases leading to increased bioavailability of minerals such as zinc whose metabolism would normally be adversely affected in the presence of considerable amounts of tannins, dietary fibre and phytate [15,18]. A detailed account of the effect of processing on the nutritionally-important components of the SB and some related health effects follows.

Effects of processing on soybean nutrients

The processing of soybeans into the many food and feed products can cause changes in their nutritive value. However, despite the changes in nutritive value, the changes that are known to occur during normal thermal processing as long as the temperatures do not exceed 100 ^{o}C for inordinately long periods, may not in any measurable way adversely affect the nutritive value of the particular soy product.

Effects of processing procedures on soybean proteins

These components may be subjected to heat, alkali, other chemical compounds or mild oxidation, all of which are known to have an influence on the nutritive value of soy products. However, even low temperature storage may have some effect on soybean protein stability. One of the storage proteins of soybeans has been reported to undergo reversible dissociation and denaturation at 2 ^{0}C [19]. When warmed, however, and held at ambient temperature, it re-associates and regains its activity [20].

Effects of heat on soybean protein

The exposure of soybeans to heat during solvent extraction, has little or no influence on their nutritive value per se as long as the temperature of extraction is in the range 60-90 ^{o}C [16]. The thermal denaturation temperature (T_d) of soybean glycinin is 92 ^{o}C [16]; this temperature is higher than the thermal denaturation temperature of most pure protein isolates, but lower than that of broad bean 11S protein, the 11S protein of sunflower and oat globulin [16]. Above the T_d, nutrient losses due to the effect of heat can occur. The main heating step in soybean processing is desolventizing-toasting, and this seems to have a predominantly beneficial effect on nutritive value. The heat inactivation of trypsin inhibitors and the heat denaturation of SB globulins, makes them more susceptible to proteolysis, thereby improving soy protein bioavailability for human foodstuffs or animal feeding [16]. Also, heat denaturation improves the foaming and emulsifying properties of soy proteins [21]. However, if the heating is excessive, e.g., autoclaving at 130 ^{o}C for 24 hr or even heating at 90-100 ^{o}C for prolonged periods even at neutral pH, the nutritive value is impaired and one mechanism is believed to be cross-linking of peptide bonds by acylation of free amino groups [17,22]. Such cross-linking makes lysine unavailable due to the acylation, or by making the peptide bonds difficult to hydrolyze. Lysine is particularly more sensitive than other amino acids because of its free primary epsilon amino group. In the surface layers of the food product, where the temperature is high, bound or free serine, cystine and cysteine are converted to a dehydroprotein intermediate that reacts with the 6-amino group of lysine to form lysinoalanine [23]. Another sensitive amino acid lost during excessive heating of soy products is tryptophan, due to the indole group. Severe heating of soy proteins can also cause formation of hydrogen sulphide from cystine by destruction of the sulfhydryl groups, thereby destroying this essential amino acid [23]. This reaction is also catalyzed by alkali and generates lysinoalanine, an unavailable and potentially toxic compound [23]. In the rat, ingestion of lysinoalanine is often accompanied by diarrhoea, pancreatic hyperplasia, and loss of hair [23]. These manifestations have been linked to formation of covalent bonds, isomerization of essential amino acid residues and possibly the appearance of toxic substances. However, these effects and renal injury (nephrotoxicity) have not been demonstrated in hamsters, mice, quails and monkeys [23], probably due to differences in the types of metabolites formed in rats vs. other animals. At the levels present in foods, protein-bound lysinoalanine apparently does not cause nephrotoxicity in humans, probably due to its excretion in the urine, as the human body does not use it [16]. Generally, when submitted to heat treatments at alkaline pH, certain other amino acid residues are also destroyed. Arginine is converted to ornithine, urea, citrulline and ammonia, while cysteine is converted into dehydroalanine [23]. The amounts of serine, threonine, and lysine in foods are also reduced at alkaline pH. These conditions may be present during alkali refining of soy oil. Many of the chemical reactions affecting amino acid residues are often accompanied by protein-protein interactions involving the formation of covalent bonds [23]. Investigations show that the decline in the biological value, protein efficiency ratio and net protein utilization is in proportion to the length and severity of the treatment applied. Since thermal denaturation is also a prerequisite to heat-induced gelation of soy proteins [16], it is advisable to have a clear understanding of the basic environmental conditions regarding protein dynamics so that structural stability and functionality of soy proteins is not adversely affected in food systems. Generally, amino acid composition affects thermal stability of proteins, with proteins that contain a large proportion of hydrophobic amino acid residues, especially Val, Ile, Leu and Phe, being more stable than the more hydrophilic proteins [20]. Soy protein has a similar digestibility to that of milk protein as it has Tyr, Phe, Ile, Leu, Lys content that is comparable to that of milk protein, but has a lower Val, Trp, Thr and Met + Cys content; it is stable to heat up to about 92 ^{o}C [16]. Also, a moisture content in the SB greater than 30% makes it easier to denature its protein due to greater hydration, swelling and unravelling [24]. Processing operations that involve the use of high pressure, shear, and high temperature including homogenization, high-speed blending and extrusion of soy products, generally result in protein denaturation with adverse consequences in some cases on soy protein digestibility and bioavailability [25]. Irreversible protein denaturation can also be explained as resulting from deamidation of aspartic acid (As) and glycine (Gln) residues, cleavage of peptide bonds at As residues, destruction of cysteine (Cys) and cystine residues, and aggregation [22, 26]. Additives such as salts and sugars affect the thermal stability of proteins in aqueous solutions. It is reported that sucrose, lactose, glucose and glycerol stabilize proteins against thermal denaturation by increasing their T_d [27].

Soy haemagglutenins are also denatured by autoclaving, extrusion cooking, sterilization, baking or domestic cooking [23]. On denaturation, the digestibility of the soy protein may improve. However, their presence may impair nutritional quality of legume diets because being glycoproteins, they are poorly digested, and also participate in chemical reactions during processing, thereby reducing protein digestibility [28]. Nevertheless, soy haemagglutenins are also potentially useful as they have been shown to contribute to intestinal mucosal growth and regeneration, thereby preventing gut atrophy [29].

Effects of alkali and other chemical agents on soybean protein

All naturally occurring amino acids are in the L form, and it is this form that is nutritionally available. Alkali treatment of proteins can cause isomerization of the L to D isomer, thereby making the particular amino acid unavailable [30]. Acid hydrolysis of foods also causes some racemization of amino acids [31], as does roasting of proteins or protein containing food above 200 ^{o}C [32]. While this reaction is known to occur, it is not considered a problem where small amounts of amino acids are isomerized. Also, in the presence of carbohydrates with free reducing groups, protein reacts with exposed carbonyl groups as the first step of the Maillard (non-enzymatic browning) reaction. The epsilon amino group of lysine is involved and lysine can become unavailable as a nutrient. Alkali, heat, and low moisture can catalyze the Maillard browning reaction. To avoid lysine loss, care must therefore be taken not to overheat soy meal for long periods of time. Most proteins are stable around neutral pH, but at extreme pH values on either side of pH 7, high net charge results in swelling and unfolding of protein molecules. This is more adverse at extreme alkaline pH than at extreme acid pH [16]. Most processing procedures with soybeans such as soy oil extraction, bleaching, extrusion, occur at alkaline pH, and, therefore, the potential loss of labile amino acids is considerable. The greater potential denaturation of proteins at alkaline pH is attributed to ionization of partially buried carboxyl, phenolic and sulfhydryl groups that cause the unravelling of the polypeptide chains as they expose themselves to the aqueous environment [16]. Most organic solvents and detergents also denature proteins due to their solubilizing effect on nonpolar side chains [33].

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Effects of oxidation on soybean protein

Heating proteins in air, exposure to peroxides formed in lipid oxidation, or exposure to H_2O_2 and benzoyl peroxide can oxidize some amino acids-particularly the sulphur amino acids and tryptophan [16]. The amino acids most susceptible to oxidation are

Met, Cys, Trp and His, but to a lesser extent, Tyr [16]. Since the sulphur amino acids are limiting in soy protein, any loss is of potential nutritional significance and should therefore be avoided. Cystine and cysteine are oxidized to cysteic acid and cysteine sulphenic acid [16]. The former is not capable of replacing cysteine nutritionally, but the less severely oxidized cysteine sulphenic acid and cystine mono- and disulphoxides can substitute for the amino acids [16]. Methionine can also be oxidized sequentially to methionine sulphoxide and then to methionine sulphone; the latter can be used nutritionally, but the former cannot [34]. Thermal treatment carried out in the presence of oxygen leads to partial destruction of the tryptophan residues in soy proteins [35]. As tryptophan is readily oxidized at both alkaline and acidic pH, this can be of concern in processed foods [35]. Above 200 ^{o}C, as well as heat treatments at alkaline pH cause isomerization of amino acid residues, leading to formation of racemic mixtures of L and D forms [30]. These conditions can be present during baking, grilling and boiling of most foods including soy products. Since D isomers have no nutritional value, racemization of an essential amino acid thus severely reduces its nutritional value [23]. Residues such as Asp, Ser, Cys, Glu, Phe, Asn, and Thr are racemized at a faster rate than other amino acid residues due to the higher electron withdrawing power of the peptide chain and the higher hydroxyl concentration; however, racemization rate is reported to be independent of protein concentration [36]. Racemization reduces the digestibility of the protein and therefore its bioavailability (due to the lower potential hydrolysis by gastric and pancreatic proteases) of the D forms in vivo compared to those containing only the L residues [16]. Some D-amino acids, such as D-proline have also been found to be neurotoxic in chicken [37], but their effects in humans have not been studied.

When lipids are present at a concentration >0.5%, there is a marked improvement of the foaming properties of soy proteins [16]. This is probably due to the greater surface activity of lipids compared to proteins, causing them to adsorb at an air-water interface, thereby inhibiting protein adsorption during foam formation. Thus lipid free soy protein and soy protein isolates are likely to display better foaming properties than lipid-contaminated preparations.

Effects of processing on soybean lipids

Exposure to high temperatures either during SB toasting, boiling or extrusion cooking, may introduce changes to lipids in soybeans and their food products in ways that can affect their nutritional value and sensory appeal. Some of these changes include lipid oxidation in the presence of oxygen, loss of oil from the raw material depending on the temperature and the time at the high temperature, and change of the fatty acids from the *cis* isomeric forms to the *trans* fatty acids forms [38]. Loss of oil may reduce the caloric value of the SB food product, although this may not often affect the energy value of the food to a noticeable level, as energy is often not the limiting consideration in mixed human diets. Lipid oxidation is an important reaction is food systems, where complex sequences of reactions result from the interaction of lipids with oxygen. The result is decomposition of unsaturated fatty acids at the double bonds, into small, volatile molecules that produce off-flavours, resulting in oxidative rancidity. These aromas are detrimental to some foods, but desirable in fried foods, cheeses and dried cereals [39]. Where lipases liberate small aroma compounds without the need for oxygen, the reaction products result in hydrolytic rancidity. These off-flavours are discerned in soy foods as "grassy" but in marine oils as "fishy" [39]. In soy oil, the presence of considerable amount of ω-6 fatty acids has been blamed partly for this phenomenon [39]. Some oxidation products may be cleaved into free radicals with extended oxidative contact of the unsaturated fatty acids in SB products with oxygen. The free radicals initiate and propagate oxidation. The linolenic, linoleic and oleic unsaturated fatty acids in soy foods are preferentially destroyed in that falling order, due in part to their decreasing relative reactivity [12]. Hydroperoxides also react with amino acids such as Lys, Cys or Met. Because lipid-protein complexation products are insoluble in water, they may be difficult to hydrolyze, and so may cause digestive problems if present in large quantities in foods [40]. These oxidized lipid-protein interaction products are reported to be important precursors of atherosclerotic plaques in vivo [41].The refining of soy oil has some minor effects on its nutritive value, for steps that are done at temperatures below 100 ^{o}C. Carotenoids are lost on bleaching, implying reduction of Vitamin A potential [13]. Although vitamin E is lost during refining, the amount remaining still makes soy oil an excellent source of vitamin E [13]. Thermal processes such as roasting and toasting do not seem to have any effect on the amount of isoflavones in soy products, but being ethanol-soluble, most lipid solvents would remove them. The most significant changes in soy oil that might have some influence on nutritive value and human health, are the changes from *cis* to *trans* configuration of fatty acids around the double bonds during hydrogenation, and, changes in frying oils after exposure to high temperatures for long periods of time [41]. During hydrogenation, the saturation of the double bonds in formerly polyunsaturated fatty acids may reduce the essential fatty acids in the resulting hydrogenated oils. Hydrogenation thus results in the loss of nutrient value of the original oil with respect to the unsaturated essential fatty acids.

Effects of hydrogenation of soybean lipids on consumer health

Trans fatty acids are found naturally in ruminant food products, albeit in small amounts, and so humans have been exposed to them for thousands of years. Also, since the increased consumption of hydrogenated oils over the last 50 years or so, no conclusive clinical evidence either in the short- or long-term, has shown any considerable toxic effects due to partially or fully hydrogenated soy oil consumption. Nevertheless, the presence of *trans* fatty acids in foods has recently elicited close scrutiny from the scientific community. Most unsaturated fatty acids in nature are found in the *cis* double-bond configuration, but during hydrogenation of vegetable oils with considerable unsaturation as for soy oil, and the processing of food in oil at high temperatures (usually >220 ^{o}C as in hydrogenation, frying and deep-oil frying), inversions of the double bonds occur resulting in *trans* fatty acid isomers [13]. The *trans* fatty acids exist in structural forms that mimic saturated fatty acids. They also have higher melting points than their *cis* counterparts, thus the effect of hydrogenation leading to the formation of the *trans* isomers of unsaturated fatty acids results in fats that are more plastic and harder than the original oils [13]. Hydrogenated vegetable oils are currently a major source of *trans* fats in human diets [42, 43]. Despite trends towards reducing *trans* fats in margarines and hydrogenated vegetable oils in developed countries, the applicable technologies are not yet widely used in edible oils processing in Africa, but are on the increase. *Trans* fats have been shown to be nearly as hypercholesterolemic as myristic or palmitic acids [44]. It was shown recently that palmitoleic acid, C16:1, alters serum lipoproteins in a manner similar to C14:0 (myristic acid) and C12:0 (lauric acid) [45]. However, *trans* fatty acids appeared less hypercholesterolemic than 14:0 (the most hypercholesterolemic saturated fatty acid) and C12:0 [45]. It was also shown that lipoprotein a (Lpa) was increased by a high *trans* fat diet compared to a stearic-enriched diet [45]. Since Lpa is a strong independent risk factor for CVD, a high *trans* fat diet may contribute to the risk of CVD [42, 46, 47]. Mensink and Katan [48] concluded that since *trans* fatty acids raise LDL-cholesterol and decrease HDL-cholesterol, they are as unfavourable as the saturated fatty acids. The American Heart Association [43] recommends lowering their dietary intake. Mozaffarian et al. [42] recommend limiting their content in foods to 2-7 g in a-2000 calorie diet (contributing 20-60 calories in the diet). In the US as of January 2006, all manufactured foods have to list the trans fatty acid content on package labels, although those with less than 0.5 g of fat/serving do not have to declare it as long as no health claim is made about the fat, fatty acid or cholesterol content [39].

Cooking of food is known to cause complex chemical changes that are often not fully understood. Exposure of fats and oils to high temperatures for prolonged periods during the frying of foods, and, the effects of heat on fats have been studied extensively [49, 50]. Fatty livers, decreased fat absorption, growth retardation, diarrhoea and interference with reproduction in female rats have been noted implying toxicity of the complex constituents [40, 51]. Despite these effects, such severely oxidized fats causing these undesirable symptoms in animals would not normally be willingly consumed by humans.

Effects of processing on soybean carbohydrates

Due to the presence of carbohydrate in soy products, some Maillard browning would be expected due to the potential reaction between exposed amino groups on amino acids and reducing sugars, especially where product processing temperatures exceed 150 ^{o}C [23]. In ruminant experiments, reduction in particle size of soy flours increased both the degradability of crude protein (CP) and nonstructural carbohydrates in the rumen [52]. In another experiment, however, heat treatment decreased the degradability of CP and increased the degradability of soy flour nonstructural carbohydrates in the rumen [53]. Moisture improves the effect of heat on the degradation of starch. Starch digestibility is improved by heating in *in vitro* tests. It was reported that heating increased metabolizable energy and amino acid bioavailability from full-fat and fat extracted soybean in the hen [52].

Effects of processing on soybean minerals

SB processing does not seem to cause large losses of trace minerals with the exception of silicon, which seems to associate with the adhering soil and dissolves in wash water and is consequently lost [54]. Sodium, K, Mg and Ca may also be lost where excessive water for washing and preparation is used and discarded. When SB is concentrated with respect to protein, it is found that there is an increase in the iron, zinc, aluminium, strontium, and selenium contents. This implies that they may be bound or intimately associated with the protein fraction. Molybdenum, Bo, Co, Mn, I and Ba show variable changes without any particular trend [54]. Generally, during processing, the majority of SB minerals follow the protein or meal. Some Ca, P and Mg can be extracted with phospholipids and become part of the oil. Others such as Fe and Cu are contaminants, since they are strong peroxidants [55]. They arise from the original beans or from metal contact during processing.

Effects of processing on soybean omega-3 fatty acids

ω-3 and 6 fatty acids which are present in almost equal proportion in soy oil, are bioactive compounds that play important roles in membrane fluidity, cellular signaling, gene expression and eicosanoid metabolism [39]. Phytosterols, conjugated linoleic acid (CLA) and carotenoids are also important bioactive compounds. Soybeans are rich plant sources of the ω-3 and -6 fatty acids, carotenoids and phytosterols. Probiotic yoghurt (a fermented dairy product) made with milk containing increased CLA and concentrated trans vaccenic acid (TVA) and which was heat treated at 85 ^{o}C for 30 min, did not show any significant reduction in the amount of CLA and TVA [56]. However, in an experiment using high amounts of ω-3 fatty acids to replace milk fat, it was shown that the process negatively affected the texture (increased syneresis and loss of firmness) of the yoghurt made, although it did not affect the typical yoghurt flavour and nutritive value [57]. However, there should be concern about the likely oxidative loss of the ω-3 fatty acids, during thermal processing and long-term storage of fortified foods.

Effects of processing on soybean vitamins

Tocopherols are inhibitors of photosensitized, singlet-oxygen- mediated oxidation of SB oil. However, despite the demonstrated stability in the absence of oxygen, Vitamin E degradation can occur in the presence of oxygen, especially when free radicals are also present. The processing of SB into tofu resulted in a 30-40% loss of vitamin E, although tofu is a greater source of tocopherols than the whole bean on a dry weight basis [55]. During oil extraction from the SB, vitamin E goes into the oil, similar to other lipid–soluble vitamins, while water soluble vitamins would be lost where broth or processed products are washed and the resulting liquids discarded. Pryde [58] reported that soy oil contains 9-12 mg/g of α-tocopherol (alpha-tocopherol), 74-102 mg/g of γ-tocopherol (gamma-tocopherol) and 24-30 mg/g of δ-tocopherol (delta tocopherol). The amount of beta-tocopherol (β-tocopherol) in the SB is insignificant, being less than 3% of the total. Soymilk processed by the rapid hydration hydrothermal cooking method had higher thiamine and protein compared to the traditionally extracted soymilk [59]. The yield of the traditionally processed SB curd also had a higher protein and fat, while the carbohydrate and ash were lower, compared to that processed by the rapid hydration hydrothermal cooking procedure. There was also variation in the amino acid composition in both the curds and soymilks by the two procedures [59]. Vitamin K and A are fairly stable during thermal processing of soy foods. Generally, different processing procedures have different effects on each vitamin depending on its structure and the environmental conditions, making it difficult to predict and generalize results.

Effects of processing on soybean isoflavones

In an experiment involving women volunteers, urinary excretion of one of the isoflavones, equol, was associated with a higher dietary intake of dietary fibre and carbohydrate. It was also shown in the same experiment that fermentation of soy decreased the isoflavone content of the product, but increased the urinary isoflavone recovery, implying that fermentation increases bioavailability of isoflavones in soy [60]. Processing of soy therefore seems to affect isoflavonoid metabolism and may need to be factored in when recommending exposure to isoflavones from soy foods. The study showed that although optimal isoflavonoid exposure for disease prevention has not been determined, urinary isoflavonoid excretion appears linear at low to moderate concentrations of 5- 20 g soy protein powder/day (i.e., approximately 9- 36 mg isoflavones/day) [60].

CONCLUSIONS AND RECOMMENDATIONS

Due to the mild conditions at which the preparatory steps for further soybean processing are performed, the loss in nutritive value is minimal. Dehulling may reduce the total mineral content of the bean, while drying at temperatures of 60-90 ^{o}C may cause little denaturation of protein, but could lead to loss of thermally unstable amino acids, depending on treatment time. Lipid-protein interaction may also affect the bioavailability of some amino acids leading to a reduction of the essential fatty acids and amino acid content. Heat inactivation of trypsin inhibitors and denaturation of soybean globulins make soy protein more susceptible to proteolysis, thereby improving its bioavailability. Many of the chemical reactions affecting amino acid residues are often accompanied by protein-protein interactions involving formation of covalent bonds, which may reduce their bioavailablity. Excessive thermal denaturation and heat-induced interactions may form mutagenic and toxic compounds. Hydrogenation results in the formation of the hypercholesterolemic trans fatty acids isomers implying potential loss of the unsaturated essential fatty acids. Overall, processing can cause changes in the sensory appeal and the nutritive value of soybeans and soy products. To minimize adverse changes, minimal washing, fermentation and thermal processing below 100 ^{o}C for short periods are recommended, although the higher temperatures used during soy oil hydrogenation will unavoidably introduce health-related adverse changes. Lowering hydrogenation temperature and changing the catalyst may reduce formation of the undesirable trans fatty acids and therefore long-term potential harm to consumer health

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