Review Article

Major Sulphur Compounds in Plants and their Role in Human Nutrition and Health – An Overview

R PRASAD
Indian Agricultural Research Institute, New Delhi 110 012, India

(Received on 15 October 2014; Accepted on 22 October 2014)

Major sulphur compounds in plants include amino acids methionine and cysteine, vitamins thiamine and biotin and others of value from the viewpoint of human health, such as alliin (a precursor of alicin), glucosinolates (GSL), glutathione (GSH) and methylsulfonylmethane (MSM). Of these, methionine and thymine are essential nutrients and humans must obtain these from plant foods. Although cysteine is not an essential amino acid, its derivative - acetylcystein or N-acetylesystein - is used for the treatment of paracetamol toxicity, mucolytic (mucus dissolving) therapy, acute renal failure and psychiatric disorders. In recent years, the plant food that has received most attention is garlic, responsible for the production of alicin, which is credited for preventing cardiovascular disorders. Similarly, vegetables from the family Brassicae, such as, broccoli, cabbage and turnip rape have gained attention due to the presence of glucosinolates, which are reported to be useful in curing cancer. Glutathionate (GSH) pool is important in preventing diseases where increased oxidative stresses are implicated or where there is protein-energy malnutrition seen as a secondary manifestation, such as in AIDS, cancer, burns, chronic digestive diseases and alcoholism. Methylsulfonylmethane (MSM) is used for treating arthritis. Since plants obtain their sulphur from soil, adequate sulphur fertilization can play an important role in producing plant products with higher amounts of S-compounds, but there have been very few agronomic studies on this subject. The main objective of this review is to emphasize the need for such studies in India, especially in view of the fact that about 42% soils are deficient in sulphur.

Key Words: Methionine; Alicin; N-acetylesystein; Glucisinolate (GSL); Glutathionate (GSH); Methylsulfonylmethane (MSM); Garlic; Broccoli; Cabbage; Turnip Rape; Rapeseed

Introduction

Sulphur is an essential element for plants as well as humans. The primary source of S for human beings are the sulphur containing amino acids (SAAs) methionine and cysteine obtained from plant products in diet. The animal products in diet also owe this to plants, because the animals obtain S from these two amino acids present in grasses, fodder and feeds. This is due to the fact that biosynthesis of organic S compounds takes place only in plants and bacteria (Parcell, 2002). In addition to SAAs, plant products also contain S containing vitamins thiamin and biotin, some odorous compounds and several other compounds, which are important from the viewpoint of human nutrition and health.

Plants in turn obtain S from soil and adequate supply of available S is a must for successful production of agricultural and horticultural crops. Deficiency of sulphur in soils is global and has been reported from China (Messick and Fan, 2007), Europe (Messick, 2003), USA (Rehm, 2005), Canada (Solberg et al., 2006) and India (Singh, 2001; Tandon, 2011). In Asia, the recent rise in sulphur deficiency in soils is due to introduction of high yielding hybrids and varieties of crops and intensive cropping systems, such as ‘rice-wheat’ and increased use of non-sulphur

*Author for Correspondence: E-mail: rajuma36@gmail.com
high analysis nitrogen and phosphorus fertilizers (Prasad, 2005). There is also reduced contribution of atmospheric sulphur due to national and international agreements for reducing industrial sulphur dioxide production (Zhao et al., 1999). In India, nearly half of the cultivated soils are deficient in available S and good yield responses to S application have been reported (Singh, 2001; Biswas et al., 2004; Tandon, 2011). Most of the agronomic studies in India are restricted to yield increase and S uptake by crops. It has been reported that limited availability of sulphur in soils may lead to synthesis and accumulation of S-poor proteins (Zhao et al., 1999; Flaete et al., 2005). No reports are available in India on the varietal differences and effect of agronomic management on SAAs and other S containing compounds in plants. This review focuses the attention for the need of such research.

**Sulphur Containing Amino Acids (SAAs)**

About 70% of sulphur in plants is present as amino acids. Of the two SAAs making up different proteins, methionine is considered essential (along with lysine, leucine, isoleucine, histidine, phenylalanine, threonine, tryptophan and valine), while cysteine (along with alanine, arginine, glycine, aspartic acid, glutamic acid, glutamine, proline, serine, tyrosine, asparagine, and selenocysteine) is considered a non-essential for humans (Furst and Stehle, 2004). Humans cannot synthesize essential amino acids and these must be obtained through diet. The recommended daily allowance (RDA) (mg/kg/day) for SAAs (methionine+cysteine) is 58 for 3-4-month infants, 27 for 2-year-old, 22 for 10-12-year-old and 13 for adults (Parcell, 2002). Information on average content of some amino acids in plant foods is presented in Table 1.

(a) **Methionine**

As already stated, methionine is an essential amino acid that cannot be synthesized by humans and must be obtained through diet. Beans, soybean and sesame in plants and of course animal foods including eggs are the main source of methionine. Methionine is an intermediate in the biosynthesis of cysteine, carotin, taurine, lecithin and phospholipids. Methionine can reduce acetaldehyde levels after alcohol ingestion and can thus lower liver-damaging effects of alcohol (Tabakoff et al., 1989). As a methyl-donor, methionine helps prevent fatty liver disease and eventual cirrhosis of the liver (Richmond, 1986). Methionine is also reported to be effective in the treatment of Parkinson’s disease (Smythies and Hasley, 1984) and acute pancreatitis (Uden et al., 1990). However, excessive methionine consumption can be harmful. Restricting methionine consumption is reported to increase life span in some animals (Alleyene, 2009). Methionine restriction can also inhibit aging related disease processes (Richie et al., 1994) and colour carcinogenesis in rats (Komninou, 2006).

An important metabolite of methionine is S-adenosylmethionine (SAMe), which is involved in many metabolic processes in human body (Chiang et al., 1996). Human body in general produces all SAMe that it needs, however, shortage of methionine or cofactors folic acid and choline required for the production of SAMe can lead to its shortage. Deficiency of SAMe can lead to depression (Reynolds et al., 1984). SAMe supplements are used for curing depression (Kagan et al., 1990) and for treating osteoarthritis (diPadova, 1987).

<table>
<thead>
<tr>
<th>Plant food</th>
<th>Lysine</th>
<th>SAAs</th>
<th>Threonine</th>
<th>Tryptophan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legumes</td>
<td>64±10</td>
<td>25±3</td>
<td>38±3</td>
<td>12±4</td>
</tr>
<tr>
<td>Cereals</td>
<td>31±10</td>
<td>37±5</td>
<td>32±4</td>
<td>12±4</td>
</tr>
<tr>
<td>Nuts &amp; Seeds</td>
<td>45±14</td>
<td>44±17</td>
<td>36±3</td>
<td>17±3</td>
</tr>
<tr>
<td>Fruits</td>
<td>45±12</td>
<td>27±6</td>
<td>29±7</td>
<td>11±2</td>
</tr>
</tbody>
</table>

Table 1: Average amino acid content (mg/g protein) in some plant foods

Adapted from: Young and Pellet (1994)
Methionine is the precursor of ethylene, which is responsible for fruit ripening, an important physiological process in plants from the viewpoint of human nutrition. The fruits which ripen due to ethylene are known as climactric and include mango, guava, banana, apple, pear, peach, apricot, avocado cantaloupe, fig, kiwi fruit, tomato etc. (Kader, 1999). The non-climactric fruits include berries, cherry, grapes, limes, oranges etc. Ripening makes fruits sweeter (by conversion of starch into sugar by amylases), softer (by reducing the amount of pectin by enzymes such as polygalacturonase), less tart (by conversion of acids to neutral molecules by kinases), fragrant (by conversion of a large number of organic molecules to volatile aromatic compounds) and red to yellow in colour (by destruction of chlorophyll) (Medicott and Thompson, 1985; Bashir and Abu-Goukh, 2003; Prasanna et al., 2007; Duana et al., 2008). Russian scientist Dimitry Neljibou was the first to point out the role of ethylene in ripening and Gane (1934) was the first to report the biosynthesis of ethylene by plants. It was later found that ethylene in plants is formed from the Cu$^{+}$-catalyzed breakdown of methionine (Lieberman and Kunishi, 1965). The bulk of the fruit industry handles (harvest, transport and storage) climactric fruits, in which ripening can be controlled by concentration and exposure to ethylene (Ritenour et al., 1999; Chomchelow et al., 2002; Dang et al., 2006). In India, a plastic cover is placed over unripe fruits and calcium carbide is placed in open containers in strategic positions. Moisture from the air reacts with calcium carbide and produces ethylene. However, industrial grade calcium carbide contains traces of arsenic and phosphorus, which can be toxic to children (Hakan, 2007).

(b) Cysteine

Cysteine plays important roles as an extracellular reducing agent, a critical substrate for protein synthesis and the rate limiting precursor of glutathione and taurine (Kleinman and Richie, 2000). In baking industry, higher cysteine residues in wheat flour produce a more extensible and pliable dough due to disulphide bonds leading to better quality bread (Alary and Kobrechel, 1987). Based on studies on mice, it has been shown that Se-methylselenocysteine can serve as a therapeutic agent which disrupts androgen receptor signaling for prostate cancer (Pinto et al., 2007).

Acetylcystein (or N-acetylcystein), a derivative of cysteine is manufactured and sold as a pharmaceutical drug and nutritional supplement and is on the WHO’s list of essential medicines needed in a basic health system (WHO 2013). It has several medicinal uses, which include:

(i) Treatment of paracetamol (acetaminophen) overdose or toxicity (Green et al. 2013),

(ii) Mucolytic (mucous-dissolving) therapy as an adjuvant in respiratory conditions with excessive and/or thick mucus production as in bronchitis, tuberculosis, pneumonia etc. (Stey et al. 2000),

(iii) Prevention of radio contrast-induced nephropathy (a form of acute renal failure) (Tapel et al. 2000),

(iv) Prevention of progressive interstitial lung disease (Poole and Black, 2011),

(v) Treatment of psychiatric disorders (Bark et al. 2013).

(c) Sulphur Fertilization and S Concentration, S:N Ratio and SAAs in Grain

Sulphur fertilization generally results in increased S concentration in grain. Ercoli et al. (2011) reported that S concentration in wheat grain increased from 1.4 to 1.6 g kg$^{-1}$ due to an application of 120 kg S ha$^{-1}$. Similarly Shivay et al. (2014) reported that S concentration in rice grain increased from 1.2 to 1.6 g kg$^{-1}$ with an application 45 kg S ha$^{-1}$. Increased S concentration leads to a decrease in N:S ratio. Coyle and McAleese (1970) reported that N:S ratio in wheat grain declined from 11-28 to 10-17 and from 26-28 to 8-10 in barley grain due to sulphur fertilization. Lerner et al. (2006) also observed that S fertilization caused significant changes in N:S ratio in wheat.
Shivay et al. (2014) found that application of 45 kg S ha$^{-1}$ reduced N:S ratio from 9.77 to 7.79 in rice grain. A reduced N:S ratio in grain suggests an increase in SAAs. Josefsson (1970) found that S fertilization increased S-containing amino acids in rapeseed. Jarvan et al. (2008) reported an increase in cysteine and methionine content in wheat grain due to S fertilization (Table 2).

**Sulphur-Containing Vitamins**

Thiamine (or thiamin or Vit B$_1$) and biotin (or Vit H or Coenzyme R) are two sulphur containing amino acids.

**(a) Thiamine**

Thiamine is one of the components of vitamin B complex. It is water-soluble. Thiamine pyrophosphate or thiamin diphosphate is a coenzyme involved in the catabolism of sugars and amino acids. Thiamin is involved in the biosynthesis of neuro-transmitter acetylcholine and $\gamma$-aminobutyric acid (GABA). It is on the list of WHO essential medicines needed in the basic health system (WHO 2013).

Just like essential amino acids, only plants, bacteria and fungi can synthesize thiamine and humans must obtain it from the food that they eat. Cereal grains are the most important source of thiamine. In cereal grains, thiamine is concentrated in the outer layer and germ, which are generally removed in the refining process. In USA and Australia, the processed wheat flour must be enriched with thiamine nitrate. Yeast and yeast extract are the most highly concentrated source of thiamine. Leavened (bakery made) wheat bread is therefore richer in thiamine than unleavened bread (*Indian chapati*). The RDA for thiamine is 1.4 mg.

Human nervous system is particularly sensitive to thiamine deficiency and well known syndromes caused by this deficiency include beriberi (Mahan and Escott-Stump, 2000; Shils et al., 2006; Spinazzi et al., 2010), Wernicke-Korsokof syndrome (alcohol abuse syndrome) (Harper, 1979; Krill, 1996) and optic neuropathy (bilateral visual loss, impaired colour perception) (Spinazzi et al., 2010).

**(b) Biotin**

Biotin is a coenzyme involved in the synthesis of fatty acids, isoleucine and valine and in gluconeogenesis. In humans, intestinal bacteria produce enough biotin and therefore there is no RDA for it, although pregnant females may need biotin supplement. Leafy green vegetables are a good source of biotin. Biotin is considered to be involved in strengthening of hair and nails and a large number of commercial formulations are marketed for this purpose although scientific proofs based on well-planned studies for it are lacking (http://en.wikipedia.org/wiki/Biotin).

**Alliin, Allicin and Diallyl Disulfide**

**(a) Alliin**

Alliin a sulfoxide, is a derivative of cysteine and is a natural constituent of fresh garlic and a precursor of allicin (Iberi, 1990).

### Table 2: Effect of sulphur fertilization on amino acid composition in wheat grain$^1$

<table>
<thead>
<tr>
<th>Fertilizer (kg ha$^{-1}$)</th>
<th>Grain (t ha$^{-1}$)</th>
<th>Protein (%)</th>
<th>Amino acid in grain (g kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cysteine</td>
</tr>
<tr>
<td>0 (control)</td>
<td>4.58</td>
<td>11.1</td>
<td>2.35(21.2)$^2$</td>
</tr>
<tr>
<td>100 N</td>
<td>5.08</td>
<td>13.9</td>
<td>2.23(16.0)</td>
</tr>
<tr>
<td>100 N +10 S</td>
<td>5.88</td>
<td>13.4</td>
<td>2.91(21.7)</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.32</td>
<td>0.4</td>
<td>0.31</td>
</tr>
</tbody>
</table>

1. Data for 2005 trial at Saku; 2. Figures in parentheses are g kg$^{-1}$ protein; Adapted from Jarvan et al. (2008)
(b) Allicin

Allicin is produced from alliin with the help of enzyme allinase when fresh garlic is chopped or crushed. Alliin and allinase are kept in separate compartments of the cell and react only when the compartments are broken. Allicin is responsible for the fresh aroma of fresh garlic (Kourounakis and Rekka, 1991), is unstable and soon changes into a series of sulfur compounds including diallyldisulfide. Allicin provides protection to the garlic plants from insect pests.

Allicin has anti-bacterial (Cutler and Wilson, 2004), anti-viral (Block, 2010) and anti-protozoal (Salama et al., 2014) properties. It is reported to reduce fat deposition (Eliat et al., 1995; Abramovitz et al., 1999), cholesterol absorption (Nijjar et al., 2010) and blood pressure (Silagy and Neil, 2003; Elkayam et al., 2003). It has also anti-inflammatory and anti-oxidant properties (Banerjee et al., 2001; Bautista et al., 2005). Raw garlic, powdered garlic supplements and aged garlic supplements are equally efficacious (Choudhary and Tomer, 2013).

(c) Effect of Fertilizers

Mirzaei et al. (2007) reported that garlic clones differed significantly in their allicin content, which varied from 0.05 to 5.64 mg g\(^{-1}\), but the effects of organic and chemical fertilizers were not significantly different.

(d) Dially-Disulfide

Dially-disulfide (DADS) is derived from garlic and few other genera of Aliaceae. In highly diluted forms, DADS is used as a flavoring agent and improves the taste of meat, vegetables and fruits. It is also an environmentally benign nematicide (Block, 2010). Some of the benefits of garlic, such as prevention of colorectal cancer (Milner, 2003; Jo et al., 2008) are due to DADS. However, DADS is a skin irritant and an allergen (Horn, 2003).

Glucosinolates (GSLs)

Glucosinolates (GSLs) are natural pungent secondary metabolites in plants of family Brassicaceae, such as, mustard, cabbage, broccoli, horse radish etc. GSLs are derived from glucose and amino acids and are water-soluble. The so-called aliphatic GSLs are derived mainly from methionine, but also from alanine, leucine, isoleucine and valine, while aromatic GSLs, such as glucobrassicin, are derived from tryptophan. So far, about 132 GSLs have been reported. When the plant material is cut, chewed or crushed, the enzyme myrocinase cleaves off glucose from GSLs in the presence of water and releases isothiocynates (commonly known as mustard oil), thiocyanates and nitriles (Glawisching et al., 2003), which are responsible for pungency and defence mechanism against insect pests (Wittstock et al., 2004). In the plants, the enzyme myrocinase and GSLs are kept in separate compartments but come in contact when the plant tissue is cut or crushed. Some GSLs are toxic (mainly as goitrogens) to humans and animals at high doses. However, recently GSLs have been reported to be involved in mitigating cancer ((Beecher, 1994; Williamson et al., 1998; Das et al., 2000; Hayes et al., 2008) and consumption of large amounts of vegetables especially broccoli, Brussels sprout and cabbage is being encouraged.

(a) Effects of Fertilizers

Staley et al. (2010) reported that GSLs in cabbage (Brassica oleracea var capitata) were three times when grown on organic manure than when it was grown on chemical fertilizers. He also reported that the content of glubrassicin was much more than sinigrin. Pradhan et al. (2007) reported that cabbage grown with human urine had as much GSLs as obtained with inorganic fertilizers; total GSLs were about 3.07 to 3.69 µmoles g\(^{-1}\) DM.

Nartis (2011) found that application of fertilizer nitrogen in 2 or 3 split applications produced more GSLs in winter turnip rape (Brassica rapa L). The amount of total GSLs in 6 cultivars studied ranged from 10.6 to 18.7µmoles g\(^{-1}\) DM. Zhao et al. (1993) observed that nitrogen application decreased GSL content in seeds of double row (Brassica napus L) in the absence of S but increased it when adequate S was applied along with nitrogen. Josefsson (1970) and Schung (1989) also reported that S fertilization increased GSLs in rapeseed (Brassica napus L). As regards vegetable turnip rape (Brassica rapa L), Kim
et al. (2001) observed that application of lower doses of N with adequate S fertilization increased GSL concentration in edible portion; total GSL content varied from 28 to 80 µmoles g⁻¹ DM and gluconapin and glucobrassicanapin were the main GSLs, which were also responsible for the bitterness.

In broccoli (Brassica oleracea var italica), Naquib et al. (2011) found that application of 50% nitrogen as chicken manure and the rest 50% as chemical fertilizer gave a GSL concentration 71.34 µmoles g⁻¹ DM in florets as compared to only 48.7 µmoles g⁻¹ DM obtained with 100% chemical fertilizer. Perez-Ballibrea et al. (2010) found that sulphur fertilization increased GSLs in broccoli sprouts during germination. Avilla et al. (2013) obtained no effect of selenium application on GSLs in broccoli.

**Glutathione (GSH)**

Glutathione (GSH) is an important antioxidant in plants, animals, fungi and some bacteria preventing damage to important cellular components caused by reactive oxygen species such as free radicals and peroxides (Pompella et al., 2003). It is a tripeptide of γ-glutamine, cysteine and glycine (Huxtable, 1986). GSH pool is important in diseases where increased oxidative stresses are implicated or where there is protein-energy malnutrition seen as a secondary manifestation, such as in AIDS, cancer, burns, chronic digestive diseases and alcoholism (Bray and Taylor, 1993).

It is not an essential nutrient and needed amounts are generally synthesized in the human body. However, it is possible to raise GSH levels in blood by daily consumption through GSL supplements (Richie et al., 2014) including those containing cysteine (Bray and Taylor, 1993). GSH has a role in iron metabolism (Kumar et al., 2011). The concentration of GSH in must (freshly pressed grape pulp that contains the skins, seeds, and stems of the fruit) determines the browning effect during the production of white wine (Jacques et al., 2011).

**Methylsulfonylmethane (MSM)**

Methylsulfonylmethane (MSM) (an oxidation product of dimethylsulfone) is found in fruits, corn, tomatoes, tea, coffee, alfalfa, human and, bovine milk and in human urine (Richmond, 1986). About 4-11 mg day⁻¹ is excreted in human urine (Williams et al., 1966). MSM contains 34% S. The concentration of sulfur in arthritic cartilage is about one-third of normal cartilage and therefore MSM is being used for treating arthritis (Parcell, 2000). MSM is also reported to reduce the duration of chiropractic (treatment and prevention of mechanical disorders of the musco-skeletal system, especially the spine) visits for treating athletic injuries. MSM is also used for treating hyperacidity, parasites, constipation and allergies and for immunomodulation (Parcell, 2000).

**Epilogue**

The year 2013 marked the 50th anniversary of the commencement of a yield revolution in wheat that ushered the Green Revolution in 1968 and assured food-security in India (Swaminathan, 2013). Higher and higher grain yield of food grains has been the goal of most plant breeding and agronomic research in the country and nutritional quality of the farm produce received only little attention. However, increasing global interest in nutraceuticals as supportive or alternative medicine in view of the undesirable side effects of chemotherapy has focused attention of the content of such compounds in farm food products (Choudhary and Tomar, 2013). Sulphur compounds in farm food products, especially from the plants of Brassicae and Alliaceae families deserve special attention. However, most agricultural universities and institutions do not have departments of food and nutrition and such studies have not been possible. It is high time that such facilities are created in agricultural universities and institutes. Until such additional facilities are developed, the Indian National Science Academy may consider organizing group discussions of scientists from the disciplines of agriculture, nutrition, pharmacy and medicine to draw out a joint program of creating such data in India. Such information has become more so important in view of the fact that compositional details have now become essential for marketing farm food products in the international trade.
References


Gane R (1934) Production of ethylene by some fruits. Nature (London) 134 1008


Harper C (1979) Wernicke's encephalopathy, a more common disease than realized (a neuropathological study of 51 cases) J Neurol Neurosurg Psychiat 42(3) 226-231


Iberi B (1990) Qualitative determination of alliin and allicin from garlic by HPLC. Planta Med 56(5) 320-326


Krill JJ (1996) Neuropathology of thiamine deficiency disorders. Metab Brain Dis 11(1) 9-17


Narits L (2011) Effect of top fertilizing on raw protein and glucosinolate content of winter turnip rape. *Agron Res* **9** (Special Issue II) 451-454


