COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Health-Affecting Compounds in *Brassicaceae*

Muhammad Jahangir, Hye K. Kim, Young H. Choi, and Robert Verpoorte

ABSTRACT: *Brassicaceae* vegetables are considered to be a staple food in many areas all over the world. *Brassica* species are not only known for their high fat and protein contents for human and animal consumption, but *Brassicaceae* vegetables are recognized as a rich source of nutrients such as vitamins (carotenoids, tocopherol, ascorbic acid, folic acid), minerals (Cu, Zn, P, Mg, among others), carbohydrates (sucrose and glucose), amino acids (for example, L-alanine, L-aspartic acid, L-glutamic acid, L-glutamine, L-histidine, L-methionine, L-phenylalanine, L-threonine, L-tryptophan, and L-valine), and different groups of phytochemicals such as indole phytoalexins (brassinin, spirobrassinin, brassilexin, camalexin, 1-methoxyspirobrassinin, 1-methoxyspirobrassinol, and methoxyspirobrassinol methyl ether), phenolics (such as feruloyl and isoferuloylcholine, hydroxybenzoic, neochlorogenic, chlorogenic, caffeic, *p*-coumaric, ferulic, and sinapic acids, anthocyanins, quercetin, and kaempferol), and glucosinolates (mainly glucoiberin, glucoraphanin, glucoalyssin, gluconapin, glucobrassicanapin, glucobrassicin, gluconasturtiin, and neoglucobrassicin). All of these phytochemicals contribute to the reported antioxidant, anticarcinogenic, and cardiovascular protective activities of *Brassica* vegetables. However, not all members of this family are equal from a nutritional viewpoint, since significant qualitative variations in the phytochemical profiles of *Brassica* species and varieties suggest differences in the health-promoting properties among these vegetables. In this article, *Brassica* phytochemicals with their nutritional value and health-promoting activities are discussed to give an overview of the literature for *Brassica* as a staple crop.

Introduction

The *Brassicaceae* (Cruciferae) family is composed of 350 genera and about 3500 species (Sasaki and Takahashi 2002), including some crops of great economical importance such as *Brassica napus* L., *Brassica rapa* L., and *Sinapis alba* L. (O'Callaghan and others 2000; Onyilagha and others 2003). These species are used as food, spices, and as a source of vegetable oils (Kaushik and Agnihotri 2000). The *Brassicaceae* vegetables represent a major part of the human diet (Verkerk and others 1997) being consumed by people all over the world (Font and others 2005; Sardi and Tordai 2005; Ferreres and others 2007) and are considered important food crops in China, Japan, India, and European countries (Heaney and Fenwick 1995; Sasaki and Takahashi 2002; Kusznierewicz and others 2008). Over the past 3 decades, *Brassica* production has grown steadily becoming an important source of oil and protein of plant origin for animal and human nutrition, respectively. Rapeseed (canola) ranks currently as the 3rd source of vegetable oil (after soy and palm) and the 3rd leading source of oil meal (after soy and cotton) (Thiyam and others 2004). *Brassica* is an inexpensive, though very nutritive, source of food, providing nutrients and health-promoting phytochemicals such as phenolic compounds, vitamins (Dekker and others 2000; Vallejo and others 2002, 2003, 2004), phytic acid, fiber, soluble sugars (Pedroche and others 2004), glucosinolates (Fowke and others 2003), minerals, polyphenols (Heimler and others 2005), fat, and carotenoids (Figure 1) (Zakaria-Rungkat and others 2000). There is currently much interest in identifying phytochemicals with useful biological activity in food (Rice-Evans and others 1997), and any significant finding related to the presence of valuable compounds in *Brassica* species will be welcomed by the food industry (Thiyam and others 2004).

There is ever-increasing evidence that a higher consumption of *Brassica* vegetables, for example, broccoli, cabbage, kale, mustard greens, Brussels sprouts, and cauliflower, reduces the risk of several types of cancer (Kristal and Lampe 2002; Wang and others 2004). The anticarcinogenic effect of these vegetables has been attributed to decomposition products of glucosinolates, indoles, and iso-thiocyanates (Zukalova and Vasak 2002), phytoalexins, and other antioxidants (Samaila and others 2004; Hanf and Gonder 2005). Indole-3-carbinol, a natural component of *Brassica* vegetables (Staub and others 2002), has an interesting anticarcinogenic potential, acting via different metabolic and hormonal pathways (Hanf and Gonder 2005) and have been proved to reduce the incidence of tumors in reproductive organs (Staub and others 2002) and the growth of human breast cancer cells (Cover and others 1998).

Overall, to date, the most promising anticarcinogenic dietary compounds have been detected in cruciferous vegetables and further elucidation of their protective mechanisms and the identification of other active constituents may contribute to the development of highly health-supporting *Brassica* varieties (Steinkellner and others 2001). Extracts of the different species of the *Brassicaceae* family show antioxidant effects (Azuma and others 1999) and decrease oxidative damage (Ferguson 1999), while

MS 20080522 Submitted 7/11/2008, Accepted 10/3/2008. Authors are with Div. of Pharmacognosy, Section Metabolomics, Inst. of Biology, Leiden Univ., Leiden, The Netherlands. Direct inquiries to author Verpoorte (E-mail: verpoort@chem.leidenuniv.nl).

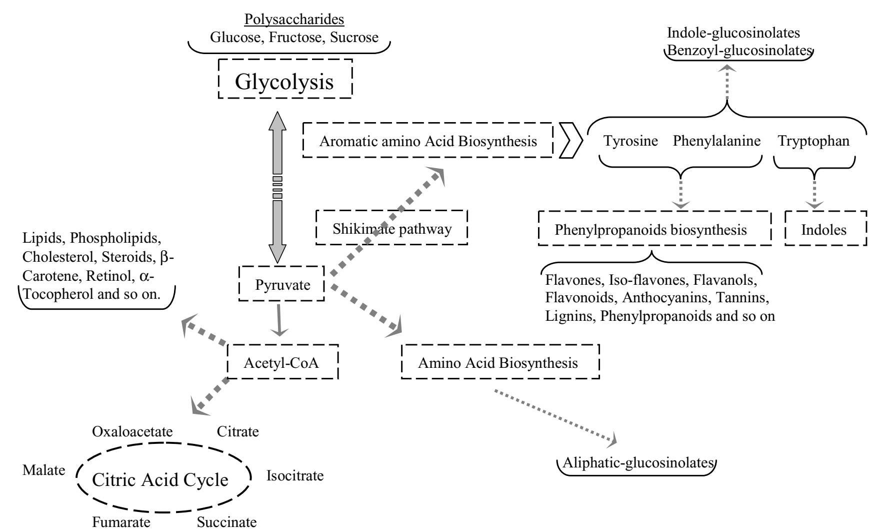


Figure 1 – General biosynthesis pathway for *Brassicacae* metabolites (Dixon and Paiva 1995; Graser and others 2000; Dixon 2001; Shirley 2001; O'Connor and Maresh 2006).

the juice of some *Brassica* species has been proved to protect human hepatoma cells from the genotoxic effects of carcinogens (Steinkellner and others 2001). However, compounds such as glucosinolates and phytates may also have a negative effect on human and animal health. For example, glucosinolates and glucosinolate by-products can be toxic and are responsible for the bitter, hot, and pungent flavors of *Brassicaceae* vegetables (Kopsell and others 2003). Also, thiocyanates, isothiocyanates, and oxazolidine-2-thiones have been shown to be goitrogenic (Mithen and others 2000), and while *Brassicaceae* vegetables can be a good source of minerals, some antinutrients, such as phytates, can decrease their bioavailability (Matthaus and Angelini 2005).

The purpose of this article is to provide an overview of health-affecting compounds identified in the *Brassica* genus.

Vitamins

Brassica vegetables contain high levels of vitamins (Heimler and others 2005), including carotenes, tocopherols (Kurilich and others 1999), vitamin C, and folic acid (Verhoeven and others 1996) (Table 1). It is a well-known fact that the first 3 vitamins have the potential to prevent and treat malignant and degenerative diseases (Kurilich and others 1999). Broccoli (*Brassica oleracea*) extracts are protective against reactive oxygen species (ROS) presumably due to the presence of vitamin C, quercetin, kaempferol, lutein, zeaxanthin (Kurilich and others 2002), α-tocopherol, γ-tocopherol, and β-carotene (Eberhardt and others 2005). Bioavailabilty is a critical feature in the assessment of the role of these compounds in human health. When 200 g of broccoli were consumed by healthy volunteers, significant changes, in serum, in both men and women were observed only for lutein, whereas for γ-tocopherol a significant change was detected in women only, whereas no changes were observed for α-tocopherol, β-carotene, and retinol (Granado and other 2006).

Carotenoids

In some *Brassica* species, carotenoid content is 2-fold higher than in spinach (Miyazawa and others 2005). Sixteen carotenoids were identified by Wills and Rangga (1996) in *B. chinensis*, *B. parachinensis*, and *B. pekinensis*, out of which lutein and β-carotene were the most abundant (Riso and others 2003). Lutein has also been isolated from extracts of fresh raw kale (*Brassica oleracea* var. *Acephala*) (Khachik and others 1999) and high levels of other carotenoids, mainly β-carotene, were also detected (Kurilich and others 1999; Kopsell and others 2003; Lefsrud and others 2006). Two other vegetables, Brussels sprouts and green cabbage, have been reported to contain significant amounts of *trans*-β-carotene and *cis*-β-carotene (Podsedek

Table 1 – Variation of vitamins (μg/g) among different *Brassicaceae* vegetables on fresh weight basis.

	Ascorbic acid	α-Carotene	β-Carotene	α-Tocopherol	Folate
Broccoli	748 ± 62^{a}	0.3^{b}	8.9^{b}	16.2^{b}	1.771^{d}
Kale	186^{e}	0.6^{b}	48.6^{b}	19.2^{b}	–
Cauliflower	499 ± 53^{a}	–	72 ± 0.5^{g}	1.7^{b}	0.53^{e}
Chinese cabbage	253^{a}	–	0.1^{c}	0.8^{c}	0.81^{f}
White cabbage	188 ± 13^{a}	0.02^{b}	0.8^{b}	1.7^{b}	–
Brussels sprouts	158^{c}	–	1.4^{c}	1.5^{c}	–

[a]Bahorun and others 2004.
[b]Kurilich and others 1999.
[c]Singh and others 2007.
[d]McKillop and others 2002.
[e]Boonstra and others 2002.
[f]Devi and others 2008.
[g]Singh and others 2001.

2005). Carotenoids present in dark green leafy vegetables might be involved in the prevention of several diseases related to oxidative stress (Riso and others 2003).

Tocopherols

The predominant tocopherol in all *Brassica* vegetables is α-tocopherol with the exception of cauliflower, which predominantly contains γ-tocopherol (Piironen and others 1986). The tocopherol content of rapeseed oil consists of 64% γ-tocopherol, 35% α-tocopherol, and less than 1% is the mixture of δ-tocopherol and plastochromanol-8 (Goffman and Mollers 2000).

Vitamin C

High levels of vitamin C have been reported in Chinese cabbage, broccoli, cauliflower, and cabbage (Bahorun and others 2004) (Table 1). The content of this vitamin in different cultivars of cabbage (*Brassica oleraceae* L.) ranges from 12 to 112.5 mg/100 g (Goldoni and others 1983).

Folic acid

Raw broccoli (McKillop and others 2002), cauliflower (Boonstra and others 2002), and cabbage contain folic acid (Puupponen-Pimia and others 2003) (Table 1), a scarce and important vitamin that acts as a coenzyme in many single carbon transfer reactions in the synthesis of DNA, RNA, and protein components (Devi and others 2008). Folic acid reduces the risk of neural tube defects (NTDs) and may be associated with the reduced risk of vascular disease and cancer (Bailey and others 2003; Cornel and others 2005), while low-folate intake has been identified as a main cause of anemia (Bollheimer and others 2005).

Minerals

Brassica plants have been found to be rich in many minerals including calcium and iron (Miyazawa and others 2005). Among the green leafy vegetables, *B. oleracea* L. *acephala* (kale) is an excellent source of minerals (Kopsell and others 2003), accumulating high levels of P, S, Cl, Ca, Fe, Sr, and K (Table 2) (Tirasoglu and others 2005). Broccoli accumulates Se to concentrations many times above that found in soil, which may greatly enhance its health-promoting properties (Finley 2003). Different *Brassica* vegetables such as cauliflower, bok choy (*B. rapa*) stems and leaves, broccoli (*B. oleracea* v. *botrytis*), and kale (*B. oleracea* v. *acephala*) are reported to have high mineral contents (Puupponen-Pimia and others 2003) (Table 2). Interestingly, all these *Brassica* vegetables exhibit excellent calcium bioavailability (Heaney and others 1993). Cabbage leaf (*B. oleracea* var. *capitata*) also contains potentially useful amounts of copper, zinc, iron, and a number of other essential minerals and trace elements (Glew and others 2005).

Brassica can be cultivated under hydroponic conditions such that lead to high levels of nutritionally important minerals such as Cr, Fe, Mn, Se, and Zn. Owing to reproducible and high concentration of minerals in the edible plant tissue small quantities of this enriched plant can be processed to make capsules or tablets that supply 100% of the recommended daily intake of these elements, with the advantage of using a natural plant source (Elless and others 2000). However, the bioavailability of some of these minerals might be reduced by the presence of glucosinolates, phytates, and phenolics (Matthaus and Angelini 2005).

Heavy metals (for example, Mo, B, Co, Se, Cd, Pb, Cr, Ni, Hg, and As) and others such as Cu, Zn, Mn, and Fe may be found in high concentration in contaminated soils and have toxic effects on plants, animals, and human beings (He and others 2005). The use of metal-accumulating plants to remove toxic metals from soil is known as phytoremediation (Salt and others 1995) and *Brassica* species such as *B. oleracea* and *B. napus*, known for their metal accumulator properties, are used for this purpose (Banuelos 2006). However, this characteristic, which constitutes an advantage for the former use entails, an important toxicological risk if these fruits and vegetables grown in contaminated soils are ingested (Dudka and Miller 1999).

Lipids

Rapeseed oil is one of the most common edible oils in the world. Its nutritive value is excellent due to its unsaturated fatty acid content (Naczk and others 1998). Mustard oil is also a significant source of unsaturated fatty acids containing about 94.2%, and only 5.4% saturated fatty acids. These are recognized as essential dietary elements with important effects on human health (Choudhury and others 1997). Mustard oil contains linolenic acid, 21.4% (omega-3); palmitic acid, 2.9%; palmitoleic acid, 0.2%; stearic acid, 1%; oleic acid, 19.4%; linoleic acid (omega-6), 9.7%; and erucic acid, 44.4% (Dwivedi and others 2003), showing an inhibition of mutagenicity (Choudhury and others 1997). Oil content in seeds of different *B. campestris* genotypes varies from 38.9% to 44.6% and major fatty acids found are oleic, linoleic, linolenic, eicosaenoic, erucic acid ranging from 10.1% to 17.3%, 5.9% to 14.5%, 5.2% to 15.0%, 7.7% to 13.7%, and 39.6% to 59.9%, respectively (Ahuja and others 1989). Canola seed oil is one of the richer sources of omega-3-unsaturated fatty acids (Hanf and Gonder 2005) and, in particular, of α-linolenic acid (Vermunt and others 2001). The oil of commercial *B. napus L.* is rich in oleic acid and contains moderate levels of linoleic and linolenic acid (Adamska and others 2004).

Cauliflower is considered to be a food of high nutritional value and some authors relate its quality to the stability of its fatty acids. Environmental stress may enhance the fatty matter content (linolenic acid) and polyphenols (Scalzo and others 2007).

Table 2—Variation of minerals (μg/g) among different *Brassicaceae* vegetables on fresh weight basis.

	Broccoli	Kale	Cauliflower	Chinese cabbage	White cabbage	Brussels sprouts
Ca	272 ± 20[a]	2860 ± 430[b]	175 ± 17[a]	470 ± 60[b]	440 ± 60[b]	356 ± 13[a]
Fe	8.7 ± 0.5[a]	4 ± 2[b]	5.0 ± 0.3[a]	2 ± 0.3[b]	1.4 ± 0.3[b]	7.6 ± 0.2[a]
Cu	0.94 ± 0.07[a]	0.4 ± 0.2[b]	0.56 ± 0.07[a]	0.4 ± 0.2[b]	0.5 ± 0.5[b]	0.9 ± 0.09[a]
Mg	181 ± 8[a]	510 ± 40[b]	145 ± 22[a]	130 ± 30[b]	140 ± 20[b]	207 ± 12[a]
K	2890 ± 70[a]	7120 ± 5170[b]	2210 ± 140[a]	2280 ± 1120[b]	2660 ± 870[b]	4250 ± 250[a]
Zn	9.5 ± 0.3[a]	2.9 ± 0.5[b]	6.4 ± 0.3[a]	2.3 ± 0.4[b]	2 ± 1[b]	5.8 ± 0.4[a]
Na	180 ± 6[a]	120 ± 40[b]	192 ± 27[a]	50 ± 20[b]	30 ± 10[b]	107 ± 7[a]
Mn	1.92 ± 0.09[a]	3 ± 1[b]	1.31 ± 0.07[a]	0.5 ± 1.4[b]	2 ± 1[b]	2.31 ± 0.13[a]

[a]Kmiecik and others 2007.
[b]Kawashima and Soares 2003.

The essential oil of *B. rapa* var. *perviridis* leaves was found to contain 48 volatile components, representing 94% to 96.6% of the oil. The main constituents were found to be 3-butenylisothiocyanate (1.4% to 29.2%), 4-pentenyl isothiocyanate (8.2% to 23.5%), 2-methyl 5-hexenenitrile (1.3% to 16.8%), 2-phenylethyl isothiocyanate (7% to 13.7%), and phytol (6.1% to 23.5%) (Miyazawa and others 2005). Volatile chemicals emitted by rapeseed oil also contain monoterpenes (limonene, sabinene, β-myrcene, and *cis*-3-hexen-1-ol acetate), sesquiterpenes, short-chain aldehydes and ketones, other green leaf volatiles, and organic sulfides including the respiratory irritant, dimethyl disulfide (McEwan and Smith 1998). The emission of volatiles from cabbage consisted mainly of monoterpenes (sabinene, limonene, α-thujene, 1,8-cineole, β-pinene, myrcene, α-pinene, and γ-terpinene). (Z)-3-Hexenyl acetate, sesquiterpene (E, E)-α-farnesene, and homoterpene (E)-4, 8-dimethyl-1, 3, 7-nonatriene were emitted mainly from herbivore-damaged plants (Vuorinen and others 2004).

In *Brassica* oils, triacylglycerols are the main constituents making up about 98% of the oils. The remaining nonglyceridic fraction consists of different lipophylic phytochemicals such as tocopherols, sterols, and sterol esters (Lechner and others 1999). Similarly, in *Brassica* oils the remaining 2% consists of sterols, phospholipids, and sphingolipids. The major sterols were identified as stigmasterol (Appelqvist and others 1981), sitosterol, campesterol, and cholesterol (Lechner and others 1999), the phospholipids as phosphatidylethanolamine and phosphatidylcholine, and the sphingolipids as cerebrosides (Hobbs and others 1996).

For the purposes of human nutrition, a high ingestion of oleic acid and a 2:1 ratio of linoleic:linolenic acid are advantageous (Adamska and others 2004). All polyunsaturated fatty acids including both linoleic and linolenic acids are essential to the human diet because they cannot be synthesized by humans (Ayaz and others 2006). However, the type of fatty acids in the dietary fat is very important, being considered, for example, as one of the detrimental factors in colon cancer development. Fats containing omega-6-polyunsaturated fatty acids were found to enhance chemically induced colon cancer (Dwivedi and others 2003), while omega-3-polyunsaturated fatty acids reduce it (Ferguson 1999; Dwivedi and others 2003). Consumption of diet rich with canola fat may also alter the fatty acid composition of lipids of adipose tissue, muscle, kidney, and liver (Rule and others 1994). A diet high in *trans*-α-linolenic acid may increase plasma LDL/HDL cholesterol and total cholesterol/HDL-cholesterol ratios. Careful deodorization prevents the formation of *trans*-α-linolenic acid and may help to improve the diet (Vermunt and others 2001).

Carbohydrates

The type and concentration of free sugars influence the flavor of *Brassica* products (Rosa and others 2001). Fructose, glucose, and sucrose are the major soluble sugars found in *Brassica* (King and Morris 1994). A comprehensive evaluation of the nutritive profiles of *Brassica* seed meals of yellow-seeded types (*B. napus*, *B. rapa*, *B. juncea*, and *B. carinata*) and conventional brown-seeded (canola) type showed that all contain sucrose (7.5% to 8.7%), oligosaccharides (2.3% to 2.5%), ash (6.9% to 7%), and nonstarch polysaccharides (20.4% to 19.7%) (Simbaya and others 1995). Fructose is the major sugar in the different types of *Brassica*, representing between 48.8% and 56.9% of the total sugar content in broccoli cvs. *Marathon* and *Senshi*, respectively, 48.7% (cv. *Mirandela*) and 53.8% (cv. *Murciana*) in the other cabbages. Glucose is the 2nd major sugar, while sucrose represents a maximum of 20.5% in broccoli cv. *Shogun* and 11.1% in cv. *Murciana* (Rosa and others 2001).

Dietary fiber

It is composed of nonstarch polysaccharides (Knudsen 2001) and is an important constituent in *Brassicaceae* vegetables, contributing to prevention of colon cancer (Rodriguez and others 2006). In white cabbage (*B. oleracea* var. *capitata*) dietary fiber represents one-third of the total carbohydrate content, the other two-third being low-molecular-weight carbohydrates, including glucose (37%), uronic acid (32%), arabinose (12%), and galactose (8%) (Wennberg and others 2002, 2006). The dietary fiber content of 6 cultivars of white cabbage (*B. oleracea* var. *capitata*) was evaluated finding that of the average total dietary fiber of 241 mg/g of dry matter, approximately 25% was soluble (Wennberg and others 2002). Dietary fiber content of other species was found to vary between 271 and 352 mg/g for the yellow-seeded *B. napus* and brown-seeded *B. napus*, respectively (Slominski and others 1999), with intermediate values in other species, such as cauliflower (302 mg/g DW), broccoli (330 mg/g DW), and cabbage (226 mg/g DW) (Puupponen-Pimia and others 2003).

Protein and Free Amino Acids

The defatted meal of *Brassica* oilseeds is a valuable source of protein for the livestock feed industry (Jensen and others 1996) and may constitute an important protein source for human nutrition thereby increasing the value of *Brassica* crops. However, the high temperatures and organic solvents used during the oil extraction process cause denaturation of proteins in *Brassica* meal (Pedroche and others 2004). Protein and free amino acid content in rapeseed meal has a high nutritive value, but the utilization of rapeseed/canola as a source of food-grade proteins for human consumption is still limited due to the presence of antinutrients such as glucosinolates, phytates, and phenolics (Mahajan and Dua 1997; Rozan and others 1997; Naczk and others 1998). Therefore, it is used only for animal feeding (Berot and others 2005). There is a variation in protein content in different groups of *Brassica*, and *B. napus* seeds have higher protein solubilities than meals from *B. rapa* seeds. Meals with higher protein solubility values also have higher foaming capacity values (Aluko and McIntosh 2001). Seeds of rape, *B. napus*, and related cruciferous oilseed crops, such as *B. campestris*, *B. juncea*, *B. carinata*, and *B. nigra* are rich sources of edible protein and rapeseed/canola meal, the by-product of the oil-extraction process, contains up to 42.7% to 50% protein (Simbaya and others 1995; Ghodsvali and others 2005).

The rapeseed (*B. napus*) meal contains napin and cruciferin as storage proteins and oleosin as a structural protein associated with oil bodies (Berot and others 2005; Ghodsvali and others 2005). The 2S albumins or napins in oilseed rape and turnip rape are potential food allergens (Puumalainen and others 2006). Free amino acids are involved in secondary plant metabolism and in the production of compounds that directly or indirectly play an important role in plant–environment interactions and human health. A total of 17 amino acids were identified (L-alanine, L-arginine, L-asparagine, L-aspartic acid, glycine, L-glutamic acid, L-glutamine, L-histidine, L-isoleucine, L-leucine, L-methionine, L-phenylalanine, L-serine, L-threonine, L-tryptophan, L-tyrosine, and L-valine) in *B. oleracea* var. *italica* (Gomes and Rosa 2000; Ayaz and others 2006). *S*-methylcysteine sulfoxide, a naturally occurring *S*-containing amino acid, is contained at high concentrations in *Brassica* vegetables such as broccoli and cabbage. Its cholesterol-lowering effects have been demonstrated in animals, observing a significant decrease of the serum level of LDL-C (14% decrease) following the oral administration of broccoli (*B. oleracea L.* var. *botrytis L.*) and cabbage (*B. oleracea L.* var. *capitata L.*) (Suido and others 2002).

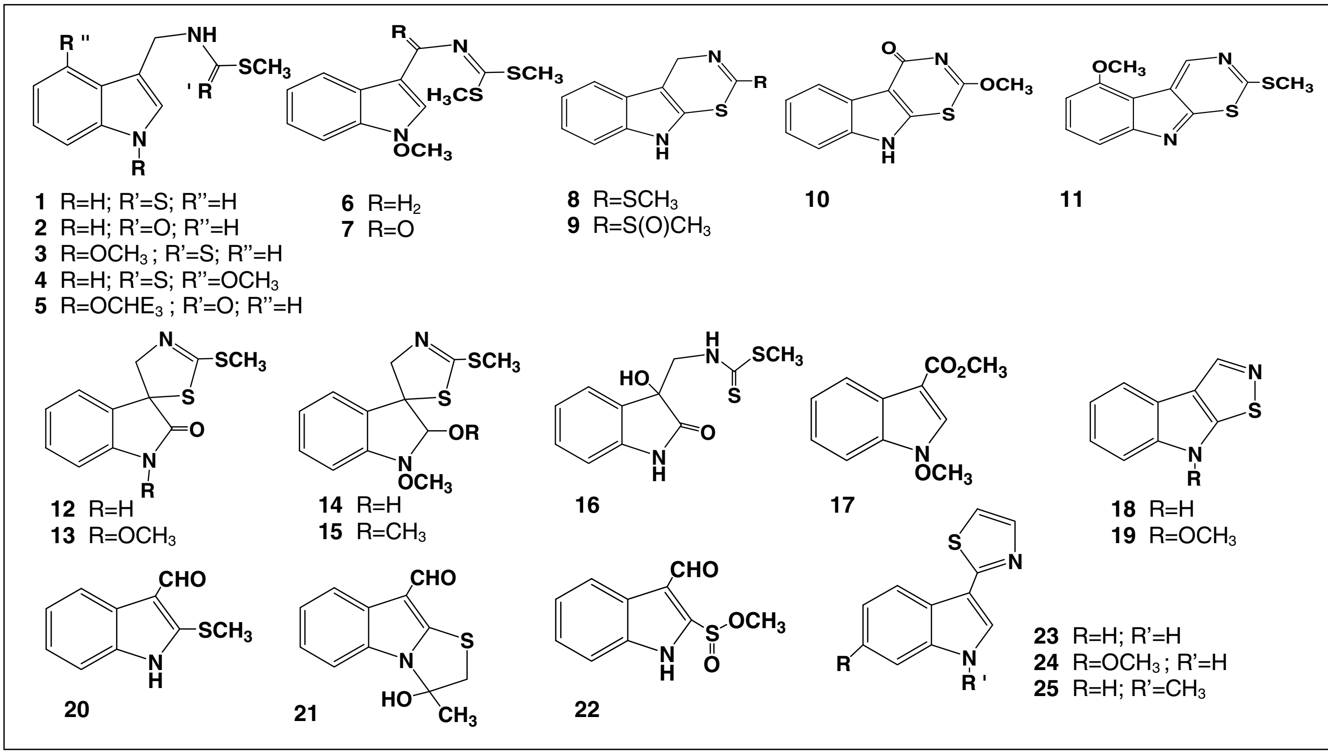


Figure 2—Structures of cruciferous phytoalexins: 1: brassinin, 2: brassitin, 3: 1-methoxybrassinin, 4: 4-methoxybrassinin, 5: 1-methoxybrassitin, 6: 1-methoxybrassenin A, 7: 1-methoxybrassenin B, 8: cyclobrassinin, 9: cyclobrassinin sulfoxide, 10: cyclobrassinone, 11: dehydro-4-methoxycyclobrassinin, 12: spirobrassinin, 13: 1-methoxyspirobrassinin, 14: 1-methoxyspirobrassinol, 15: 1-methoxyspirobrassinol methyl ether, 16: dioxibrassinin, 17: methyl 1-methoxyinodole-3-carboxylate, 18: brassilexin, 19: sinalexin, 20: brassicanal A, 21: brassicanal B, 22: brassicanal C, 23: camalexin, 24: 6-methoxycamalexin, 25: 1-methylcamalexin (Pedras and others 2000).

Indoles

Plants may respond to pathogen attack by producing phytoalexins (Morrissey and Osbourn 1999). Phytoalexins are a group of structurally diverse molecules (Grayer and Harborne 1994; Smith 1996) that are generally nonspecific in their antimicrobial activities (Smith 1996; Rogers and others 1996). A number of phytoalexins have been isolated from crucifers (Figure 2) (Pedras and others 2000).

In *Brassica* indole phytoalexin (camalexin) synthesis is induced as a response to pathogen attack and ROS generating abiotic elicitors (Reuber and others 1998; Roetschi and others 2001). These phytoalexins inhibit the growth of human cancer cells and thus may have a potential use as chemopreventive agents (Samaila and others 2004). Several indole phytoalexins found in *Brassica* vegetables, brassinin, spirobrassinin, brassilexin, camalexin, 1-methoxyspirobrassinin, 1-methoxyspirobrassinol, and methoxyspirobrassinol methyl ether, have been found to possess significant antiproliferative activity against various cancer cells, while others, such as cyclobrassinin, spirobrassinin, and brassinin also exhibited chemopreventive activity in models of mammary and skin carcinogenesis (Mezencey and others 2003).

Brassicaceae species contain a range of signaling and regulatory compounds known to be involved in general defense mechanisms activated by pathogen and herbivore attacks on plants (Kaplan and others 2004). These include salicylic acid, ethylene, H_2O_2, and jasmonic acid (an acid-derived oxylipin) (Kurilich and others 1999) and signal peptides, such as systemin (Ryan and others 2002; Ryan and Pearce 2003; Halitschke and Baldwin 2005). Some of these are bioactive compounds that exhibited anticancer activity in animals when added to experimental diets (Kurilich and others 1999). In particular, jasmonic acid and its derivatives, which represent the best characterized class of signal compounds, mediating the defense responses to wounding and herbivore attack in *Brassicaceae* (Creelman and Mullet 1997; Beale and Ward 1998; Blee 1998; Devoto and Turner 2003; Farmer and others 2003), have been proved to inhibit the proliferation of human prostate cancer cells, while not affecting normal human blood cells (Samaila and others 2004; Flescher 2005).

Phenylpropanoids, Flavonoids, and Tannins

Flavonoids, hydroxycinnamic acids, phenylpropanoids, and other minor compounds (Table 3) are considered to be among the health promoting compounds in *Brassicacae* species (Pascale and others 2007). Plant polyphenols are multifunctional, having diverse biological activities apart from acting as reducing agents (Rice-Evans and others 1996). Phenolics also contribute to the bitter, astringent, and unpleasant flavor of rapeseed, though the threshold of this unpleasant flavor is higher for individual phenolic compounds than for the mixture (Naczk and others 1998). In spite of this, they are considered to be beneficial and harmless components of rapeseed meal.

The contribution of *Brassica* vegetables to health improvement has generally been associated with their antioxidant capacity and, undoubtedly, phenolic compounds are the major antioxidants of *Brassica* vegetables (Ninfali and Bacchiocca 2003; Podsedek 2005; Singh and others 2006). Phenolics is a generic term that

Table 3—Variation of phenolics (μg/g) among different *Brassicaceae* vegetables on fresh weight basis.

	Quercetin	Kaempferol	Apigenin	Lutein
Brassica oleracea L. var. *Italica* (Broccoli)	137[a]	46[a]	–	6.8[c]
Brassica oleracea L. var. *botrytis* L. (Cauliflower)	39[a]	12[a]	2[a]	1.3[c]
Brassica campestris var. *Chinensis* (Chinese cabbage)	390[a]	96[a]	45[a]	0.2[c]
Brassica rapa L. Subsp. *Sylvestris*	102[b]	334[b]	–	–
Brassica oleracea var. *capitata* (white cabbage)	51[a]	–	8[a]	1.4[c]

[a]Bahorun and others 2004.
[b]Pascale and others 2007.
[c]Singh and others 2007.

refers to a large number of compounds that can be classified in groups, namely, phenolic acids, flavonoids, isoflavonoids, lignans, stilbenes, and complex phenolic polymers (Dewick 2001). As mentioned previously, these antioxidants have proved to be good for human health and also useful as food preservatives (Kroon and Williamson 1999). Mustard seeds have a chemopreventive potential and enhance the antioxidant defence system. Their inclusion in the diet may very probably contribute to reducing the risk of cancer incidence in the human population (Gagandeep and others 2005). A rapeseed phenolic extract has shown a stronger antioxidant activity than many artificial antioxidants (Wanasundara and Shahidi 1994) and exhibited a greater efficiency on a mole-to-mole basis than natural antioxidants such as vitamin C, vitamin E, and β-carotene (Rice-Evans and others 1996).

Species of the *Brassicaceae* family are generally rich in polyphenols. *B. rapa* (Naczk and others 1998) and *B. oleracea* L. var. *botrytis* contain a high amount of phenolic compounds (Llorach and others 2003). Phenolic contents of several species have been reported, such as Chinese cabbage (1189 ± 125 μg/g), broccoli (822 ± 89 μg/g), cauliflower (278 ± 15 μg/g), and white cabbage (153 ± 21 μg/g) on a fresh weight basis (Wanasundara and Shahidi 1994; Bahorun and others 2004). In the case of broccoli, hydroxycinnamic acids such as ferulic, sinapic, caffeic, and protocatechuic acids were reported to be the most abundant and important bioactive compounds (Robbers and others 1996; Robbins and others 2005). Four hydroxycinnamic acids (caffeic, *p*-coumaric, ferulic, and sinapic acid) were identified in the water-soluble phenolic fraction of the leaves of oilseed rape (*Brassica napus* L. var. *oleifera*) (Solecka and others 1999) and gallic, protocatechuic, *p*-hydroxybenzoic, vanillic, syringic, salicylic, *p*-cumaric, caffeic, ferulic, and sinapic acid were identified in kale (*B. oleraceae* L. var. *acephala* DC.) (Ayaz and others 2008). The main phenolics in rapeseed meal were determined to be sinapine, which constitutes over 73% of its free phenolic acid content and sinapic acid (Thiyam and others 2004), while rapeseed oil contains vinylsyringol apart from sinapine and sinapic acid (Vuorela and others 2003, 2005). An efficient peroxynitrite scavenger activity has been described for sinapic acid (3,5-dimethoxy-4-hydroxycinnamic acid), which has shown to contribute to the cellular defence against this powerful cytotoxic free radical, thus avoiding peroxynitrite-mediated disorders (Zou and others 2002). Besides the typical seed constituent sinapine, large amounts of choline esters of other phenolic acids have been detected in *Brassicaceae* species, for example, feruloyl- and isoferuloylcholine and hydroxybenzoic acid (Regenbrechta and Strack 1985). *Brassicaceae* plants accumulate glucose esters (1,6-di-*O*-sinapoylglucose), gentiobiose esters (1-*O*-caffeoylgentiobiose and 1,2,60-tri-*O*-sinapoylgentiobiose) of phenolic acids, and kaempferol conjugates (Alfred and others 2005).

Flavonoids are one of the most common and widely distributed groups of plant phenolics. Over 5000 different flavonoids have been described to date and they are classified into at least 10 chemical groups. Among them, flavones, flavonols, flavanols, flavanones, anthocyanins, and isoflavones are particularly common in the human diet (Berlin 1997). As these compounds have interesting biological activities, these are being used in numerous medical treatments (Caporale 1995; Morton and others 2000) connected to cancer-prevention (Chu and others 2000, Birt and others 2001) and cardiovascular system protection, including inhibition of oxidative damage (Omenn 1995; Williams and others 2004). At higher doses, however, flavonoids may act as mutagens, pro-oxidants that generate free radicals, and as inhibitors of key enzymes involved in hormone metabolism (Skibola and Smith 2000).

Flavones are involved in various interactions with other organisms, microbes as well as insects and other plants (Siqueira and others 1991). Pharmacological activities have been described for various flavonoids (for example, quercetin, apigenin, catechins), which have shown an anti-inflammatory action by inhibiting cycloxygenase-2 and inducible nitric oxide synthase (Marchand 2002). The flavonols quercetin, kaempferol, and isorhamnetin are among the flavonoid derivatives present in *Brassica* species (Nielsen and others 1998; Vallejo and others 2002; Onyilagha and others 2003; Chun and others 2004). Two main flavonol glycosides, quercetin 3-*O*-sophoroside and kaempferol 3-*O*-sophoroside, are present in broccoli florets. Three minor glucosides of quercetin and kaempferol, isoquercitrin, kaempferol 3-*O*-glucoside, and kaempferol diglucoside, have also been detected. The quercetin and kaempferol glycosides were present in florets at a level of 43 and 94 μg/g DW, respectively (Price and others 1998). Glycosylated kaempferol derivatives from the external leaves of tronchuda cabbage (*B. oleracea* L. var. *costata* DC) have been reported by Ferreres and others (2005). Total flavonoid content in Chinese cabbage, broccoli, cauliflower, and white cabbage is 944, 316, 172, and 102 μg/g, on a fresh weight basis, respectively (Bahorun and others 2004). Onyilagha and others (2003) reported the accumulation of derivatives of flavonols such as quercetin in *Camelina sativa*; quercetin and kaempferol in *Crambe hispanica* var. *glabrata*; quercetin, kaempferol, and isorhamnetin in *Brassica napus*; kaempferol and isorhamnetin in *Sinapis alba*. The constitutive flavonoids of *B. napus*, isorhamnetin-3-sophoroside-7-glucoside and kaempferol-3,7-diglucoside, are effective deterrents of armyworm (Onyilagha and others 2004). Analysis of *B. alba* extracts revealed the presence of 3,5,6,7,8-pentahydroxy-4-methoxy flavone in shoots, as well as 2,3,4,5,6-pentahydroxy chalcone and 3,5,6,7,8-pentahydroxy flavone in roots and root exudates. Apigenin was also found in the shoots and roots (Ponce and others 2004).

Anthocyanins are potent antioxidants and consequently may be chemoprotective (Giusti and Wrolstad 2003). *Brassicacae* provide a variety of anthocyanins. Cauliflower and red cabbage showed differences in their anthocyanin profiles: cyanidin-3,5-diglucoside was absent in cauliflower, while it was well represented in red cabbage, together with the characteristic anthocyanin of *Brassica* genus, cyanidin-3-sophoroside-5-glucoside. The *p*-coumaryl and feruloyl esterified forms of cyanidin-3-sophoroside-5-glucoside were predominant in cauliflower, while the sinapyl ester was mostly present in red cabbage (Scalzo and others 2008). Red pigmentation of red cabbage is caused by anthocyanins. Red cabbage contains more than 15 different anthocyanins, which are acylglycosides of cyanidin (Dyrby and others 2001). Red radish (*Raphanus sativus* L.) contains significant amounts of anthocyanins of which 12 acylated anthocyanins were isolated and analyzed spectroscopically to determine their structure. Six of these were identified as anthocyanin glycosides with 1 or 2 hydroxycinnamic acids (Otsuki and others 2002). Total proanthocyanidins content in brocolli was found to be 12 and 7 μg/g in cauliflower, calculated over fresh weight (Bahorun and others 2004).

Five lignans, 5 neolignans, 2 sesquilignans, and 1 dilignan were identified in a phytotoxic extract of *Brassica fruticulosa* (Cultillo and others 2003). These compounds exhibited interesting antimicrobial, antifungal, and/or herbicidal activities that are believed to participate in plant defense mechanisms (Erdemoglu and others 2004). These compounds also have cancer-preventive effects (Hanf and Gonder 2005).

Tannins have an adverse effect on the nutritive value of rapeseed meal proteins or isolated proteins (Durkee 1971). These compounds suppress the availability of essential amino acids (Sadeghi and others 2006) and may form complexes with essential minerals, proteins, and carbohydrates (Shahidi 1995). Tannins have also a profound inhibitory effect on the digestion of carbohydrates and proteins in particular (McSweeney and others 2005). In *Brassicaceae* vegetables, different amounts of tannins have been reported (Heimler and others 2005). Inositol hexaphosphate (phytic acid) and condensed tannins are reported in *B. carinata* (Matthaus and Angelini 2005), both of which play an important role in iron binding (Shahidi 1995). Cabbage and turnip contain various amounts of phytic acid, tannic acid, and/or oxalic acid. Tannic acid was found at 12.66 mg/g (fresh weight basis) in cabbage. Levels of both tannic acid and phytic acid can be significantly ($P < 0.05$) reduced by different blanching methods (Mosha and others 1995). The total amount of tannins in rapeseed/canola hulls ranged from 19.13 to 62.13 mg/g of oil-free hulls. Insoluble tannins predominated in canola/rapeseed hulls and comprised 70% to 95.8% of total tannins present. The amounts of sodium-dodecyl-sulphate-extractable tannins were comparable to those of soluble tannins but constituted only 4.7% to 14.1% of insoluble tannins present (Naczk and others 2000).

Glucosinolates

Sulfur-containing phytochemicals of 2 different types are present in *Brassica* (Cruciferae) vegetables (cabbage, broccoli, and so on): glucosinolates and *S*-methyl cysteine sulfoxide. Glucosinolates (Figure 3) are thioglucosides containing a cyano group and a sulfate group (Zrybko and others 1997).

Glucosinolates are derived from amino acid biosynthesis (Figure 1) and are important secondary metabolites in *Brassicaceae* family, involved in plant defense against pests and diseases (Zrybko and others 1997). For example, glucoiberin, glucoraphanin, glucoalyssin, gluconapin, glucobrassicanapin, glucobrassicin, gluconasturtiin, and neoglucobrassicin are health-promoting compounds found in broccoli inflorescences (*B. oleracea* L., var. *italica*, cv. Marathon) (Vallejo and others 2004). These compounds have both positive and negative nutritional effects (Mithen 2001), appearing to posess anticarcinogenic properties, but also quite different toxicological effects (Stoewsand 1995). The effects of specific glucosinolate degradation products on individual organisms vary and are not always known. If used in excessive quantity, many of these compounds can be highly toxic (Brown and Morra 2005).

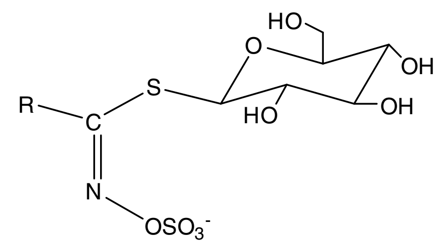


Figure 3 — Basic structure of glucosinolates.

Glucosinolates and their concentrations vary among the different groups of *Brassicaceae* (Table 4) (Windsor and others 2005). In Brussels sprouts, cabbage, cauliflower, and kale, the predominant glucosinolates were found to be sinigrin and glucobrassicin. Brussels sprouts also had significant amounts of gluconapin (Kushad and others 1999). The predominant glucosinolates in broccoli are 4-methylsulfinylbutyl glucosinolate (glucoraphanin) (Iori and others 2004), 3-butenyl glucosinolate (gluconapin), and 3-indolylmethyl glucosinolate (glucobrassicin) (Kushad and others 1999). Cruciferous vegetables of the *Brassica* genus (for example, Brussels sprouts, cauliflower, and broccoli) contain high levels of an indolylmethyl glucosinolate commonly known as glucobrassicin (Rose and others 2005). A great number of glucosinolates have been identified in *B. oleracea* var. *capitata f. alba*, namely glucoiberin, progoitrin, epiprogoitrin, sinigrin, glucrafanin, gluconapoleiferin, glucoalisin, gluconapin, 4-hydroxybrassicin, glucobrassicanapin, glucobrassicin, glucosasturein, methoxyglucobrassicin, and neoglucobrassicin (Kusznierewicz and others 2008). The major glucosinolates detected in different varieties of *B. oleracea* were 2-propenyl, 3-methyl-sulphinylpropyl, and indol-3-yl-methyl, which accounted for an average of 35%, 25%, and 29%, respectively of the total glucosinolate content, while in *B. rapa*, but-3-enyl represented 86% of the total, with pent-4-enyl and 2-phenylethyl as the other major glucosinolates. The average total glucosinolate content of the flower buds was determined to be 2518 μmol/100 g DW in troncha (*B. oleracea* var. *tronchuda*) and 4979 μmol/100 g DW in nabo (*B. rapa*), which is much higher than the highest amounts reported for broccoli (*B. oleracea* var. *italica*) (Rosa 1997). As in other *Brassicaceae* seeds and plants, rapeseed contains up to 5% of glucosinolates, which are partially decomposed during rapeseed processing or storage. When plant material is crushed, as in food preparation or chewing, a thioglucosidase-mediated autolytic process is initiated, generating indole-3-carbinol, glucose, and thiocyanate (Bradfield and Bjeldanes 1991). These, together with other important degradation products, such as isothiocyanates, vinyl-oxazolidinethione, and nitriles, contaminate the crude rapeseed oils, impairing their hydrogenation and transesterification and ultimately may be harmful to human consumption (Velisek and others 1990). The main glucosinolate breakdown products of *Brassica* vegetables are the sinigrin breakdown product 1-cyano-2,3-epithiopropane, the gluconapin hydrolysis product 3-butenyl isothiocyanate, the glucobrassicin metabolite ascorbigen, and low concentrations of other indole glucosinolate-derived hydrolysis products such as neoascorbigen and 3,3′-diindolylmethane (Smith and others 2005).

Rapeseed meal, a by-product of rapeseed oil production, also contains glucosinolates, which together with phytic acid

Table 4—Variation of glucosinolate contents (μg/g) among different *Brassicaceae* vegetables on dry weight basis.[A]

	Cabbage	Broccoli	Brussels sprouts	Cauliflower	Kale
Glucoiberin	2289 ± 380[a]	697 ± 127[a]	42 ± 84[c]	–	3455 ± 591[d]
Glucoraphanin	17[a]	3208 ± 528[a]	3099[c]	218 ± 131[c]	1361[b]
Progoitrin	452 ± 20[a]	1017 ± 68[a]	2922[c]	120 ± 40[c]	524[b]
Gluconapin	472 ± 26[a]	96 ± 37[a]	4654[c]	111 ± 74[c]	372 ± 37[c]
Sinigrin	3443 ± 939[a]	35 ± 143[c]	3261[c]	3332 ± 36[c]	3400 ± 322[d]
Glucoalysin	–	90 ± 45[c]	90 ± 45[c]	–	–
Glucoerucin	–	–	–	–	1206[b]
Glucobrassicin	1315 ± 13[a]	1566 ± 130[a]	1431 ± 89[c]	715 ± 716[c]	353 ± 1029[c]
Neoglucobrassicin	38 ± 19[a]	458 ± 29[a]	95 ± 48[c]	95 ± 95[c]	353[d]
4-Methoxygluco-brassicin	214 ± 24[a]	124 ± 5[a]	–	–	–

[A]Calculation is made by conversion of μmol to μg on dry weight basis.
[a]Verkerk and others 2001.
[b]Kushad and others 2004.
[c]Kushad and others 1999.
[d]Cartea and others 2008.

contributes to its anti-nutritional properties (Fenwick and Heaney 1983; Tripathi and Mishra 2007). Goitrin, a naturally occurring compound in cruciferous vegetables, can easily be nitrosated if in contact with nitrites in gastrointestinal conditions, yielding the mutagenic compound N-nitroso-oxazolidone, with loss of sulfur (Luthy and others 1984). Additionally, goitrin, which is a decomposition product of progoitrin (Figure 4), is known to be strongly goitrogenic, inhibiting the synthesis of thyroid hormones, thyroxine, and tri-iodine-thyronine by a selective binding of iodine that prevents iodine intake by the thyroid gland (Zukalova and Vasak 2002).

The other decomposion products of glucosinolates, as mentioned previously, are thiocyanates, isothiocyanates, and oxazolidine-2-thiones (Figure 5) (Heaney and Fenwick 1995; Wittstock and Halkier 2002), and have also been shown to be goitrogenic. The benzyl-, phenethy-, allyl-isothiocyanate, and sulforaphane are formed through the hydrolysis of their naturally occurring precursor glucosinolates, glucotropaelin, gluconasturtiin, sinigrin, and glucoraphanin, respectively, by myrosinase (Smith and Yang 2000). However, under certain conditions, the glucosinolate aglycones may yield a nitrile rather than an isothiocyanate. Nitriles such as *S*-l-cyano-2-hydroxy-3-butene and 1-cyano-2-hydroxy-3,4-epithiobutane are the most toxic of the normal glucosinolate hydrolysis products, with a human lethal dose of 170 and 178 mg/kg, respectively (Fenwick and Heaney 1983). These negative effects of glucosinolates have led to research directed at finding methods to reduce the glucosinolate content in the seeds of some *Brassica* crops (Font and others 2005). Other processes intended to avoid toxicity of the meal include heat treatment of the seeds prior to removal of the oil. This inactivates myrosinase and subsequent breakdown of glucosinolates when the meal is consumed (Fenwick and Heaney 1983). High or low glucosinolate contents of the seed of some varieties of *B. napus* correlate positively with glucosinolate levels in the roots, at least during the early stages of *in vitro* plant development (O'Callaghan and others 2000).

Glucosinolates are also responsible for the bitter acidic flavors of *Brassicacea* species (Kopsell and others 2003) and the hydrolysis by-products of glucosinolates mentioned previously, such as isothiocyanates, nitriles, and thiocyanates, are responsible for the hot and pungent taste of the mustard that is often objected to by consumers (Zrybko and others 1997). Many of these degradation products are volatile (Valette and others 2006) and also play an important role in the characteristic aroma or off-odor of *Brassicacae* (Miyazawa and others 2005). A great deal of research has been carried out on the volatiles of these species. Cruciferous vegetables, for example, have been reported to contain substantial quantities of isothiocyanates (Kawanishi and others 2005). Volatiles and semi-volatiles from *B. oleracea* L. var. *botrytis* (L.) seeds were identified as cyanides such as 4-(methylthio) butyl-cyanide, 3-(methylthio) propyl cyanide, and isothiocyanates such as 4-(methylthio) butyl-isothiocyanate (Valette and others 2003). In *B. rapa* L. var. *perviridis*, 6 isothiocyanates were detected in the steam volatiles and identified as sec-butylisothiocyanate, 3-butenylisothiocyanate, 4-pentenylisothiocyanate, benzyl-isothiocyanate, 2-phenylethylisothiocyanate, and 5-methylthiopentylisothiocyanate. Three nitriles were also detected and identified as 2-methyl-5-hexenenitrile, 3-phenylpropiononitrile, and 6-methylthiohexanonitrile (Miyazawa and others 2005). In *Brassica oleracea* L. var. *Botrytis* L. 35 volatile and semi-volatile constituents were detected (Valette and others 2003). Dimethyl sulfide, dimethyl disulfide, dimethyl trisulfide, hexanal, 3-*cis*-hexen-1-ol, nonanal, ethanol (Valette and others 2003; Jacobsson and others 2004), and hex-3(Z)-enol were identified as major constituents representing, respectively, 30.2%, 24.2%, and 21.7% of the volatiles (Valette and others 2003).

Various interesting bioactivities have also been reported for hydrolysis and breakdown products of glucosinolates (O'Callaghan and others 2000; Griffiths and others 2001), such as strong bactericidal, antifungal properties (Fenwick and Heaney 1983; Rosa and others 1997; Tierens and others 2001), and health

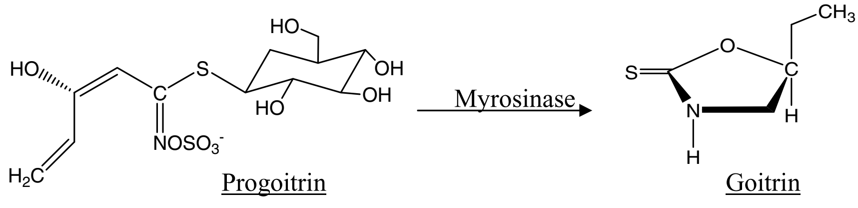
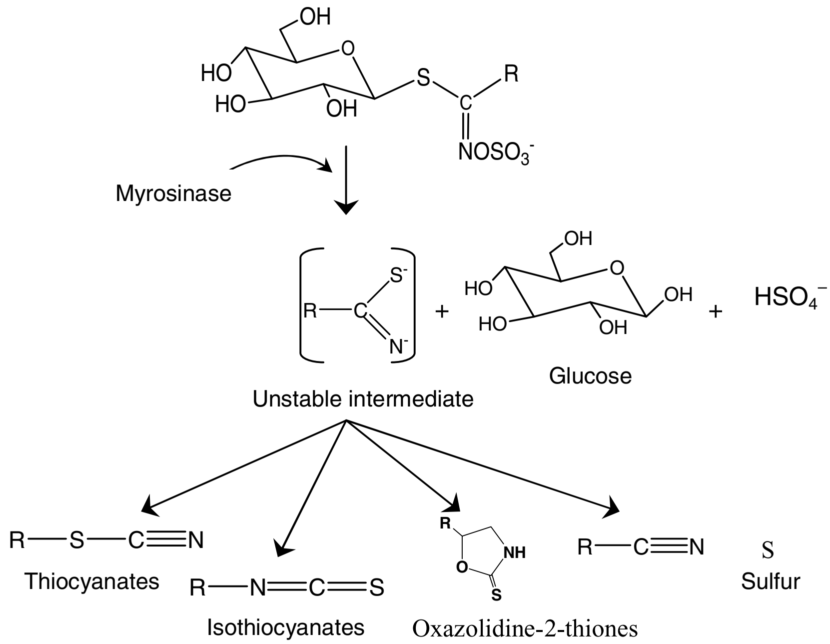


Figure 4—Conversion of progoitrin to goitrin by myrosinase.

Figure 5 — Glucosinolate degradation.



promoting effects for plants and humans (Wittstock and Halkier 2002; Font and others 2005). Some of these glucosinolates have a potential application in the industry; for example, an aqueous extract of *B. nigra* seeds might be included in industrial biofilms as an antimicrobial agent (Saraviaa and Gaylardeb 1998). The breakdown products of glucosinolates assist in the activity of important naturally occurring, direct- acting antioxidants such as tocopherols and also enhance the synthesis of glutathione, one of the most abundant intracellular direct antioxidants (Hogge and others 1988; Fahey and Talalay 1999). Working on rapeseed oil cake (*Brassica campestris* L. subsp. *napus*), Nagatsu and others (2004) isolated different antioxidant compounds (indolacetonitrile, S-1-methoxy-1-(3,5-dimethoxy-4-hydroxyphenyl) ethane, 4-hydroxy-indol-acetonitrile, and 4-hydroxy-phenyl-acetonitrile), which showed a strong antioxidant activity as evaluated by the ferric thiocyanate method.

Certain glucosinolates, particularly the isothiocyanates and nitriles, have been shown to modify both xenobiotic metabolizing enzymes and induce cell cycle arrest and apoptosis. It is likely that a combination of these responses explains the chemo-preventive characteristics of *Brassica* and that a combination of different cruciferous vegetables could provide optimal protection (Smith and Yang 2000; Lund 2003). The isothiocyanate chemopreventive activity could be due to its powerful inhibition of different enzymes such as glutathione *S*-transferases (GSTs) in humans (Seow and others 2002; Ambrosone and others 2004). Another potential cancer-blocking action, which was described for both intact and thioglucoside glucohydrolase-treated glucosinolates, as assessed by induction of GSTs activity, was found to be dependent on the nature of the side chain of the parent glucosinolate (Tawfiq and others 1995). Another naturally occurring isothiocyanate, sulforaphane, that is present in *Brassica* vegetables has been shown to block the formation of tumors (Liang and others 2005) and together with 7-methylsulfinylheptyl isothiocyanates in broccoli (*B. oleracea* var. *italica*) extract exhibited an inhibitory effect on 12-*O*-tetradecanoylphorbol-13-acetate-induced cancer cell invasion and matrix metalloproteinase-9 activity in human breast cancer cells (Rose and others 2005) and lowers the probability of acquiring colon and rextal cancers (Branca and others 2002). It was also proved to inhibit *Helicobacter pylori* infection, blocking gastric tumor formation. This suggests that broccoli consumption could prevent chronic atrophic gastritis induced by *H. pylori* infection and, thus, this type of stomach cancer (Sato and others 2004). Naturally, the wide range of glucosinolate content among different groups of *B. oleracea* would result in significant differences in their health-promoting properties (Kushad and others 1999).

Indole-3-carbinol (I-3-C) is another glucosinolate breakdown product found in vegetables of the *Brassica* genus (cabbage, broccoli sprouts, Brussels sprouts, cauliflower, bok choy, and kale). Some research points to this compound as a promising anticancer agent against prostate cancer and reducing the incidence and multiplicity of mammary tumors (Hsu and others 2005; Rahman and Sarkar 2005). Coinciding with these studies, oral administration of I-3-C has been shown to have a possible beneficial effect on estrogen metabolism in humans andepidemiological studies support the claim that high intakes of I-3-C may have a broad chemo-preventive effect (Brignall 2001). Conversely, 5,6,11,12,17,18-hexahydrocyclonona[1,2-b:4,5-b:7,8-b] triindole (CTr), a major digestive product of indole-3-carbinol, has been proved to exhibit strong estrogenic activities increasing proliferation of estrogen-dependent breast tumor cells. Thus, the contribution of CTr to the cancer preventive or cancer-promoting effects of I-3-C remains to be established (Xue and others 2005). In plants, levels of secondary metabolites, such as glucosinolates are controlled by a number of factors. Although it is possible to increase levels of glucosinolates in plants by genetic manipulation, to enhance a particular pharmacological benefit, such a step would be premature and must await a more thorough understanding of the extremely complex interactions of these compounds and their metabolites (Heaney and Fenwick 1995).

Future Prospects

Many anti-cancer agents are of plant origin, but their actual function or the mechanism behind the role they play in the plant has not yet been fully elucidated. For example, plant-derived molecules with known roles in plant cell death may be novel candidates for use in clinical oncology, but a better understanding of the molecular and cellular mechanism of action of such compounds and their structure–activity relationships is necessary for the development of new derivatives of these molecules with more favorable chemopreventive activities. Different classes of anti-cancer compounds merit continued research at a basic and pharmacological level to yield novel chemotherapeutic agents. However, to correctly evaluate the effect of such compounds in food, it is necessary to bear in mind that some constituents such as phenolic acids, tannins, and other anti-nutritional compounds may form complexes with nutritionally important compounds, reducing their bioavailability and thus lowering the nutritional value of *Brassica* products. Additonal studies are needed to determine the amount of isothiocynates or their metabolites that reach target tissues, and the concentration needed to exert biological effects (Smith and Yang 2000). Further elucidation of the protective mechanisms of food and the identification of active constituents is needed.

Enhancing the phytonutrient content of plant foods through selective breeding or genetic improvement is a powerful tool for dietary disease prevention. However, most, if not all, of these bioactive compounds confer a bitter, acid, or astringent taste to the food, which is rejected by most consumers. Moreover, in the past, some of these compounds have even viewed as plant-based toxins and, as a result, the food industry routinely removes these compounds from plant foods through selective breeding and a variety of debittering processes. This poses a dilemma for the designers of functional foods because increasing the content of bitter phytonutrients for health may clash with consumer choices. Studies on phytonutrients and health, taking sensory factors and food preferences into account, constitute an important area of research.

Another aspect of these valuable *Brassica* vegetables that deserves full attention is the edaphic conditions in which they are grown. These plants can be biofortified by growing them in a high mineral-containing medium, attaining high levels of nutritionally important minerals that can be used to produce dietary supplements. But this advantage, which is due to their metal tolerance (and allows their use for phytoremediation as previously explained), can be negative as observed in crops that are irrigated with polluting metals. The excessive heavy metals (macro or micro nutrients in excess) and plant and human pathogenic microbes concentrated in the soil from this water cause stress conditions for plants. Quality parameters of *Brassicacea* vegetables are very susceptible to great changes with these stress conditions that produce different effects on the levels of *Brassica* vegetables metabolites, affecting their flavor and leading to the changes in nutritional value. Studies are needed to clarify the route of exposure, mechanisms of sensitization, and clinical importance of these phenomenons.

Another question about cruciferous vegetables is their flavonoid content. Epidemiological data indicate that the present rate of consumption of these vegetables is beneficial. However, earlier studies also raised the question of the advantages of recommending an increased consumption of *Brassica* vegetables and/or phytochemical supplements. One of the reasons for this lies in the flavonoid content of these vegetables, which, as explained previously, is quite high in some of the species. Unfortunately, the potentially toxic effects of excessive flavonoid intake are still largely ignored. It is known that at high doses, flavonoids may act as mutagens, that is, pro-oxidants that generate free radicals, so that their adverse effects may well outweigh their beneficial ones. It is imperative that further research be conducted to learn more about the toxicological properties of flavonoids, apart from other putative health promoting compounds in *Brassica* vegetables, thus clarifying the balance of potential adverse and beneficial effects included in their mechanisms of action.

Conclusions

Brassica vegetables represent a major part of the human diet all over the world providing nutritionally significant constituents, such as phenolic compounds, vitamins, fiber, soluble sugars, minerals, fat, and carotenoids. Cruciferous vegetables are a source of some very promising chemopreventive dietary constituents, which may protect against free radical damage and LDL oxidation implicated in the pathogenesis of cardiovascular diseases, as well as DNA damage and cancer. This might be useful information from the point of view of identifying appropriate raw materials rich in these protective components, for the development of safe food products and additives with appropriate antioxidant properties. As mentioned previously, *Brassica* plants are rich in many metals including calcium and iron-containing compounds. However, there are substantial variations both within and between subspecies, which suggest a difference in potential health benefits depending on genotype, as well as on the growth conditions and environment. This review provides a massive body of evidence supporting the nutritional value of *Brassica* vegetables and should ultimately lead the population to better food choices.

Acknowledgment

The Higher Education Commission (HEC) of Pakistan is gratefully acknowledged for the support of author Muhammad Jahangir.

References

Adamska E, Cegielska-Taras T, Kackzmarek Z, Szala L. 2004. Multivariate approach to evaluating the fatty acid composition of seed oil in a doubled haploid population of winter oilseed rape (*Brassica napus* L.). J Appl Genetics 45:419–25.

Ahuja KL, Batta SK, Raheja RK, Labana KS, Gupta ML. 1989. Oil content and fatty acid composition of promising Indian *Brassica campestris* L. *toria* genotypes. Plant Foods Hum Nutr 39:155–60.

Alfred B, Carsten M, Jurgen S, Manfred N, Victor W, Dieter S. 2005. Formation of a complex pattern of sinapate esters in *Brassica napus* seeds, catalyzed by enzymes of a serine carboxypeptidase-like acyltransferase family? Phytochemistry 66:1334–45.

Aluko RE, McIntosh T. 2001. Polypeptide profile and functional properties of defatted meals and protein isolates of canola seeds. J Sci Food Agric 81:391–6.

Ambrosone CB, McCann SE, Freudenheim JL, Marshall JR, Zhang Y, Shields PG. 2004. Breast cancer risk in premenopausal women is inversely associated with consumption of broccoli, a source of isothiocyanates, but is not modified by GST genotype. J Nutr 134:1134–8.

Appelqvist LD, Kornfeldt AK, Wennerholm JE. 1981. Sterols and steryl esters in some *Brassica* and sinapis seeds. Phytochemistry 20:207–10.

Ayaz FA, Glew RH, Millson M, Huang HS, Chuang LT, Sanz C, Hayyrlyoglu-Ayaz S. 2006. Nutrient contents of kale (*Brassica oleraceae* L. var. acephala DC.). Food Chem 96:572–9.

Ayaz FA, Hayirlioglu-Ayaz S, Alpay-Karaoglu S, Gruz J, Valentova K, Ulrichova J, Strnad M. 2008. Phenolic acid contents of kale (*Brassica oleraceae* L. var. *acephala* DC.) extracts and their antioxidant and antibacterial activities. Food Chem 107:19–25.

Azuma K, Ippoushi K, Ito H, Higashio H, Terao J. 1999. Evaluation of antioxidative activity of vegetable extracts in linoleic acid emulsion and phospholipid bilayers. J Sci Food Agric 79:2010–6.

Bahorun T, Luximon-Ramma A, Crozier A, Aruoma OI. 2004. Total phenol, flavonoid, proanthocyanidin and vitamin C levels and antioxidant activities of Mauritian vegetables. J Sci Food Agric 84:1553–61.

Bailey LB, Rampersaud GC, Kauwell GPA. 2003. Folic acid supplements and fortification affect the risk for neural tube defects, vascular disease and cancer: evolving science. J Nutr 133:1961–8.

Banuelos GS. 2006. Phyto-products may be essential for sustainability and implementation of phytoremediation. Environ Pollut 144:19–23.

Beale MH, Ward JL. 1998. Jasmonates: key players in the plant defense. Nat Prod Rep 15:533–48.

Berlin J. 1997. Secondary products from plant cell cultures. In: Rehm HJ, Reed G, Puhler A, Stadler P, editors. Biotechnolgy: a multivolume comprehensive treatise. 2nd ed. Federal Republic of Germany, VCH. p 593–640.

Berot S, Compoint JP, Larre C, Malabat C, Gueguen J. 2005. Large-scale purification of rapeseed proteins (*Brassica napus* L.). J Chromatogr B 818:35–42.

Birt DF, Hendrich S, Wang W. 2001. Dietary agents in cancer prevention: flavonoids and isoflavonoids. Pharmacol Ther 90:157–77.

Blee E. 1998. Phytooxylipins and plant defense reactions. Progr Lipid Res 37:33–72.

Bollheimer CL, Buettner R, Kullmann A, Kullmann F. 2005. Folate and its preventive potential in colorectal carcinogenesis. How strong is the biological and epidemiological evidence? Crit Rev Oncol Hemat 55:13–36.

Boonstra AM, Verhoef P, Konings EJM, Dusseldorp MV, Matser A, Hollman PCH, Meyboom S, Kok FJ, West CE. 2002. Influence of processing on total, monoglutamate and polyglutamate folate contents of leeks, cauliflower, and green beans. J Agric Food Chem 50:3473–8.

Bradfield CA, Bjeldanes LF. 1991. Modification of carcinogen metabolism by indolylic autolysis products of *Brassica oleraceae*. Adv Exp Med Biol 289:153–63.

Branca F, Li G, Goyal S, Quiros CF. 2002. Survey of aliphatic glucosinolates in Scilian wild and cultivated *Brassicaceae*. Phytochemistry 59:717–24.

Brignall MS. 2001. Prevention and treatment of cancer with indole-3-carbinol. Altern Med Rev 6:580–9.

Brown J, Morra MJ. 2005. Glucosinolate-containing seed meal as a soil amendment to control plant pests. Subcontract Report 2000–2002, Univ. of Idaho, Moscow, Idaho. p 1–199.

Caporale LH. 1995. Chemical ecology: a view from the pharmaceutical industry. Proc Natl Acad Sci USA 92:75–82.

Cartea ME, Velasco P, Obregon S, Padilla G, Haro A. 2008. Seasonal variation in glucosinolate content in *Brassica oleracea* crops grown in northwestern Spain. Phytochemistry 69:403–10.

Choudhury AR, Das T, Sharma A. 1997. Mustard oil and garlic extract as inhibitors of sodium arsenite-induced chromosomal breaks *in vivo*. Cancer Lett 121:45–52.

Chu YH, Chang CL, Hsu HF. 2000. Flavonoid content of several vegetables and their antioxidant activity. J Sci Food Agric 80:561–6.

Chun OK, Smith N, Sakagawa A, Lee CY. 2004. Antioxidant properties of raw and processed cabbages. Int J Food Sci Nutr 55:191–9.

Cornel MC, Smit DJ, Berg LTW. 2005. Folic acid—the scientific debate as a base for public health policy. Reprod Toxicol 20:411–5.

Cover CM, Hsieh SJ, Tran SH. 1998. Indole-3-carbonyl inhibits the expression of cyclin-dependent kinase-6 and induces a G1-cell cycle arrest of human breast cancer cells independent of estrogen recptor signalling. J Biol Chem 273:3838–47.

Creelman RA, Mullet JE. 1997. Biosynthesis and action of jasmonates in plants. Ann Rev Plant Physiol Plant Mol Biol 48:355–81.

Cultillo F, Abrosca BD, Dellagreca M, Fiorentino A, Zarrelli A. 2003. Lignans and neolignans from *Brassica fruticulosa*: effects on seed germination and plant growth. J Agric Food Chem 51:6165–72.

Dekker M, Verkerk R, Jongen WMF. 2000. Predictive modelling of health aspects in the food production chain: a case study on glucosinolates in cabbage. Trends Food Sci Technol 11:174–81.

Devi R, Arcot J, Sotheeswaran S, Ali S. 2008. Folate contents of some selected Fijian foods using tri-enzyme extraction method. Food Chem 106:1100–4.

Devoto A, Turner JG. 2003. Regulation of jasmonate-mediated plant responses in *Arabidopsis*. Ann Bot 92:329–37.

Dewick PM. 2001. The biosynthesis of shikimate metabolites. Nat Prod Rep 18:334–55.

Dixon RA. 2001. Natural products and plant disease resistance. Nature 411:843–7.

Dixon RA, Paiva NL. 1995. Stress-induced phenylpropanoid metabolism. Plant Cell 7:1085–97.

Dudka S, Miller WP. 1999. Permissible concentrations of arsenic and lead in soils based on risk assessment. Water Air Soil Poll 113:127–32.

Durkee AB. 1971. The nature of tannin in rapeseed (*Brassica campestris*). Phytochemistry 10:1583–5.

Dwivedi C, Muller LA, Goetz-Parten DE, Kasperson K, Mistry VV. 2003. Chemopreventive effects of dietary mustard oil on colon tumor development. Cancer Lett 196:29–34.

Dyrby M, Westergaard N, Stapelfeldt H. 2001. Light and heat sensitivity of red cabbage extract in soft drink model systems. Food Chem 72:431–7.

Eberhardt MV, Kobira K, Keck A, Juvik JA, Jeffery EH. 2005. Correlation analyses of phytochemical composition, chemical, and cellular measures of antioxidant activity of Broccoli (*Brassica oleracea L.* var. *italica*). J Agric Food Chem 53:7421–31.

Elless MP, Blaylock MJ, Huang JW, Gussman CD. 2000. Plants as a natural source of concentrated mineral nutritional supplements. Food Chem 71:181–8.

Erdemoglu N, Sener B, Choudhary MI. 2004. Bioactivity of lignans from *Taxus baccata*. Z Naturforsch C 59:494–8.

Fahey JW, Talalay P. 1999. Antioxidant functions of sulforaphane: a potent inducer of phase II detoxication enzymes. Food Chem Toxicol 37:973–9.

Farmer EE, Almeras E, Krishnamurthy V. 2003. Jasmonates and related oxylipins in plant responses to pathogenesis and herbivory. Curr Opin Plant Biol 6:372–8.

Fenwick GR, Heaney RK. 1983. Glucosinolates and their breakdown products in cruciferous crops, foods and feeding stuffs. Food Chem 11:249–71.

Ferguson LR. 1999. Prospects for cancer prevention. Mutat Res 428:329–38.

Ferreres F, Sousa C, Valentao P, Seabra RM, Pereira JA, Andrade PB. 2007. Tronchuda cabbage (*Brassica oleracea* L. var. *costata* DC) seeds: phytochemical characterization and antioxidant potential. Food Chem 101:549–58.

Ferreres F, Valentao P, Llorach R, Pinheiro C, Cardoso L, Pereira JA, Sousa C, Seabra RM, Andrade PB. 2005. Phenolic compounds in external leaves of Tronchuda cabbage (*Brassica oleracea L.* var. *costata* DC). J Agric Food Chem 53:2901–7.

Finley JW. 2003. Reduction of cancer risk by consumption of selenium-enriched plants: enrichment of broccoli with selenium increases the anticarcinogenic properties of broccoli. J Med Food 6:19–26.

Flescher E. 2005. Jasmonates-a new family of anti-cancer agents. Anticancer Drugs 16:911–6.

Font R, del Rio-Celestino M, Cartea E, Haro-Bailon A. 2005. Quantification of glucosinolates in leaves of leaf rape (*Brassica napus* ssp. pabularia) by near-infrared spectroscopy. Phytochemistry 66:175–85.

Fowke JH, Chung FL, Jin F, Qi D, Cai Q, Conaway C, Cheng J, Shu X, Gao Y, Zheng W. 2003. Urinary isothiocyanate levels, *Brassica*, and human breast. Cancer Res 63:3980–6.

Gagandeep, Dhiman M, Mendiz E, Rao AR, Kale RK. 2005. Chemopreventive effects of mustard (*Brassica compestris*) on chemically induced tumorigenesis in murine forestomach and uterine cervix. Hum Exp Toxicol 24:303–12.

Ghodsvali A, Khodaparast MHH, Vosoughi M, Diosady LL. 2005. Preparation of canola protein materials using membrane technology and evaluation of meals functional properties. Food Res Int 38:223–31.

Giusti MM, Wrolstad RE. 2003. Acylated anthocyanins from edible sources and their applications in food systems. Biochem Eng J 14:217–25.

Glew RS, VanderJagt DJ, Bosse R, Huang YS, Chuang LT, RH, Glew RH. 2005. The nutrient content of three edible plants of the Republic of Niger. J Food Compos Anal 18:15–27.

Goffman FD, Mollers C. 2000. Changes in tocopherol and plastochromanol-8 contents in seeds and oil of oilseed rape (*Brassica napus* L.) during storage as influenced by temperature and air oxygen. J Agric Food Chem 48:1605–9.

Goldoni JS, Bonassi IA, Conceicao FA. 1983. Comparative study of vitamin C of cabbage cultivars (*Brassica oleraceae* L., var. *capitata* L.), before and after their processing in sauerkraut. Arch Latinoam Nutr 33:45–56.

Gomes MH, Rosa E. 2000. Free amino acid composition in primary and secondary inflorescences of 11 broccoli (*Brassica oleracea* var *italica*) cultivars and its variation between growing seasons. J Sci Food Agric 81:295–9.

Granado F, Olmedilla B, Herrero C, Perez-Sacristan B, Blanco I, Blazquez S. 2006. Bioavailability of carotenoids and tocopherols from broccoli: *in vivo* and *in vitro* assessment. Exp Biol Med 231:1733–8.

Graser G, Schneider B, Oldham NJ, Gershenzon J. 2000. The methionine chain elongation pathway in the biosynthesis of glucosinolates in *Eruca sativa* (*Brassicaceae*). Arch Biochem Biophys 378:411–9.

Grayer RJ, Harborne JJ. 1994. A survey of antifungal compounds from higher plants 1982–1993. Phytochemistry 37:19–42.

Griffiths DW, Deighton N, Birch ANE, Patrian B, Baur R, Stadler E. 2001. Identification of glucosinolates on the leaf surface of plants from the Cruciferae and other closely related species. Phytochemistry 57:693–700.

Halitschke R, Baldwin IT. 2005. Jasmonates and related compounds in plant–insect interactions. J Plant Growth Regul 23:238–45.

Hanf V, Gonder U. 2005. Nutrition and primary prevention of breast cancer: foods, nutrients and breast cancer risk. Eur J Obstet Gyn R B 123:139–49.

He ZL, Yang XE, Stoffella PJ. 2005. Trace elements in agroecosystems and impacts on the environment. J Trace Elem Med Biol 19:125–40.

Heaney RK, Fenwick GR. 1995. Natural toxins and protective factors in *Brassica* species, including rapeseed. Nat Toxins 3:233–7.

Heaney RP, Weaver CM, Hinders SM, Martin B, Packard PT. 1993. Absorbability of calcium from *Brassica* vegetables: broccoli, bok choy, and kale. J Food Sci 58:1378–80.

Heimler D, Vignolini P, Dini MG, Vincieri FF, Romani A. 2005. Antiradical activity and polyphenol composition of local *Brassicaceae* edible varieties. Food Chem 99:464–9.

Hobbs DH, Hume JH, Rolph CE, Cooker DT. 1996. Changes in lipid composition during floral development of *Brassica campestris*. Phytochemisty 42:335–9.

Hogge LR, Reed DW, Underhill EW, Haughn GW. 1988. HPLC separation of glucosinolates from leaves and seeds of *Arabidopsis thaliana* and their identification using thermospray liquid chromatography-mass spectrometry. J Chromtogr Sci 26:551–6.

Hsu JC, Zhang J, Dev A, Wing A, Bjeldanes LF, Firestone GL. 2005. Indole-3-carbinol inhibition of androgen receptor expression and downregulation of androgen responsiveness in human prostate cancer cells. Carcinogenesis 26:1896–904.

Iori R, Barillari J, Rollin P. 2004. Comment on *in vitro* gastrointestinal digestion study of broccoli inflorescence phenolic compounds, glucosinolates, and vitamin C. J Agric Food Chem 52:7432–3.

Jacobsson A, Nielsen T, Sjoholm I. 2004. Influence of temperature, modified atmosphere packaging, and heat treatment on aroma compounds in broccoli. J Agric Food Chem 52:1607–14.

Jensen CR, Mogensen VO, Mortensen G, Fieldsend JK, Milford GFJ, Andersen MN, Thage JH. 1996. Seed glucosinolate, oil and protein contents of field-grown rape (*Brassica napus* L.) affected by soil drying and evaporative demand. Field Crop Res 47:93–105.

Kaplan F, Kopka J, Haskell DW, Zhao W, Schiller KC, Gatzke N, Sung DY, Guy CL. 2004. Exploring the temperature-stress metabolome of *Arabidopsis*. Plant Physiol 136:4159–68.

Kaushik N, Agnihotri A. 2000. GLC analysis of Indian rapeseed-mustard to study the variability of fatty acid composition. Biochem Soc T 28:581–3.

Kawanishi S, Oikawa S, Murata M. 2005. Evaluation for safety of antioxidant chemopreventive agents. Antioxid Redox Sign 7:1728–39.

Kawashima LM, Soares LMV. 2003. Mineral profile of raw and cooked leafy vegetables cosumed in southern Brazil. J Food Compos Anal 16:605–11.

Khachik F, Steck A, Pfander H. 1999. Isolation and structural elucidation of (13Z,13′Z,3R,3′R,6′R)-lutein from marigold flowers, kale, and human plasma. J Agric Food Chem 47:455–61.

King GA, Morris SC. 1994. Early compositional changes during postharvest senescence of broccoli. J Am Soc Hortic Sci 119:1000–5.

Kmiecik W, Lisiewska Z, Korus A. 2007. Retention of mineral constituents in frozen brassicas depending on the method of preliminary processing of the raw material and preparation of frozen products for consumption. Eur Food Res Technol 224:573–9.

Knudsen KEB. 2001. The nutritional significance of “dietary fibre” analysis. Animal Feed Sci Technol 90:3–20.

Kopsell DE, Kopsell DE, Randle WM, Coolong TW, Sams CE, Curran-Celentano J. 2003. Kale carotenoids remain stable while flavor compounds respond to changes in sulfur fertility. J Agric Food Chem 51:5319–25.

Kristal AR, Lampe JW. 2002. *Brassica* vegetables and prostate cancer risk: a review of the epidemiological evidence. Nutr Cancer 42:1–9.

Kroon PA, Williamson G. 1999. Hydroxycinnamates in plants and food: current and future perspectives. J Sci Food Agric 79:355–61.

Kurilich AC, Jeffery EH, Juvk JA, Wallig MA, Klein BP. 2002. Antioxidant capacity of different broccoli (*Brassica oleracea*) genotypes using the oxygen radical absorbance capacity (ORAC) assay. J Agric Food Chem 50:5053–7.

Kurilich AC, Tsau GJ, Brown A, Howard L, Klein BP, Jeffery EH, Kushad M, Wallig MA, Juvik JA. 1999. Carotene, tocopherol, and ascorbate contents in subspecies of *Brassica oleracea*. J Agric Food Chem 47:1576–81.

Kushad MM, Brown AF, Kurilich AC, Juvik JA, Klein BP, Wallig MA, Jeffery EHJ. 1999. Variation of glucosinolates in vegetable crops of *Brassica oleracea*. J Agric Food Chem 47:1541–8.

Kushad MM, Cloyd R, Babadoost M. 2004. Distribution of glucosinolates in ornamental cabbage and kale cultivars. Sci Horticult 101:215–21.

Kusznierewicz B, Bartoszek A, Wolska L, Drzewiecki J, Gorinstein S, Namiesnik J. 2008. Partial characterization of white cabbages (*Brassica oleracea* var. *capitata f. alba*) from different regions by glucosinolates, bioactive compounds, total antioxidant activities and proteins. LWT Food Sci Technol 41:1–9.

Lechner M, Reiter B, Lorbeer E. 1999. Determination of tocopherols and sterols in vegetable oils by solid-phase extraction and subsequent capillary gas chromatographic analysis. J Chromatogr A 857:231–8.

Lefsrud MG, Kopsell DA, Kopsell DE, Randle WM. 2006. Kale carotenoids are unaffected by, whereas biomass production, elemental concentrations, and selenium accumulation respond to, changes in selenium fertility. J Agric Food Chem 54:1764–71.

Liang H, Yuan Q, Xiao Q. 2005. Purification of sulforaphane from *Brassica oleracea* seed meal using low-pressure column chromatography. J Chromatogr B 828:91–6.

Llorach R, Espian JC, Tomaas-Barberaan FA, Ferreres F. 2003. Valorization of cauliflower (*Brassica oleracea* L. var. *botrytis*) by-products as a source of antioxidant phenolics. J Agric Food Chem 51:2181–7.

Lund E. 2003. Non-nutritive bioactive constituents of plants: dietary sources and health benefits of glucosinolates. Int J Vitam Nutr Res 73:135–43.

Luthy J, Carden B, Friederich U, Bachmann M. 1984. Goitrin—a nitrosatable constitutent of plant foodstuffs. Experientia 40:452–3.

Mahajan A, Dua S. 1997. Nonchemical approach for reducing antinutritional factors in rapeseed (*Brassica campestris* var. *Toria*) and characterization of enzyme phytase. J Agric Food Chem 45:2504–8.

Marchand LL. 2002. Cancer preventive effects of flavonoids—a review. Biomed Pharmacother 56:296–301.

Matthaus B, Angelini LG. 2005. Anti-nutritive constituents in oilseed crops from Italy. Ind Crop Prod 21:89–99.

McEwan M, Smith MWH. 1998. Identification of volatile organic compounds emitted in the field by oilseed rape (*Brassica napus* ssp. *oleifera*) over the growing season. Clin Exp Allergy 28:332–8.

McKillop DJ, Pentieva K, Daly D, McPartlin JM, Hughes J, Strain JJ, Scott JM, McNulty H. 2002. The effect of different cooking methods on folate retention in various foods that are amongst the major contributors to folate intake in the UK diet. Brit J Nutr 88:681–8.

McSweeney CS, Gough J, Conlan LL, Hegarty MP, Palmer B, Krause DO. 2005. Nutritive value assessment of the tropical shrub legume *Acacia angustissima*: anti-nutritional compounds and *in vitro* digestibility. Anim Feed Sci Technol 121:175–90.

Mezencey R, Mojzis J, Pilatova M, Neoplasma KP. 2003. Antiproliferative and cancer chemopreventive activity of phytoalexins: focus on indole phytoalexins from crucifers. Neoplasma 50:239–45.

Mithen RF. 2001. Glucosinolates and their degradation products. Adv Bot Res 35:213–32.

Mithen RF, Dekker M, Verkerk R, Rabot S, Johnson IT. 2000. The nutritional significance, biosynthesis and bioavailability of glucosinolates in human foods. J Sci Food Agric 80:967–84.

Miyazawa M, Nishiguchi T, Yamafuji C. 2005. Volatile components of the leaves of *Brassica rapa* L. var. *perviridis Bailey*. Flav Frag J 20:158–60.

Morrissey JP, Osbourn AE. 1999. Fungal resistance to plant antibiotics as a mechanism of pathogenesis. Microbiol Mol Biol Rev 708–24.

Morton LW, Caccetta RA, Puddey IB, Croft KD. 2000. Chemistry and biological effects of dietary phenolic compounds: relevance to cardiovascular disease. Clin Exp Pharmacol Physiol 27:152–9.

Mosha TC, Gaga HE, Pace RD, Laswai HS, Mtebe K. 1995. Effect of blanching on the content of antinutritional factors in selected vegetables. Plant Foods Hum Nutr 47:361–7.

Naczk M, Amarowicz R, Pink D, Shahidi F. 2000. Insoluble condensed tannins of canola/rapeseed. J Agric Food Chem 48:1758–62.

Naczk M, Amarowicz R, Sullivan A, Shahidi F. 1998. Current research developments on polyphenolics of rapeseed/canola: a review. Food Chem 62:489–502.

Nagatsu A, Sugitani T, Mori Y, Okuyama H, Sakakibara J, Mizukami H. 2004. Antioxidants from rape (*Brassica campestris* var. *Japonica Hara*) oil cake. Nat Prod Res 18:231–9.

Nielsen JK, Norbaek R, Olsen CE. 1998. Kaempferol tetraglucosides from cabbage leaves. Phytochemistry 49:2171–6.

Ninfali P, Bacchiocca M. 2003. Polyphenols and antioxidant capacity of vegetables under fresh and frozen conditions. J Agric Food Chem 51:2222–6.

O'Callaghan KJ, Stone PJ, Hu X, Griffiths DW, Davey MR, Cocking EC. 2000. Effects of glucosinolates and flavonoids on colonization of the roots of *Brassica napus* by *Azorhizobium caulinodans*. Appl Environ Microb 66:2185–91.

O'Connor SE, Maresh JJ. 2006. Chemistry and biology of monoterpene indole alkaloid biosynthesis. Nat Prod Rep 23:532–47.

Omenn GS. 1995. What accounts for the association of vegetables and fruits with lower incidence of cancers and coronary heart diseases? Ann Epidemiol 5:333–5.

Onyilagha J, Bala A Hallett R, Gruber M, Soroka J, Westcott N. 2003. Leaf flavonoids of the cruciferous species, *Camelina sativa, Crambe* spp., *Thlaspi arvense* and several other genera of the family *Brassicaceae*. Biochem Syst Ecol 31:1309–22.

Onyilagha JC, Lazorko, Gruber MY, Soroka JJ, Erlandsoni MA. 2004. Effect of flavonoids on feeding preference and development of the crucifer pest. J Chem Ecol 30:109–24.

Otsuki T, Matsufuji H, Takeda M, Toyoda M, Goda Y. 2002. Acylated anthocyanins from red radish (*Raphanus sativus* L.). Phytochemistry 60:79–87.

Pascale SD, Maggio A, Pernice R, Fogliano V, Barbieri G. 2007. Sulphur fertilization may improve the nutritional value of *Brassica rapa* L. subsp. *sylvestris*. Eur J Agron 26:418–24.

Pedras MSC, Okanga FI, Zaharia IL, Khan AQ. 2000. Phytoalexins from crucifers: synthesis, biosynthesis, and biotransformation. Phytochemistry 53:161–76.

Pedroche J, Yust MM, Lqari H, Giron-Calle J, Alaiz M, Vioque J, Millan F. 2004. *Brassica carinata* protein isolates: chemical composition, protein characterization and improvement of functional properties by protein hydrolysis. Food Chem 88:337–46.

Piironen V, Syvaoja EL, Varo P, Salminen K, Koivistoinen P. 1986. Tocopherols and tocotrienols in Finnish foods: vegetables, fruits, and berries. J Agric Food Chem 34:742–6.

Podsedek A. 2005. Natural antioxidants and antioxidant capacity of *Brassica* vegetables. LWT Food Sci Technol 40:1–11.

Ponce MA, Scervino JM, Erra-Balsells R, Ocampo JA, Godeas AM. 2004. Flavonoids from shoots, roots and roots exudates of *Brassica alba*. Phytochemistry 65:3131–4.

Price KR, Casuscelli F, Colquhoun IJ, Rhodes MJC. 1998. Composition and content of flavonol glycosides in broccoli florets (*Brassica olearacea*) and their fate during cooking. J Sci Food Agric 77:468–72.

Puumalainen TJ, Poikonen S, Kotovuori A, Vaali K, Kalkkinen N, Reunala T, Turjanmaa K, Palosuo T. 2006. Napins, 2S albumins, are major allergens in oilseed rape and turnip rape. J Allergy Clin Immun 117:426–32.

Puupponen-Pimia R, Hakkinen ST, Aarni M, Suortti T, Lampi A, Eurola M, Piironen V, Nuutila AM, Oksman-Caldentey K. 2003. Blanching and long-term freezing affect various bioactive compounds of vegetables in different ways. J Sci Food Agric 83:1389–402.

Rahman KW, Sarkar FH. 2005. Inhibition of nuclear translocation of nuclear factor-{kappa} B contributes to 3,3′-diindolylmethane-induced apoptosis in breast cancer cells. Cancer Res 65:364–71.

Regenbrechta J, Strack D. 1985. Distribution of 1-sinapoylglucose: choline sinapoyltransferase activity in the *Brassicaceae*. Phytochemistry 24:407–10.

Reuber TL, Plotnikova JM, Dewdney J, Rogers EE, Wood W, Ausubel FM. 1998. Correlation of defence gene induction defects with powdery mildew susceptibility in *Arabidopsis* enhanced disease susceptibility mutants. Plant J 16:473–87.

Rice-Evans CA, Miller NJ, Paganga G. 1996. Structure-antioxidant activity relationships of flavonoids and phenolic acids. Free Radical Bio Med 20:933–56.

Rice-Evans CA, Miller NJ, Paganga G. 1997. Antioxidant properties of phenolic compounds. Trends Plant Sci 152–9.

Riso P, Brusamolino A, Ciappellano S, Porrini M. 2003. Comparison of lutein bioavailability from vegetables and supplement. Int J Vitam Nutr Res 73:201–5.

Robbers JE, Speedie MK, Tyler VE. 1996. Pharmacognosy and pharmacobiotechnology. Baltimore, Md.: Lippincott Williams and Wilkins. 337 p.

Robbins R, Keck AS, Banuelos G, Finley J. 2005. Cultivation conditions and selenium fertilization alter the phenolic profile glucosinolate and sulforaphane content of broccoli. J Med Foods 8:204–14.

Rodriguez R, Jimenez A, Fernandez-Bolanos J, Guillen R, Heredia A. 2006. Dietary fibre from vegetable products as source of functional ingredients. Trends Food Sci Technol 17:3–15.

Roetschi A, Si-Ammour A, Belbahri L, Mauch F, Mauch-Mani B. 2001. Characterization of an *Arabidopsis-Phytophtora* pathosystem: resistance requires a functional, PAD2 gene and is independent of salicylic acid, ethylene and jasmonic acid signalling. Plant J 28:293–305.

Rogers EE, Glazebrook J, Ausubel FN. 1996. Mode of action of *Arabidopsis thaliana* phytoalexin camalexin and its role in *Arabidopsis*—pathogen interactions. Mol Plant Microbe In 9:748–57.

Rosa E, David M, Gomes MH. 2001. Glucose, fructose and sucrose content in broccoli, white cabbage and Portuguese cabbage grown in early and late seasons. J Sci Food Agric 81:1145–9.

Rosa EA. 1997. Glucosinolates from flower buds of Portuguese *Brassica* crops. Phytochemistry 44:1415–9.

Rosa EAS, Heaney RK, Fenwick GR, Portas CAM. 1997. Glucosinolates in crop plants. Horticult Rev 19:99–215.

Rose P, Huang Q, Ong CN, Whiteman M. 2005. Broccoli and watercress suppress matrix metalloproteinase-9 activity and invasiveness of human MDA-MB-231 breast cancer cells. Toxicol Appl Pharm 209:105–13.

Rozan P, Lamghari R, Linder M, Villaume C, Fanni J, Parmentier M, Mejean L. 1997. *In vivo* and *in vitro* digestibility of soybean, lupine, and rapeseed meal proteins after various technological processes. J Agric Food Chem 45:1762–9.

Rule DC, Bushboom JR, Kercher CJ. 1994. Effect of dietary canola on fatty acid composition of bovine adipose tissue, muscle, kidney, and liver. J Anim Sci 72:2735–44.

Ryan CA, Pearce G. 2003. Systemins: A functionally defined family of peptide signals that regulate defensive genes in *Solanaceae* species. Proc Natl Acad Sci USA 100:14577–80.

Ryan CA, Pearce G, Scheer J, Moura DS. 2002. Polypeptide hormones. Plant Cell 14:251–64.

Sadeghi MA, Rao AGA, Bhagya S. 2006. Evaluation of mustard (*Brassica juncea*) protein isolate prepared by steam injection heating for reduction of antinutritional factors. LWT Food Sci Technol 39:911–7.

Salt DE, Blaylock M, Kumar NPB. 1995. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plant. Nat Biotechnol 13:468–74.

Samaila D, Ezekwudo DE, Yimam KK, Elegbede JA. 2004. Bioactive plant compounds inhibited the proliferation and induced apoptosis in human cancer cell lines, *in vitro*. Trans Int Biomed Inform Enabling Tech Symp J 1:34–42.

Saraviaa SGG, Gaylardeb CC. 1998. The antimicrobial activity of an aqueous extract of *Brassica nigra*. Int Biodeter Biodegr 41:145–8.

Sardi E, Tordai E. 2005. Determination of fully N-methylated compound in different cabbage and beetroot varieties. Acta Biol Szeg 49:43–5.

Sasaki K, Takahashi T. 2002. A flavonoid from *Brassica rapa* flower as UV-absorbing nectar guide. Phytochemistry 61:339–43.

Sato K, Kawakami N, Ohtsu T, Tsutsumi A, Miyazaki S, Masumoto T, Horie S, Haratani T, Kobayashi F, Araki S. 2004. Broccoli consumption and chronic atrophic gastritis among Japanese males: an epidemiological investigation. Acta Med Okayama 58:127–33.

Scalzo RL, Bianchi G, Genna A, Summa C. 2007. Antioxidant properties and lipidic profile as quality indexes of cauliflower (*Brassica oleracea* L. var. *botrytis*) in relation to harvest time. Food Chem 100:1019–25.

Scalzo RL, Genna A, Branca F, Chedin M, Chassaigne H. 2008. Anthocyanin composition of cauliflower (*Brassica oleracea* L. var. *botrytis*) and cabbage (*B. oleracea* L. var. *capitata*) and its stability in relation to thermal treatments. Food Chem 107:136–44.

Seow A, Yuan J, Sun C, Berg DVD, Lee1 H, Yu MC. 2002. Dietary isothiocyanates, glutathione S-transferase polymorphisms and colorectal cancer risk in the Singapore Chinese health study. Carcinogenesis 23:2055–61.
Shahidi F. 1995. Antinutrients and phytochemical in food. Washington, D.C.: American Chemical Society. 344 p.
Shirley BW. 2001. Flavonoid biosynthesis. A colorful model for genetics, biochemistry, cell biology, and biotechnology. Plant Physiol 126:485–93.
Simbaya J, Slominski BA, Rakow G, Lloyd D, Campbell LD, Downey RK, Bello JM. 1995. Quality characteristics of yellow-seeded *Brassica* seed meals: protein, carbohydrates, and dietary fiber components. J Agric Food Chem 43:2062–6.
Singh G, Kawatra A, Sehgal S. 2001. Nutritional composition of selected green leafy vegetables, herbs and carrots. Plant Food Hum Nutr 56:359–64.
Singh J, Upadhyay AK, Bahadur A, Singh B, Singh KP, Rai M. 2006. Antioxidant phytochemicals in cabbage (*Brassica oleracea* L. var. *capitata*). Scientia Horticulturae 108: 233–7.
Singh J, Upadhyay AK, Prasad K, Bahadur A, Rai M. 2007. Variability of carotenes, vitamin C, E and phenolics in *Brassica* vegetables. J Food Compos Anal 20:106–12.
Siqueira JO, Safir GR, Nair MG. 1991. Stimulation of vesicular-arbuscular mycorrhiza formation and growth of white clover by flavonoid compounds. New Phytol 118:87–93.
Skibola CF, Smith M. 2000. Potential health impacts of excessive flavonoid intake. Free Rad Biol Med 29:375–83.
Slominski BA, Simbay J, Campbell LD, Rakow G, Guenter W. 1999. Nutritive value for broilers of meals derived from newly developed varieties of yellow-seeded canola. Anim Feed Sci Technol 78:249–62.
Smith CJ. 1996. Accumulation of phytoalexins: defence mechanism and stimulus response system. New Phytol 132:1–45.
Smith TJ, Yang CS. 2000. Effect of organosulfur compounds from garlic and cruciferous vegetables on drug metabolism enzymes. Drug Metabol Drug Interact 17:23–49.
Smith TK, Lund EK, Clarke RG, Bennett RN, Johnson IT. 2005. Effects of Brussels sprout juice on the cell cycle and adhesion of human colorectal carcinoma cells (HT29) *in vitro*. J Agric Food Chem 53:3895–901.
Solecka D, Boudet AM, Kacperska A. 1999. Phenylpropanoid and anthocyanin changes in low-temperature treated winter oilseed rape leaves. Plant Physiol Biochem 37:491–6.
Staub RE, Feng C, Onisko B, Bailey GS, Firestone GL, Bjeldanes LF. 2002. Fate of indole-3-carbinol in cultured human breast tumor cells. Chem Res Toxicol 15:101–9.
Steinkellner H, Rabot S, Freywald C, Nobis E, Scharf G, Chabicovsky M, Knasmüller S, Kassie F. 2001. Effects of cruciferous vegetables and their constituents on drug metabolizing enzymes involved in the bioactivation of DNA-reactive dietary carcinogens. Mutat Res 480–1:285–97.
Stoewsand GS. 1995. Bioactive organosulfur phytochemicals in *Brassica oleracea* vegetables: a review. Food Chem Toxicol 33:537–43.
Suido H, Tanaka T, Tabei T, Takeuchi A, Okita M, Kishimoto T, Kasayama S, Higashino K. 2002. A mixed green vegetable and fruit beverage decreased the serum level of low-density lipoprotein cholesterol in hypercholesterolemic patients. J Agric Food Chem 50: 3346–50.
Tawfiq N, Heaney RK, Plumb JA, Fenwick GR, Musk SR, Williamson G. 1995. Dietary glucosinolates as blocking agents against carcinogenesis: glucosinolate breakdown products assessed by induction of quinone reductase activity in murine hepa1c1c7 cells. Carcinogenesis 16:1191–4.
Thiyam U, Kuhlmann A, Stöckmann H, Schwarz K. 2004. Prospects of rapeseed oil by-products with respect to antioxidative potential. C R Chim 611–6.
Tierens KFMJ, Thomma BPHJ, Brouwer M, Schmidt JR, Kistner K, Porzel A, Mauch-Mani B, Cammue BPA, Broekaert WF. 2001. Study of the role of antimicrobial glucosinolate-derived isothiocyanates in resistance of *Arabidopsis* to microbial pathogens. Plant Physiol 125:1688–99.
Tirasoglu E, Cevik U, Ertugral B, Apaydin G, Baltas H, Ertugrul M. 2005. Determination of trace elements in cole (*Brassica oleraceae* var. *acephale*) at Trabzon region in Turkey. J Quant Spectrosc RA 94:181–7.
Tripathi MK, Mishra AS. 2007. Glucosinolates in animal nutrion: a review. Anim Feed Sci Technol 132:1–27.
Valette L, Fernandez X, Poulain S, Lizzani-Cuvelier L, Loiseau A. 2006. Chemical composition of the volatile extracts from *Brassica oleracea* L. var. *botrytis* "Romanesco" cauliflower seeds. Flav FrAgric J 21:107–10.
Valette L, Fernandez X, Poulain S, Loiseau AM, Lizzani-Cuvelier L, Levieil R, Restier L. 2003. Volatile constituents from Romanesco cauliflower. Food Chem 80:353–8.
Vallejo F, Gil-Izquierdo A, Perez-Vicente A, Garcia-Viguera C. 2004. *In vitro* gastrointestinal digestion study of broccoli inflorescence phenolic compounds, glucosinolates, and vitamin C. J Agric Food Chem 52:135–8.
Vallejo F, Tomas-Barberan F, Garcia-Viguera C. 2003. Health-promoting compounds in broccoli as influenced by refrigerated transport and retail sale period. J Agric Food Chem 51:3029–34.
Vallejo F, Tomas-Barberan FA, Garcia-Viguera C. 2002. Potential bioactive compounds in health promotion from broccoli cultivars grown in Spain. J Sci Food Agric 82:1293–7.
Velisek J, Davidek J, Michova J, Pokorny J. 1990. Rapid gas chromatographic determination of volatile degradation products of glucosinolates in rapeseed oil. J Chromatogr A 502:167–70.
Verhoeven DTH, Goldbohm RA, Poppel G, Verhagen H, Brandt PA. 1996. Epidemiological studies on *Brassica* vegetables and cancer risk. Cancer Epidemiol Biomar Preven 5:733–48.
Verkerk R, Dekker M, Jongen WMF. 2001. Post-harvest increase of indolyl glucosinolates in response to chopping and storage of *Brassica* vegetables. J Sci Food Agric 81:953–8.
Verkerk R, Gaag MSVD, Dekker M, Jongen WMF. 1997. Effects of processing conditions on glucosinolates in cruciferous vegetables. Cancer Lett 114:193–4.
Vermunt SHF, Beaufrere B, Riemersma RA, Sebedio JL, Chardigny J, Mensink RP. 2001. Dietary *trans*-a-linolenic acid from deodorised rapeseed oil and plasma lipids and lipoproteins in healthy men: the *Trans*LinE study. Brit J Nutr 85:387–92.
Vuorela S, Kreander K, Karonen M, Nieminen R, Hamalainen M, Galkin A, Laitinen L, Salminen J, Moilanen E, Pihlaja K, Vuorela H, Vuorela P, Heinonen M. 2005. Preclinical evaluation of rapeseed, raspberry, and pine bark phenolics for health related effects. J Agric Food Chem 53:5922–31.
Vuorela S, Meyer AS, Heinonen M. 2003. Quantitative analysis of the main phenolics in rapeseed meal and oils processed differently using enzymatic hydrolysis and HPLC. Eur Food Res Technol 217:517–23.
Vuorinen T, Reddy GVP, Nerg A, Holopainen JK. 2004. Monoterpene and herbivore-induced emissions from cabbage plants grown at elevated atmospheric CO_2 concentration. Atmos Environ 38:675–82.
Wanasundara UN, Shahidi F. 1994. Canola extract as an alternative natural antioxidant for canola oil. J Am Oil Chem Soc 71:817–22.
Wang LI, Giovannucci EL, Hunter D, Neuberg D, Su L, Christiani DC. 2004. Dietary intake of cruciferous vegetables, glutathione S-transferase (GST) polymorphisms and lung cancer risk in a Caucasian population. Cancer Cause Control 15:977–85.
Wennberg M, Ekvall J, Olsson K, Nyman M. 2006. Changes in carbohydrate and glucosinolate composition in white cabbage (*Brassica oleracea* var. *capitata*) during blanching and treatment with acetic acid. Food Chem 95:226–36.
Wennberg M, Engqvist G, Nyman M. 2002. Effects of harvest time and storage on dietary fibre components in various cultivars of white cabbage (*Brassica oleracea* var. *capitata*). J Sci Food Agric 82:1405–11.
Williams RJ, Spencer JPE, Rice-Evans C. 2004. Flavonoids: Antioxidants or signalling molecules. Free Rad Bio Med 36:838–49.
Wills RBH, Rangga A. 1996. Determination of carotenoids in Chinese vegetables. Food Chem 56:451–5.
Windsor AJ, Reichelt M, Figuth A, Svatos A, Kroymann J, Kliebenstein DJ, Gershenzon J, Mitchell-Olds T. 2005. Geographic and evolutionary diversi.cation of glucosinolates among near relatives of *Arabidopsis thaliana* (*Brassicaceae*). Phytochemistry 66:1321–33.
Wittstock U, Halkier BA. 2002. Glucosinolates research in the *Arabidopsis* era. Trends Plant Sci 7:263–9.
Xue L, Schaldach CM, Janosik T, Bergmanc J, Bjeldanes LF. 2005. Effects of analogs of indole-3-carbinol cyclic trimerization product in human breast cancer cells. Chem Biol Interact 152:119–29.
Zakaria-Rungkat F, Djaelani M, Setiana, Rumondang E, Nurrochmah. 2000. Carotenoid bioavailability of vegetables and carbohydrate-containing foods measured by retinol accumulation in rat livers. J Food Comp Anal 13:297–310.
Zou Y, Kim AR, Kim JE, Choi JS, Chung HY. 2002. Peroxynitrite scavenging activity of sinapic acid (3,5-dimethoxy-4-hydroxycinnamic Acid) isolated from *Brassica juncea*. J Agric Food Chem 50:5884–90.
Zrybko CL, Fukuda EK, Rosen RT. 1997. Determination of glucosinolates in domestic and wild mustard by high-performance liquid chromatography and photodiode-array detection. J Chromatogr A 767:43–52.
Zukalova H, Vasak J. 2002. The role and effect of glucosinolates of *Brassica* species—a review. Rostlinna Vyroba 48:175–80.